CLF

A publication of the CLF WBLCA Benchmark Study (v2)

The California Carbon Report:

An Analysis of the Embodied and Operational Carbon Impacts of 30 Buildings

REPORT | MAY 2024

CLF Carbon Leadership Forum

CBE CENTER FOR THE BUILT ENVIRONMENT

ABOUT THE CARBON LEADERSHIP FORUM

The Carbon Leadership Forum accelerates the transformation of the building sector to radically reduce the greenhouse gas emissions attributed to materials (also known as embodied carbon) used in buildings and infrastructure.

We research, educate, and foster cross-collaboration to bring the embodied carbon of buildings and infrastructure down to zero.

ABOUT UC BERKELEY CENTER FOR THE BUILT ENVIRONMENT

The Center for the Built Environment (CBE) is a collaborative research center at the University of California, Berkeley. CBE is a place where prominent industry leaders and internationally recognized researchers cooperate to produce substantial, holistic and far-sighted research on buildings. CBE's mission is to improve the environmental quality and energy efficiency of buildings by providing timely, unbiased information on building technologies, design and operation strategies.

AUTHORS

The research team from the Carbon Leadership Forum at the University of Washington College of Built Environments and the University of California Berkeley Center for the Built Environment:

- Brad Benke, Researcher, Carbon Leadership Forum, University of Washington
- Matt Roberts, Postdoctoral Researcher, Center for the Built Environment, University of California Berkeley
- Yang Shen, Researcher, Carbon Leadership Forum, University of Washington
- Steph Carlisle, Researcher, Carbon Leadership Forum, University of Washington
- Mel Chafart, Researcher, Carbon Leadership Forum, University of Washington
- Kate Simonen, Executive Director, Carbon Leadership Forum, University of Washington

Author contributions: Writing - original draft: B.B., M.R., and Y.S.; Writing - review and editing: B.B., M.R., Y.S., S.C., K.S., and M.C.; Conceptualization: K.S.; Methodology: B.B., M.R., Y.S., S.C., and K.S.; Data curation: M.C., B.B., Y.S., and M.R.; Formal analysis: Y.S. and B.B.; Visualization and Graphics: Y.S., B.B., and M.R.

CITATION

Benke, B., Roberts, M., Shen, Y., Carlisle, S., Chafart, M., and Simonen, K. (2024). The California Carbon Report: An Analysis of the Embodied and Operational Carbon Impacts of 30 Buildings. Carbon Leadership Forum, University of Washington. Seattle, WA. http://hdl.handle.net/1773/51287

COPYRIGHT

This report can be found at https://carbonleadershipforum.org/california-carbon/

COMPETING INTERESTS STATEMENT

The Carbon Leadership Forum receives gifts from sponsors, including manufacturers and trade associations, which are listed here: https://carbonleadershipforum.org/our-sponsors/. The Center for the Built Environment (CBE) at the University of California, Berkeley, is advised and funded in part, by many partners that represent a diversity of organizations from the building industry, including manufacturers, building owners, facility managers, contractors, architects, engineers, government agencies, and utilities.

ACKNOWLEDGMENTS

The research team would like to thank the Alfred P. Sloan Foundation, the ClimateWorks Foundation, and the Breakthrough Energy Foundation for supporting this research project.

Thank you to the data contributors of this study who provided substantial time and effort in submitting building project data for this report and sharing feedback with the research team:

- *Arup*
- *EHDD Architecture*
- *Gensler*
- *GGLO*
- *Glumac*
- *Kieran Timberlake*
- *HOK*
- *Miller Hull*
- *Mithun*
- *ZGF Architects*

Thank you to the CLF WBLCA Benchmark Study (v2) pilot phase participants who helped test and inform the data collection methods used for this study:

- *GGLO*
- *Kieran Timberlake*
- *LMN Architects*
- *Miller Hull*
- *Mithun*
- *Perkins Will*

Additionally, thank you to the research staff that engaged with this project during its initiation, helped develop background research for its execution, and/or provided technical review:

- Milad Ashtiani, Researcher, Carbon Leadership Forum, University of Washington
- Allison Hyatt, (former) Researcher, Carbon Leadership Forum, University of Washington
- Fiona Greer, Postdoctoral Researcher, Department of Civil and Environmental Engineering, University of California, Berkeley

EXECUTIVE SUMMARY

In this report, we explored using building data collected from design practitioners to estimate the embodied and operational carbon impacts of 30 new construction building projects in the State of California. The State of California was chosen for this preliminary study owing to its unique climate, large population, geographic size, rapidly decarbonizing electrical grid, ambitious climate targets, and quickly evolving policy landscape. By analyzing the embodied and operational carbon impacts of the buildings, we sought to answer the following questions:

- What is the projected balance of emissions between operational and embodied carbon over time for a sample of new buildings in California?
- What are reasonable estimates of embodied and operational carbon intensities for the buildings analyzed?
- What are the most significant contributors to embodied carbon impacts from different building scopes, elements, or materials?
- What are the current gaps and challenges within industry practices toward developing comprehensive whole life carbon assessments?
- How do the results vary based on changes to LCA methods and assumptions?

Assessment methods and data

Environmental life cycle assessment (LCA) methods and data were used to evaluate the global warming potential (GWP, measured in units of carbon dioxide equivalents or CO_2e) for both the material impacts (embodied carbon intensity or ECI) and operating impacts of electricity and natural gas usage (operational carbon intensity or OCI) of multiple buildings over a 60-year reference period.

Based on available data, the primary comparison of embodied and operating impacts was limited to the physical building scope of structure and enclosure. Additionally, 19 of the assessed buildings included interior construction LCA results. Life cycle stages included upfront carbon (A1-A4), use (B4-B6), and end-of-life (C2-C4) based on the scope of data available and current industry practices. The study excluded biogenic carbon stored in materials and Module D for impacts outside the system boundary of the building.

Quantities of materials, energy consumed, and resulting carbon impacts were estimated using secondary data sources. Results of LCA studies performed by industry professionals using building sector LCA tools were evaluated to generate material quantity estimates aligned with embodied carbon estimates. The operational electricity and natural gas consumption were estimated from both modeled and predicted building energy use depending on what data was provided. Operational carbon emissions over the life span were estimated using average annual grid carbon intensities following grid decarbonization scenarios extended from the National Renewable Energy Lab's Cambium dataset 'mid-case' predictive scenario.

Key findings

For the 30 buildings studied, the following findings over a 60-year study period studying structure, enclosure, and operating impacts are summarized:

1. The median embodied carbon impacts of structure and enclosure alone accounted for a larger share of emissions than operational carbon when grid decarbonization is included.
2. If the projected grid emissions assume no decarbonization and match existing conditions over the full life cycle, the median operational carbon impacts exceeded those of embodied around the year 2037.
3. The median lifetime carbon impacts of the buildings in the study were approximately:
    a. 390 kg CO_2e/m^2 for embodied carbon intensity (ECI)
    b. 230 kg CO_2e/m^2 for operational carbon intensity (OCI)
    c. 730 kg CO_2e/m^2 for total carbon intensity
4. While embodied carbon impacts tended to be higher than those of operational carbon on average, the range of operational carbon impacts was wider. This was largely dictated by the energy source that the buildings depended on (electricity vs. natural gas). Buildings that reduced or eliminated the use of natural gas had substantially lower operational carbon emissions than those that did not.
5. We found statistically insignificant correlations between building types or categorizations of buildings and higher or lower embodied carbon impacts. While categorizing and organizing embodied carbon impacts, the following trends were identified based on averages across projects:
    - When embodied carbon impacts were categorized by life cycle stages, material manufacturing (A1-A3) were the largest contributors,
    - When categorized by building elements, structural systems were the largest contributors, and
    - When categorized by material division, concrete and metals were the largest contributors.
6. The cumulative impacts of interiors can be significant, increasing the ECI of projects by an average of approximately 65 kg CO_2e/m^2, or an average of an 18% increase in ECI when compared to structure and enclosures only.
7. Not all building components were included and some life cycle stages were omitted for both embodied and operational carbon impacts. Thus, the values reported in this study underestimate the whole life carbon impacts of buildings.

Limitations

The findings of this report are not generalizable due to limitations of the study. The largest of these include a lack of data to fully quantify and verify all potential whole life carbon impacts of the projects studied and a limited sample size for drawing conclusions. Additionally, this study focuses solely on global warming potential (GWP) and does not consider other environmental impact categories that could be quantified using LCA.

Other significant limitations of this study included:

Methods and data quality

- Data supplied by data contributors was not verified.
- Operational energy use was represented by a single annual average estimate.
- Biogenic carbon was not considered which can significantly impact findings for wood structures.
- Dynamic radiative forcing from the timing of emissions was not considered. Current and future emissions were rated as the same.

Building element scope

- The level of completeness and resolution to which building elements were included was not verified.
- Building interiors were included in some, but not all, models studied.
- Sitework, mechanical, electrical, and plumbing (MEP), and furnishings were excluded.
- No information was collected to quantify the impacts of refrigerants.
- Insufficient information was collected regarding the size and composition of the on-site energy generation and/or storage technologies to incorporate these technologies within the assessment scope.

Building life cycle stage scope

- No information was collected for construction impact (A5), fugitive emissions and other use impacts (B1), maintenance (B2), repair (B3), operational water use (B7), user activities (B8), or deconstruction/demolition (C1).
- Module D is excluded and thus potential impacts and benefits of waste treatment and recovery are not included.

Future research

Based on the limitations and findings from the present study, several recommendations were formulated to guide future research and inform design and policy developments.

Carbon accounting methodologies

Further work is needed to update and align how GHG emissions are calculated and reported. This includes:

- Biogenic carbon within background LCI data sources, LCA tools, and reporting
- Integrating dynamic radiative forcing analysis to evaluate the importance of near-term versus future GHG emissions and removals

On-site renewables and building energy demand profiles

Expand the scope of the assessment to account for the embodied carbon impacts of all on-site energy generation and on-site energy storage technologies that are part of a building including their replacement, recycling, and end-of-life impacts. The use of on-site energy generation and on-site energy storage technologies elevates the importance of time-of-use grid carbon intensity factors and appropriate granularity of building demand profiles. As such, the operational energy use impacts and the time-of-use grid carbon intensities should be further investigated to determine the appropriate granularity needed from both the consumer-side (building) and the producer-side (grid) to make appropriate net-zero energy and/or net-zero carbon claims for operational energy use (B6).

Physical building element scope

Future work should address current gaps within the physical scope of building-scale assessments, including the lack of information and lack of completeness for the following building elements:

- MEP systems, including on-site energy generation and storage
- Site impacts
- Interiors and furnishings, fixtures & equipment (FF&E)

Temporal life cycle stage scope

Future work is also required to include life cycle stages that are not regularly considered within current practices:

- Site preparation, demolition of existing structures, construction stage emissions (including duration and techniques), and treatment of construction waste (A5)
- Refrigerant type, leakage, and other fugitive emissions (B1)
- Repair, maintenance, and refurbishment of building elements (B2, B3, B5)
- End-of-life impacts, particularly deconstruction (C1)
- The benefits and loads that occur outside the system boundary for the assessment (Module D)

Geographic and typological iterations

This study used a small and limited sample of new building projects in the State of California. In order to develop broadly generalizable findings, the sample size and sampling method should be refined.

TABLE OF CONTENTS

1. INTRODUCTION

1.1 Background

Addressing climate change is one of the greatest environmental challenges our global society has ever faced. Our built environment plays a critical role in climate change mitigation as it is a significant source of greenhouse gas (GHG) emissions. Buildings are responsible for approximately 37% of global energy and process-related GHG emissions (United Nations Environment Programme, 2022). Emissions need to be reduced, avoided, and eliminated wherever possible to mitigate the worst consequences of climate change. Despite recent efforts from designers, builders, developers, and policymakers in the United States (US) to reduce the impacts of buildings, US emissions still grew in 2022 by about 0.8%, and of that percentage, the building sector saw the highest emissions growth largely due to extreme temperatures and natural gas consumption (IEA, 2023). As global temperatures are only continuing to increase, it is clear that greater and more immediate decarbonization of our buildings and infrastructure is necessary. Actors in the built environment are promoting strategies targeted at reducing the environmental impacts of buildings while at the same time developing a more complete understanding of the scale and sources of environmental impacts that are associated with our buildings.

The US building sector and its stakeholders are aware of these challenges. Many governments, agencies, design companies, builders, and developers have proposed net-zero commitments to drive change across the sector. There have also been dramatic increases in both the quantity and quality of voluntary commitments and mandatory policies targeting emission reductions for buildings. In the US, voluntary embodied and/or operating carbon commitments have been declared for building services (MEP 2040), structural systems (SE 2050), and entire buildings (Architecture 2030). Additionally, green building rating systems such as the US Green Building Council's (USGBC) Leadership in Energy and Environmental Design (LEED) and the International Living Future Institute's (ILFI) Living Building Challenge both offer net-zero certifications. Similarly, policymakers at both the state and national levels have been passing successful legislation to achieve emissions reductions, and many of these policies rely heavily on building-related decarbonization. California, specifically, has been a leader within the US in building decarbonization codes and policies to date.

In 2022, and as part of California's Climate Commitment, multiple laws were passed to reduce the state's GHG emissions (Office of Governor Gavin Newsom, 2022). Additionally, California has stringent energy codes (CEC 2022), established the first Buy Clean Policy in the country (Assembly Bill No. 262, Chapter 816, Sections 3500-3505, 2017), and passed the first statewide building codes (ICC, 2022) which included building life cycle assessment. Such legislation establishes clear goals and places California on legally binding pathways to reach a 90% renewable electricity grid by 2035 and a 100% renewable grid by 2045 and achieve statewide net-zero carbon emissions by 2045. If California is successful in implementing these goals and continues its push to electrify buildings, then the operational carbon impacts of its building stock should decrease dramatically. However, if the embodied carbon impacts from buildings do not decarbonize in the same timeframe, then a significant source of emissions may be left unabated.

Though all of these commitments and policies vary in their scopes and ambition levels, they all ultimately seek to reduce GHG emissions in alignment with Paris Agreement targets. Progress has been made throughout the building design, construction, and policy communities. Still, building decarbonization at scale has continued to prove challenging. There are data gaps to be filled, industry practices to be improved, more policies to be developed, and improvements to be undertaken for the entire LCA data ecosystem (Lewis et al., 2023). To truly achieve building decarbonization at the scale and speed required, a more holistic approach to GHG accounting and reduction is necessary.

1.2 Purpose

In this study, we investigated the use of whole life carbon assessment (WLCA) through a sample of 30 buildings sourced from design practitioners. In doing so, we sought to answer the following questions:

- What is the projected balance of emissions between embodied and operational carbon over time for a sample of new buildings in California?
- What are reasonable estimates of embodied and operational carbon intensities for the buildings analyzed?
- What are the most significant contributors to embodied carbon impacts from different buildings' scopes, elements, or materials?
- What are the current gaps and challenges within industry practices toward developing comprehensive whole life carbon assessments?
- How do the results vary based on changes to LCA methods and assumptions?

The target audience for this report is researchers and policymakers.

2. WHOLE LIFE CARBON ASSESSMENT OF BUILDINGS

Environmental impacts occur at all life cycle stages of a building's life, as summarized in **Figure 1**. This includes all GHG impacts resulting from activities associated with raw material extraction and product manufacturing to the construction, use, and end-of-life of the building. Reducing GHG emissions across all of these life cycle stages requires addressing both embodied carbon and operational carbon. **Embodied carbon** refers to the GHG emissions resulting from the manufacturing, transportation, installation, maintenance, replacement, and disposal of construction materials used in buildings. Importantly, a significant proportion of embodied carbon impacts occur before a building is even occupied. In contrast, **operational carbon** refers to the GHG emissions due to building energy consumption (including the burning of fossil fuels on-site or generating the electricity used to heat, cool, and light a building). These emissions don't occur until the building starts operating and cumulatively add up over time. The distinction between these two types of emissions is not only useful for understanding where building-related emissions come from but also when they are emitted and how they can be addressed.

When considered together, the sum of all GHG emissions over a building's full life cycle is referred to as **whole life carbon (WLC)**, and the practice of accounting for these combined emissions is known as **whole life carbon assessment (WLCA)**. While not fundamentally different from the life cycle assessment (LCA) of buildings, WLCA focuses specifically on carbon emissions whereas LCA can assess multiple environmental impacts across all life cycle stages, as indicated by international LCA standards such as EN 15978 or ISO 21931.

Whole life Carbon (WLC)

refers to the greenhouse gas (GHG) emissions resulting from the materials, construction, and use of a building over its entire life cycle, including its demolition and disposal.

Whole life Carbon Assessment (WLCA)

a life cycle assessment (LCA) of an entire building, spanning over its full life cycle, evaluating global warming potential only.

Life Cycle Assessment (LCA)

a systematic set of procedures for compiling and evaluating the inputs and outputs of materials and energy, and the associated environmental impacts directly attributable to a product or process throughout its life cycle.

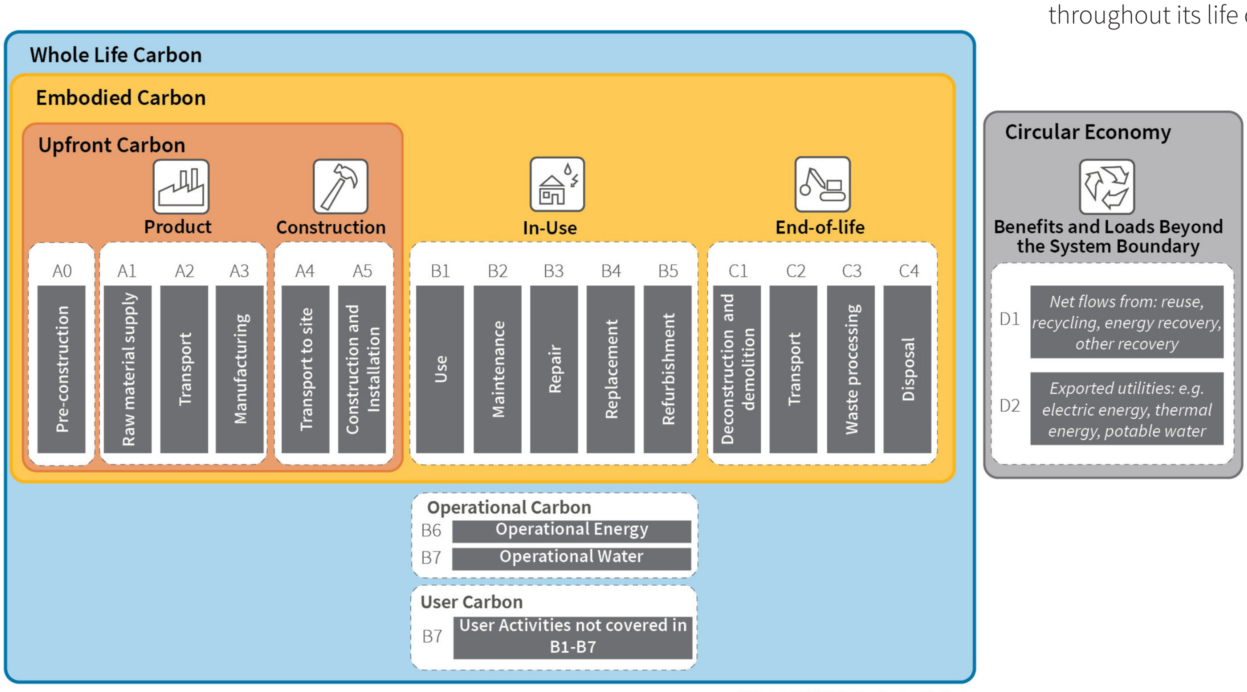

Figure 1. Building life cycle stages of a whole life carbon assessment. Stages are defined by EN15978-1:2011 and ISO 21931-1:2022. Graphically adapted by authors from RICS Whole Life Carbon Assessment 2nd Edition (RICS, 2023).

2.1 Alignment with standards

Wherever possible, we referenced international standards for whole life carbon accounting such as draft ASHRAE/ICC 240P, hereafter referred to as "240P," (BSR/ASHRAE/ICC, 2024) and RICS Whole Life Carbon Assessment 2nd Edition (RICS, 2023). However, as outlined in Section 3.2, the majority of data analyzed in this study were collected from design practitioners and therefore may not always adhere to methods outlined in available standards. Importantly, the methodology used and resulting analyses for this study are limited in both their temporal and physical scope and do not represent the entire system boundary of a comprehensive LCA. In addition, this study focuses exclusively on global warming potential (GWP) measured in units of carbon dioxide equivalent.

2.2 Modeling variability

LCA models can vary widely in their accuracy depending on the goal, scope, purpose of the assessment, methods, and assumptions used by the LCA modeler. Additionally, different modeling standards, guidelines, LCA tools, and datasets used in the assessment can cause significant differences in results. The actual embodied carbon emissions of a building can also differ between the as-built and design stages owing to changes that occur during the construction process. While efforts were made to conduct quality assurance and harmonize portions of this data in our study, it is inherently difficult to verify the accuracy of LCA models that have not been third-party verified. As such, LCA models are not always directly comparable. They were taken here as a proxy for the real-world embodied carbon emissions of constructed buildings, but it should be noted that the completeness and accuracy of embodied carbon data analyzed for this study cannot be fully verified.

Standards

formal documents, typically mandatory, that establish uniform technical criteria, methods, processes, and requirements for WBLCA. They are typically produced by third-party standardization organizations and require the formal consensus of technical experts before publication.

Global Warming Potential (GWP)

the potential climate change impact of a product or process as measured by an LCA, reported in units (typically kilograms) of carbon dioxide equivalent (CO_2e).

Comparability

the extent to which LCA results can be appropriately compared – a function of (i) the extent to which the objects of assessment are technically and functionally equivalent, and (ii) the extent to which the LCAs use equivalent modeling methods and data sources (so that differences in results are due to differences in actual emissions rather than artifacts of the modeling process).

Verification / Verified

these terms are used generically throughout this report to refer to the process of recreating, reproducing, and/or ensuring that LCA results are based on appropriate data, calculated consistently and correctly, provide justification of completeness, and conform with applicable WBLCA standards.

3. METHODOLOGY

3.1 Case study buildings

The foundation of this case study report is a collection of 30 new construction building projects and associated LCA models, collected from design practitioners (primarily architects and engineers) through an open call for data as part of the Carbon Leadership Forum WBLCA Benchmark Study (v2). To be considered for inclusion in this study, the projects had to represent real buildings that were either constructed or intended to be constructed in California. These buildings were also required to follow minimum modeling scope (i.e., structure and enclosure).

The size of this data sample was small and varied, and should not be considered representative of all construction in the State of California. This summary provides a quantitative and qualitative description of the types of buildings that were analyzed for this study and highlights the types of projects that were largely missing. Only select building design attributes and characteristics are described here. A full list of parameters that are collected for this study can be found in Appendix C and Appendix D, which will be explored further in future research.

3.1.1 Building attributes

The buildings are divided into 7 use types including office, public assembly, health care, education, residential multi-family, warehouse, and public order and safety. The building use types are largely based on the Commercial Buildings Energy Consumption Survey (CBECS) (U.S. EIA, 2021) categorization system, with exceptions made for highly unique project types. These individual use types were then grouped into broader use type categories. **Figure 2** shows the use type categories as well as the specific use types within each category. Twelve (12) of the buildings were commercial offices, four (4) were commercial use types other than offices, nine (9) were multi-family residential, and five (5) were neither commercial nor multi-family and have been classified as "Other."

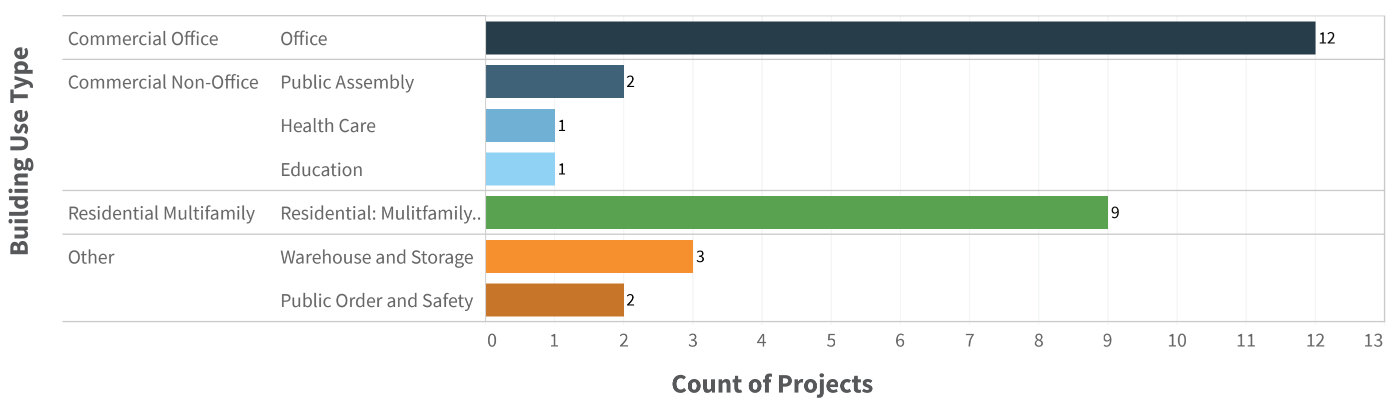

Figure 2. Count of buildings by use type category and specific use type.

The studied buildings were of a variety of sizes, both in terms of total floor area and number of stories above grade, ranging from a 1,500 ft^2 single-story building to a 500,000 ft^2 three-story building. **Figure 3A** shows the distribution of buildings by floor area, while **Figure 3B** displays them by stories above grade. Notably, half of the buildings (15) were less than 100,000 ft^2. Similarly, nine of the buildings were single-story and only two of the buildings were over 11 stories. This sample of buildings is biased towards smaller, modest-sized construction and lacks very large or very tall projects.

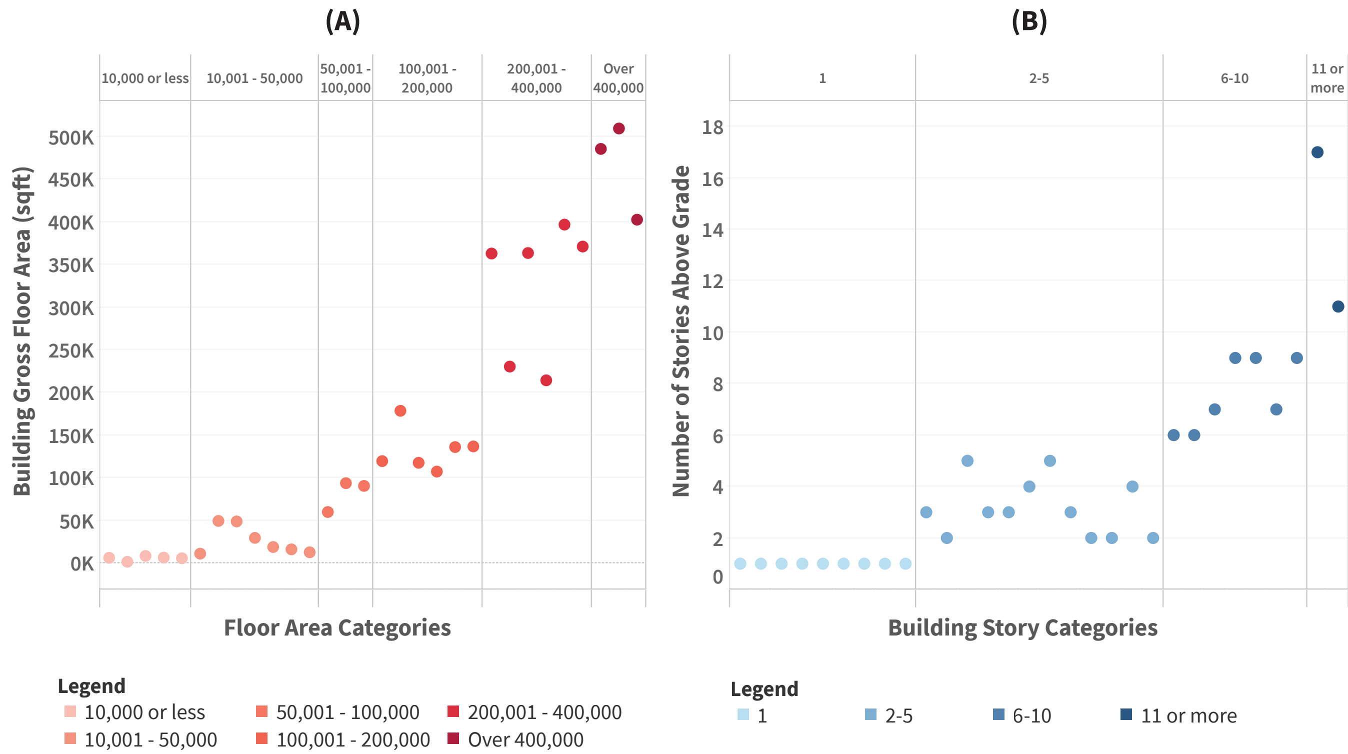

Figure 3. Representation of buildings included within the study. Based on project gross floor area per floor area category (A, left), and number of stories above grade per number of stories categories (B, right).

As shown in **Figure 4**, the majority of buildings (28) are located within Climate Zone 3B and 3C, which covers most of coastal and inland California and encompasses the main population centers of Los Angeles, San Diego, and the San Francisco Bay Area. None of the studied buildings were located within Climate Zones 4-6, which includes areas of Northern and Eastern California. In addition, the studied buildings have a variety of primary structural systems.[1] Eleven (11) of the buildings have entirely reinforced concrete frames and floors as the primary structural system. Twelve (12) of the buildings employ a structural steel/concrete hybrid system, and seven (7) rely on wood as the primary structural framing material (mass timber and/or light wood frame). In total, 21 buildings were assessed using Tally LCA, and the other 9 were assessed using One Click LCA.

1. Primary structural systems were designated based on a combination of the primary horizontal and vertical gravity systems of the buildings as defined in Appendix C.

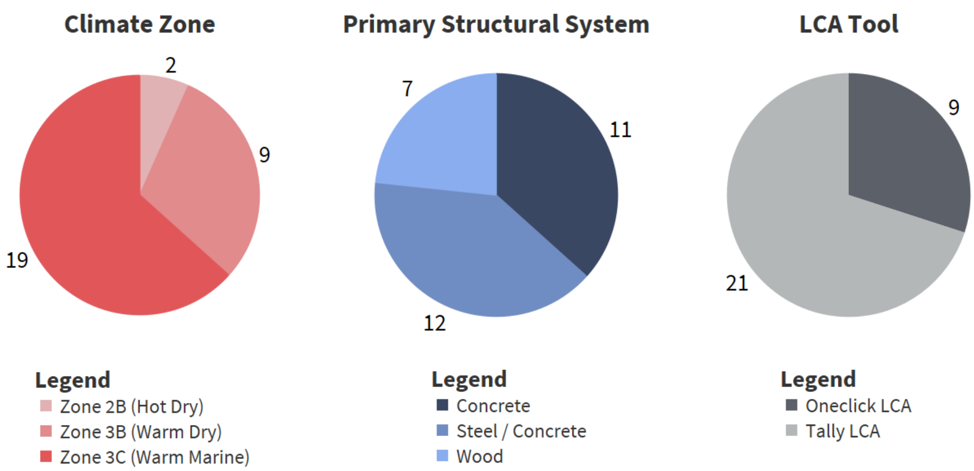

Figure 4. Summary of number of buildings by climate zone (left) primary structural system (center), and LCA tool used (right).

Table 1 summarizes the seismic design category for the case study buildings and their respective International Building Code (IBC) Construction Types. The vast majority of projects (24) were located in seismic design category D. This design category is rare for most of the US but highly prevalent for buildings in California, and it requires buildings to meet more stringent structural design requirements. In terms of the IBC Construction Type, Type II-B buildings (typically steel, concrete, or masonry structures without extensive fire protective assemblies) are the most prevalent.

Table 1. Number of buildings by seismic design category and IBC Construction Type for building dataset.

	IBC Construction Type							
Seismic Design Category	**Type I-A**	**Type I-B**	**Type II-B**	**Type III-A**	**Type V-A**	**Type V-B**	**Unknown**	**Totals**
C	0	0	0	2	1	0	0	3
D	1	5	8	2	0	5	3	24
E	0	1	2	0	0	0	0	3
Totals	1	6	10	4	1	5	3	

Energy use categories were created for the projects based on their energy sources. **Table 2** summarizes the energy use categories by building use type. The two primary energy use types are all-electric buildings (those that rely entirely on electricity as an energy source) and electric/gas buildings (those that rely at least partially on the combustion of natural gas as an energy source). Notably, more than half of the buildings are all-electric (19) and 11 of the buildings include some amount of natural gas combustion. Though the potential benefits of on-site renewable energy sources are excluded from our results,[2] we listed which projects contained photovoltaics.

2. The potential benefits of on-site PV are analyzed separately in Appendix B Section B.2.1.

Table 2. Cross-tabulation of the number of projects by use type and energy use categories.

Use Type Category	Energy Use Category All-Electric (With PV)	All-Electric (Without PV)	Electric / Gas (With PV)	Electric / Gas (Without PV)	Totals
Commercial Office	6	1	0	5	12
Commercial Non-Office	0	2	1	1	4
Multi-family Residential	3	3	1	2	9
Other	1	3	1	0	5
Totals	10	9	3	8	

3.2 Data collection

The building models and associated performance data used in this study were submitted by design practitioners (primarily architects and/or engineers) through an open call for data as part of the CLF WBLCA Benchmark Study (V2). For projects to be considered within this study, they had to meet the criteria listed in full in Appendix C.

Data contributors were required to submit three distinct types of information for each building project:

- **Project Attributes:** General descriptions and physical characteristics of designed or constructed building projects (e.g., project location, construction type, building use, floor area, height, parking type, structural system, building code cycle). These were submitted in data entry templates developed for the study.
- **Embodied Carbon Data:** Comprehensive whole building life cycle assessment (WBLCA) results per project that included material quantities and full life cycle impacts, as well as attributes of the WBLCA analysis (e.g., date of analysis, physical scope included, reference study period). This data was submitted in the form of direct exports of Tally LCA and One Click LCA modeling software.
- **Operational Energy Use Data:** Measured and/or modeled operational energy consumption data of the building's mechanical, electrical, and plumbing systems (e.g., total energy use intensity, energy loads per end-use, fuel sources, on-site renewable energy generation) were submitted in data entry templates developed for the study.

A data collection user guide (Appendix C) and data entry template (Appendix D) were developed for this study to help ensure consistency and alignment in the data collected. For project attributes, these documents included a full list of design parameters as well as guidelines for how they should be calculated and reported. Among many others, this included guidance for determining project use type, gross floor area, parking components, window-to-wall ratios, and structural system classifications, to name a few. Additionally, the user guide required data contributors to meet requirements for the types of building projects they submitted, their corresponding WBLCA results, and their operational energy uses. The data collection process is summarized in **Figure 5**.

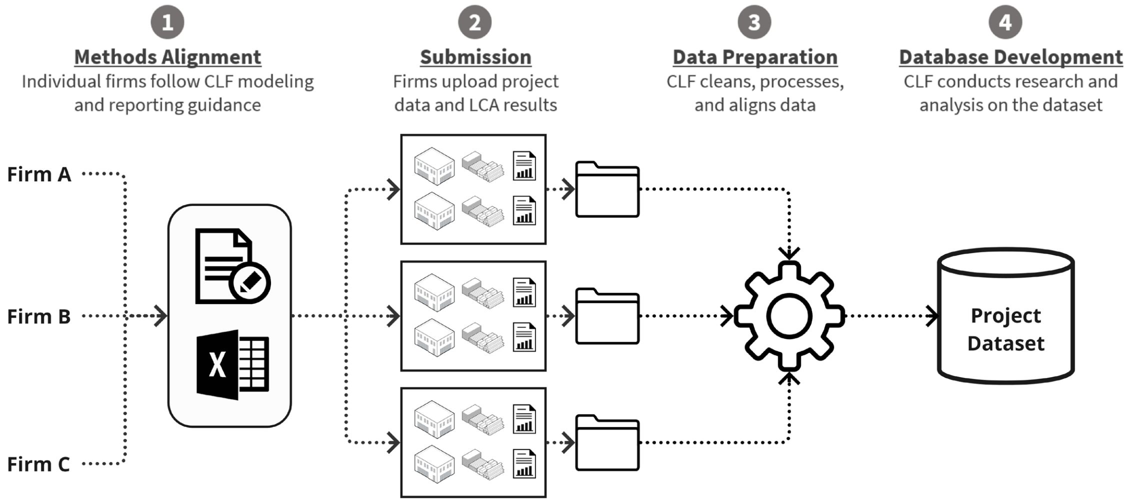

Figure 5. Data collection proccess used for this study.

3.3 LCA scope and boundaries

3.3.1 Life cycle stages

This study uses the life cycle stages outlined in EN 15978 and ISO 21931. Currently, available building LCA tools only cover a selection of these life cycle stages due to limitations in data availability and data quality. As all WBLCA models used in this study were initially conducted using two software packages (i.e., Tally LCA and One Click LCA), the life cycle stages included in this study match the system boundary and stages represented in those tools and that were applicable to our data collection requirements outlined in Section 3.2. **Figure 6** outlines the stages and modules included in the scope of this study.

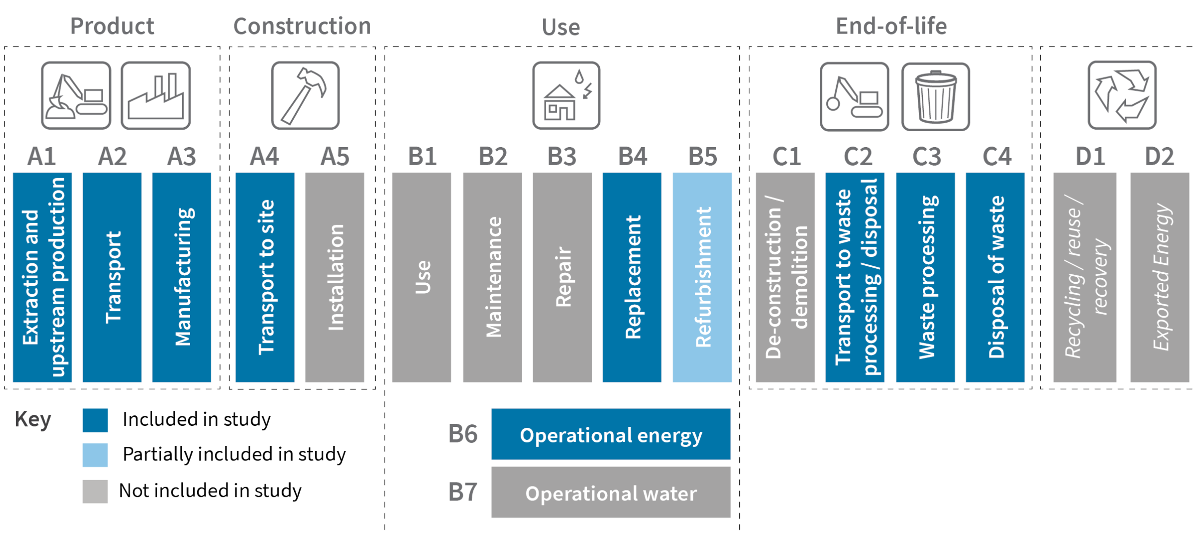

Figure 6. Life cycle stages included in this study. Dark blue indicates modules included in the study, light blue indicates stages that were partially included, and grey indicates stages not included. Life cycle stages are based on EN 15978-1 and ISO 21931-1.

3.3.2 Building elements

The models in this report are aligned with WBLCA modeling guidance outlined in Appendix C. While a whole building LCA model aims to be comprehensive, there is no single standard for building element scope, and many projects struggle with the availability of data and the time necessary to accurately represent some model elements. Additionally, for comparative LCA, it is important to align building element scope and assumptions across models. For this study, data contributors were advised to model the physical scope of buildings to the maximum resolution possible within the capabilities of the selected LCA software, and as appropriate for a Construction Documentation (CD) or As-Built model. As such, all models collected should have a high degree of design resolution and contain reasonably accurate material take-offs for all required scopes. However, verification of model resolution was not performed.

Building elements are characterized in this study using Omniclass Table 21 (Levels 1 and 2) (CSI, 2011) as recommended by draft ASHRAE/ICC 240P (BSR/ASHRAE/ICC, 2024). The minimum physical scope required for all projects collected was the primary structural system and exterior enclosure of the buildings. The majority of the projects that were submitted (19 out of 30 building projects) also contained interior construction and finishes. **Table 3** indicates the physical scopes that were included by projects in the dataset for each use type category. In Section 4.3.1 we explore the influence of including and excluding the carbon impacts from interiors. Building services (i.e., MEP), sitework (civil and landscape elements), and equipment and furnishings (FF&E) are not included in the scope of this assessment.

Table 3. Cross-tabulation of the number of projects by use type and the physical scope categories that were included in the LCA results of this study. Abbreviations include (S) Structure; (E) Enclosure; and (I) Interior Construction and Finishes.

	Physical Scope Included		
Building Use Type	**SE**	**SEI**	**Totals**
Commercial Office	5	7	12
Commercial Non-Office	2	2	4
Multi-family Residential	1	8	9
Other	3	2	5
Totals	11	19	

3.3.3 Reference study period

All building models were evaluated using a reference study period of 60 years, per North American guidance (LEED, ILFI, ASHRAE/ICC 240P).

3.3.4 Construction completion year

The raw data collected for this study represented real-world building projects that were either constructed or intended to be constructed between 2017 and 2024. For our analysis and results, this data is shown as though each building was newly constructed in 2024 in order to align the grid decarbonization scenarios for each building's operational emissions profile.

CLF | CBE

3.3.5 Reference unit

Embodied carbon intensities (ECIs) in the report were measured in kg CO_2e/m^2 and normalized using gross floor area (GFA). For ECI calculations, the floor area of attached or integrated parking structures was included, as they contribute to the core building structure and cannot be easily separated from the building boundary. Surface parking lots were excluded.[3] Generally speaking, this approach results in lower ECI values for projects with parking structures than would otherwise be the case if normalized to the internal gross floor area only (excluding attached/integrated parking).[4]

Operational carbon intensities (OCIs) along with the operational energy use demands that were used to create them were based on the gross floor area of the respective building excluding any attached or integrated parking structures, where applicable. This GFA boundary was used as a proxy for "conditioned floor area," the floor area unit from which typical energy models and resulting energy demands are often calculated. The actual conditioned floor area was not collected as a building attribute from data contributors, which is a simplification and limitation of the operational energy calculation methods used in this report.

Whole life carbon intensities (WLCIs) were calculated as the sum of ECI and OCI defined above.

3.4 Embodied carbon data and assumptions

3.4.1 LCA tool and background data

The building LCA models used in this study were produced by design practitioners using either Tally LCA (version 2018.09.27.01 or later) or One Click LCA (LEED for US/Canada, TRACI version). Athena Impact Estimator for Buildings was also an accepted LCA tool; however, none of the provided projects were assessed using it. These building-sector-specific LCA tools allow modelers to produce Bill of Material (BoM) estimates from a 3D design and documentation software, such as Revit. Using Tally LCA or One Click LCA, these material quantities can be joined with life cycle inventory (LCI) data and a range of other background data sources that provide details for future life cycle stages, such as material replacement, or activities at the end of life. Both Tally LCA and One Click LCA provide similar functionality and can be used to comply with WBLCA modeling and reporting requirements for LEED, Living Building Challenge, and other WBLCA policies.

Both tools follow international standards ISO 14040-14044 and ISO 21931:2022 which guide the calculation methods and reporting of life cycle assessment models for building and civil engineering works. Depending on the tool and version, these tools are also compliant with EN 15804:2012 and EN 15978:2011.

Tally LCA and One Click LCA each have their own proprietary material databases which mainly consist of generic or average data based on North American production. Both tools include product-specific data from environmental product declarations (EPDs) to a lesser extent. There is currently no publicly accessible or transparent source of material LCI data that covers the scope required for a whole building LCA model.

Tally LCA and One Click LCA also have notable differences in default assumptions for transportation distances and modes, material replacement rates, end-of-life scenarios, and methods for quantifying the impacts of biogenic carbon, among others. While these

Normalization

refers to the process of adjusting values measured on different scales (in this report, GWP and GFA) to a notionally common scale (in this report, ECI, OCI, and WLCI).

Embodied Carbon Intensity (ECI)

the GWP intensity associated with the embodied emissions of a building expressed as kg CO_2e/m^2.

Operational Carbon Intensity (ECI)

the GWP intensity associated with the operational emissions of a building expressed as kg CO_2e/m^2.

Whole life Carbon Intensity (WLCI)

the GWP intensity associated with all emissions of a building expressed as kg CO_2e/m^2.

3. Definitions and categories were created to clarify the types of parking structures to which this was applicable. See "Attached Parking Type" in Appendix C for more information.

4. See Appendix B Section B.2.3 for additional discussion and analysis on floor area normalization methods.

methods and considerations can lead to differences in model results, assessing the variability associated with background data and scenario assumptions was outside the scope of this study.

3.4.2 Material replacement

Materials and assemblies were modeled as full unit replacements according to service life assumptions provided by the LCA tool and reviewed or amended by data contributors using their professional judgment. Per ISO 21931, material replacement scenarios were modeled using present-day manufacturing emissions and do not assume changes to manufacturing efficiency or future decarbonization. This static approach is consistently applied to assumptions about future building operational performance in Section 3.5.3.

3.4.3 Biogenic carbon

Biogenic carbon refers to the exchange of carbon dioxide between the atmosphere and biomass material (CEN, 2019). Typically, this accounts for the removal of carbon dioxide from the atmosphere as the biomass grows, therefore sequestering or storing the biogenic carbon content within the biomass until it is then emitted to the atmosphere at the end-of-life (Arehart et al., 2021). Since the origin of wood products could not be verified based on the information collected for the studied buildings and the current approach for quantifying biogenic carbon differs across the tools allowed in this study, the impacts of biogenic carbon were omitted from this study's scope.

3.4.4 Fugitive emissions

The impacts of refrigerants, fire suppression gases, or other forms of industrial gases were excluded from the scope of this study owing to limitations of data collection. Notably, the impacts of refrigerant leakage can be significant and should be considered in future studies (CIBSE, 2021; RICS, 2023).

3.5 Operational carbon data and assumptions

3.5.1 Project data for operational energy use

Data contributors were asked to submit the operational energy use of the projects using measured data (from actual utility bills) and/or modeled data (from building energy simulations). Four different options for reporting energy use are summarized in **Table 4.** The options form a hierarchy for the sources of data used to calculate the operational impacts within this report. Measured utility energy use data (option 1) was the most desirable option as it represents the true energy consumption for the building by fuel source. Options 2 and 3 report the modeled operational energy use (generated from building energy simulation models) based on the amount of energy from the electricity grid, natural gas, and other fuel sources or renewable energy (if applicable). Option 4 reported net site energy use intensity (EUI). Data contributors were also asked if the buildings were all-electric, if they used any combustion energy sources, and how much on-site renewable energy they generated, if any.

Table 4. Operational energy use data provided by data contributors.

Option	Description of options	Provided for:
1	Measured Utility Energy Use: actual measured energy use of the building's primary fuel sources from utility bills covering a full calendar year	4 buildings
2	Modeled Hourly Energy Use: modeled results from a predictive energy model report by fuel source, in hourly format, and covering a full calendar year	2 buildings[5]
3	Modeled Annual Energy Use: modeled energy use impacts from a predictive energy model report by fuel source, in yearly format	4 buildings
4	Modeled Site pEUI: modeled total site EUI from a predictive energy model report	11 buildings
None	No energy use data provided by data contributor	9 buildings

The operational energy use data provided for each building was then used to establish an energy profile including annual energy demand, grid electricity, and natural gas or other fossil fuel sources. Point-in-time building consumption profiles were not collected. All emissions factors were based on annual average consumption and production values. **Figure 7** provides a schematic of the hierarchy of the data considered when creating the default annual energy demand of the represented buildings.

When energy use options 1-3 were provided, they were used directly to calculate the energy demand of the buildings. For buildings where only the modeled site EUIs were provided (option 4, 11 buildings), the contributions (percentages) of electricity and natural gas were calculated based on the CEC Building Energy Benchmarking Program (California Energy Commission, 2022). This Building Energy Benchmarking Program discloses measured annual energy use data for large commercial and multifamily residential buildings that are reported to the CEC. The CEC data was filtered by building typology, building size, year built, and location (all of which were based on the building description, classification, and other project information provided by the data contributor). To be as representative as possible for the corresponding buildings within this study, the CEC data was used to calculate average electricity and natural gas EUIs based on the selection criteria used to filter the data.

For buildings where no operational energy use data was provided (9 buildings), the energy demand was established as an EUI based on data from the California Building Energy Benchmarking Program, operated by the CEC (California Energy Commission, 2022).

5. To align with the annual average data provided by all other projects, hourly data, when provided, was converted to annual average for this study.

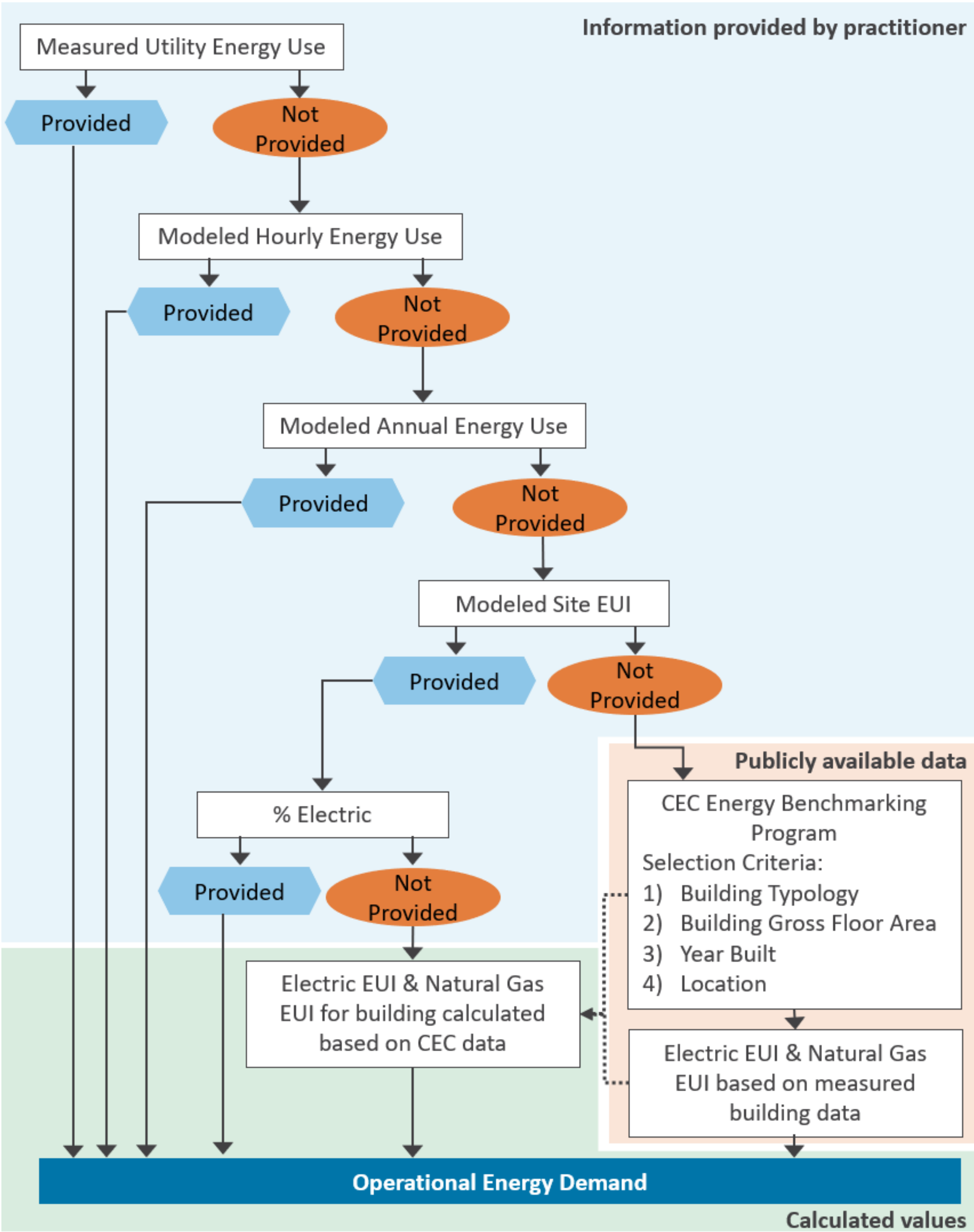

Figure 7. Schematic hierarchy of the data used to calculate the operational energy demand of each building.

3.5.2 Building energy simulation models

This study relied heavily (though not exclusively) on building energy simulation models (BES/BEM) conducted by design practitioners to estimate the actual energy consumption of real-world buildings. These simulations are intended to predict the energy consumption of buildings but can vary widely in their accuracy depending on the type of energy model (U.S. Department of Energy, 2011), standards (ANSI/ASHRAE/IES, 2018, 2019; U.S. Department of Energy, 2011), and tools (DOE2, 2018; Roudsari et al., 2013; U.S. DOE, 2017) used for their creation, along with the assumptions of the energy modeler. Similar to the multiple LCA tools that were allowed for this study, energy model results may not always be comparable, and no restrictions were placed on these methods and assumptions for data contributors. Though energy simulations are imperfect estimates, they were taken here as a proxy for real-world energy consumption.

3.5.3 Energy efficiency and fuel source improvements

Per ISO 21931 modeling guidance, the buildings analyzed were assumed to remain at the same level of energy efficiency over their 60-year study period, and no significant building retrofit or upgrades were assumed. Additionally, the models did not make any assumptions of future or potential changes to building use, or occupancy, which too could alter future energy consumption profiles. In reality, buildings can be upgraded over time with better mechanical, electrical, and plumbing systems, which can make them more efficient. Assuming a constant energy use efficiency is an oversimplification of actual building operations and maintenance, but remained a boundary of this study and a requirement of most static WBLCA modeling and reporting guidance.

Similarly, the emissions from on-site natural gas combustion were assumed to remain constant. This static approach to future scenarios is also consistently applied to material replacement as described in Section 3.4.2.

3.5.4 On-site energy generation and exported energy

The amount of energy generated from on-site photovoltaics (PV) was provided by the data contributors. However, no information was provided on the size, chemical composition, manufacturing location, or ancillary equipment associated with the on-site generation. Therefore, the embodied impacts and operational benefits from on-site generation have been excluded from the main body of this report.[6] Future work should assess the importance of building demand profiles, on-site energy generation profiles, and respective time-of-use grid carbon intensities for buildings that aim to make net-zero energy and net-zero carbon claims.

The export of electricity to the grid (life cycle stage D2) was excluded from this study. The perceived benefits from exporting excess generation from on-site photovoltaics to the grid depend on the grid's capacity to store excess generation and the amount of variable intermittent renewable generation (i.e., wind and solar) within the grid structure. In many instances, grids with high amounts of photovoltaic generation and low energy-storage capacity receive minimal to no benefits from receiving exported excess generation. This is because the grid is already saturated with low-carbon electricity at the time of generation and there is no means to store this excess energy.

3.5.5 Grid decarbonization scenarios and emissions factors

Emissions factors for grid electricity were used from draft standard ASHRAE/ICC 240P to analyze the operational energy use impacts of the buildings within this study (BSR/ASHRAE/ICC, 2024). These emissions factors are based on NREL's Cambium dataset mid-case scenario (Gagnon et al., 2023) and adjusted for annual carbon emissions by 240P. They include assumptions about grid decarbonization over time and were used here as a reasonable representation of potential future grid decarbonization in the State of California. Within the State of California, S.B. 100 mandates that 100% of retail

6. The potential operational energy and operational carbon benefits of PV are analyzed separately in Appendix B Section B.2.1. The embodied impacts of PV were not estimated.

electricity be generated using zero-carbon sources by 2045. The emission impacts from using natural gas as a fuel source in buildings are also estimated by draft ASHRAE/ICC 240P. These include combustion and pre-combustion values from the US Environmental Protection Agency and NREL's US Life Cycle Inventory Database, respectively. Throughout the main body of this report, global warming potential assessed over a 100-year time horizon (GWP100) was used to facilitate comparisons between embodied and operational carbon.[7]

The emissions factors used throughout this study represent the average annual grid carbon intensity. However, electricity grids are formed from different types of generation plants that are used to meet electricity demand. Generation plants can be used to supply a base demand, with little fluctuation in generation capacity, or can change their generation capacity to meet changes in demand placed on the grid (Hitchin & Pout, 2002). In addition, electricity grids are employing an increasing amount of renewable energy generation systems to meet increases in electricity demand while reducing the reliance on fossil fuels (Pimm et al., 2021). As such, electricity grids are not static, and the use of time-dependent grid emissions would more accurately determine the operational emissions from buildings with a variable demand profile.

Average Grid Emissions

the impact associated with the entire generation mix used to produce energy for a given time period (total emissions divided by the total amount of energy generated).

7. The choice of time horizon is discussed and analyzed further in Appendix B Section B.2.4.

4. RESULTS AND ANALYSIS

This section presents the results of all 30 buildings, assessed over a 60-year reference study period. Impacts are reported as Embodied Carbon Intensity (ECI), Operational Carbon Intensity (OCI), and Whole Life Carbon Intensity (WLCI), which are expressed in kilograms of carbon dioxide equivalent per square meter (kg CO_2e/m^2). The results are shown for all 30 buildings, and adjustments have been made to align the scope of models as described previously in Section 3.2 and Section 3.3.

Unless noted otherwise, all results are shown for Modules A-C, for structure and enclosure only, and excluding biogenic carbon impacts and the benefits of photovoltaics. All values reported represent global warming potential assessed over a 100-year time horizon (GWP100).[8] Total operational carbon emissions and intensities were calculated based on annual average emissions using gross floor area excluding parking structures, while all embodied carbon emissions and intensities were calculated and normalized based on gross floor area, including parking structures when present.[9] Whole life carbon intensities reported are the sum of embodied and operational carbon, respectively. When listed, carbon intensity values have been rounded to the nearest ten units, and percentages to the nearest percent. When average GWP values or percentages are listed, they refer to mean, unless stated otherwise. All impacts presented are estimates only.

The values displayed throughout this section are based on a small dataset with limited physical and temporal scope. They are not intended to serve as generalizable baselines, targets, limits, or thresholds for the carbon impacts of buildings.

4.1 Whole life carbon results

The whole life carbon intensity (WLCI) of all individual buildings assessed is displayed in **Figure 8** up until 2084 (60-year reference study period). The y-axis shows ECI and OCI with OCI broken out into emissions associated with electricity use and those of natural gas combustion, and the x-axis shows individual project numbers.[10] Here, buildings are grouped by building use category. The figure shows large variations in total carbon intensities across different buildings (230-2230 kg CO_2e/m^2). The sample sizes between building use categories were quite small and correlations were unclear. However, commercial office and multi-family residential showed the narrowest WLCI ranges at 440-1460 kg CO_2e/m^2 and 260-1050 kg CO_2e/m^2, respectively.

In 21 of the 30 projects we analyzed, embodied carbon impacts from the structure and enclosure alone were larger than operational carbon impacts. While there were significant variations in ECI across buildings (190-690 kg CO_2e/m^2), the range of OCI was much wider (10-1710 kg CO_2e/m^2). The buildings with the highest total emissions (for instance #1, 22, and 24) were spread across building use categories and all showed significantly larger OCIs from natural gas combustion compared to other buildings. Notably, the buildings with the lowest OCIs (#9, 6, and 20) were all very low energy-consuming warehouses. The variability of OCI and ECI across the dataset is explored further in Section 4.2 and Section 4.3 respectively.

Embodied Carbon Intensity

the GWP intensity associated with the embodied emissions of a building expressed as kg CO_2e/m^2. For this report, these values were normalized by gross floor area including parking structures, where applicable.

Operational Carbon Intensity

the GWP intensity associated with the operational emissions of a building expressed as kg CO_2e/m^2. For this report, these values were normalized by gross floor area excluding parking structures, where applicable.

Whole Life Carbon Intensity

the GWP intensity associated with all emissions of a building expressed as kg CO_2e/m^2. For this report, these values were the sum of embodied and operational carbon intensities.

8. Different time horizons (i.e. 20-year and 100-year) are presented and discussed in Appendix B Section B.2.4.

9. The type of floor area calculation method used for normalizing carbon intensities is an important consideration for LCA modeling and reporting which can significantly alter the carbon intensities of certain projects. See Appendix B Section B.2.3 for additional analysis and discussion.

10. Project numbers were randomly assigned and are shown in some figures to distinguish individual buildings.

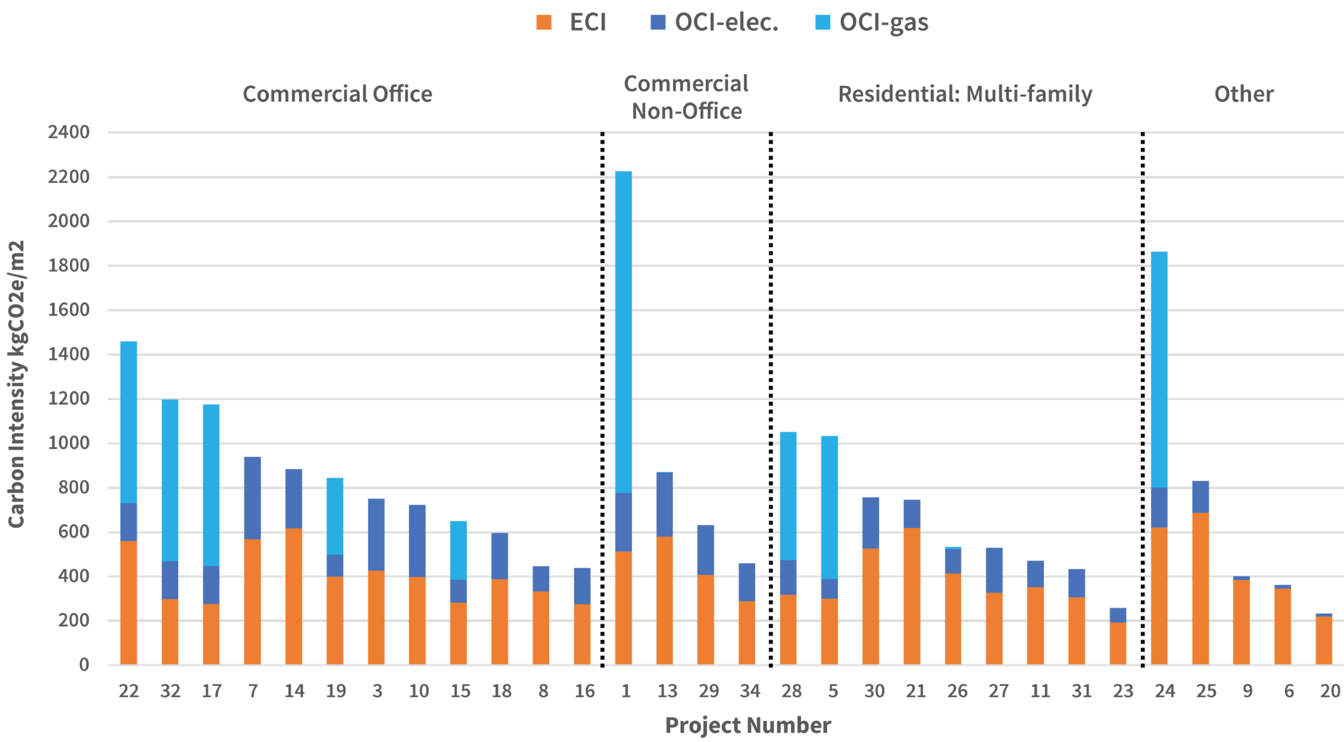

Figure 8. Embodied carbon intensity (ECI) and operational carbon intensity (OCI) of individual buildings. Results are shown for a 60-year reference study period with operational carbon impacts colored to show emissions associated with electricity consumption (dark blue) and natural gas combustion (light blue). Buildings are grouped by building use category.

In **Figure 9** and **Table 5**, the OCI, ECI, and WLCI of all buildings analyzed (30 buildings) are compared. Wide ranges of whole life carbon impacts can be observed across our dataset due to the variation in both embodied and operational carbon and the types of projects assessed. On average, embodied carbon impacts were found to be larger than those of operational carbon, while the range of operational carbon impacts was found wider than those of embodied. Notably, results showed a large difference between the mean and median OCI of projects due to several significant outliers. Operational carbon variability across this dataset is explored further in Section 4.2.

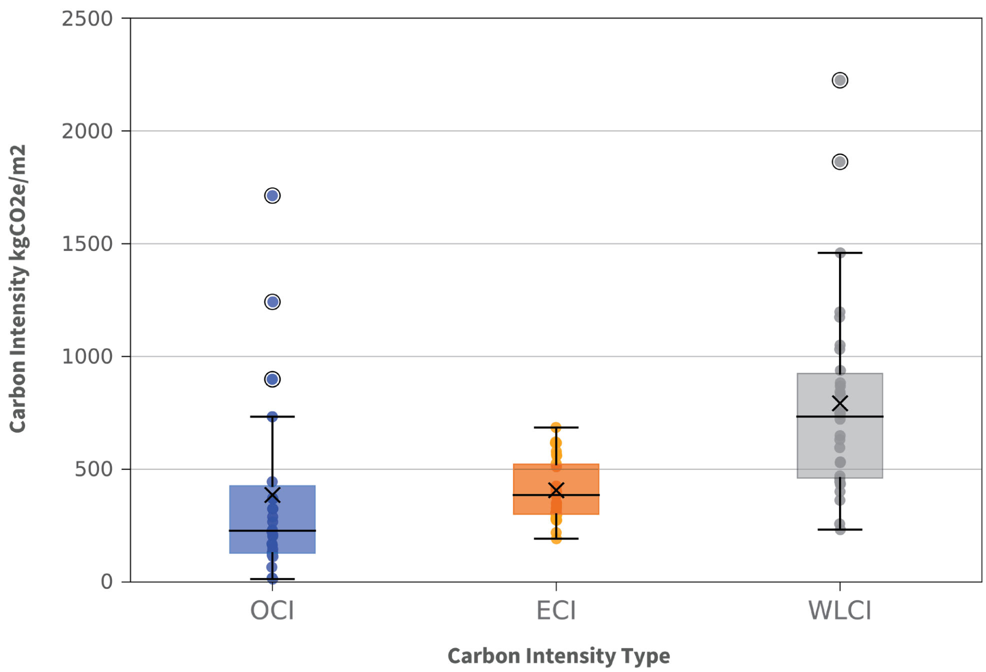

Figure 9. Operational carbon intensity (OCI), embodied carbon intensity (ECI), and whole life carbon intensity (WLCI) boxplots for all buildings. Results are shown for a 60-year reference study period with the mean values shown as a cross (x) and median values as a horizontal solid line within the box plots.

Table 5. Minimum, 1st quartile, median, mean, 3rd quartile, and maximum values of ECI, OCI, and WLCI from analyzed buildings under a 60-year reference study period. Values in this table are in kg CO_2e/m^2 and rounded to the nearest 10 units as a significant integer.

	Min	1st qt	Median	Mean	3rd qt	Max
ECI	190	300	390	410	520	690
OCI	10	130	230	390	430	1710
WLCI	230	460	730	790	920	2220

The contribution of embodied and operational carbon to total carbon impacts also varied widely across projects, as shown in percentages in **Figure 10** and **Table 6.** When looking at all buildings, the contribution of embodied carbon made up between 23-96% of all project emissions representing an average of 60%. Operational carbon contributions ranged from 4-77% with an average of 40%. Importantly, these relative percentages of embodied carbon impacts to total emissions would increase if more physical building elements were included in this study. For instance, if building elements from interiors and MEP were included, the percentages attributable to embodied carbon would increase. Even under the limited physical scope of structures and enclosures, this analysis illustrates the significance of embodied carbon impacts. It also suggests that although embodied carbon impacts were typically larger than operational carbon across our data sample, the balance between embodied and operational carbon varied widely and prioritizations for carbon reductions may vary, depending on the type of building.

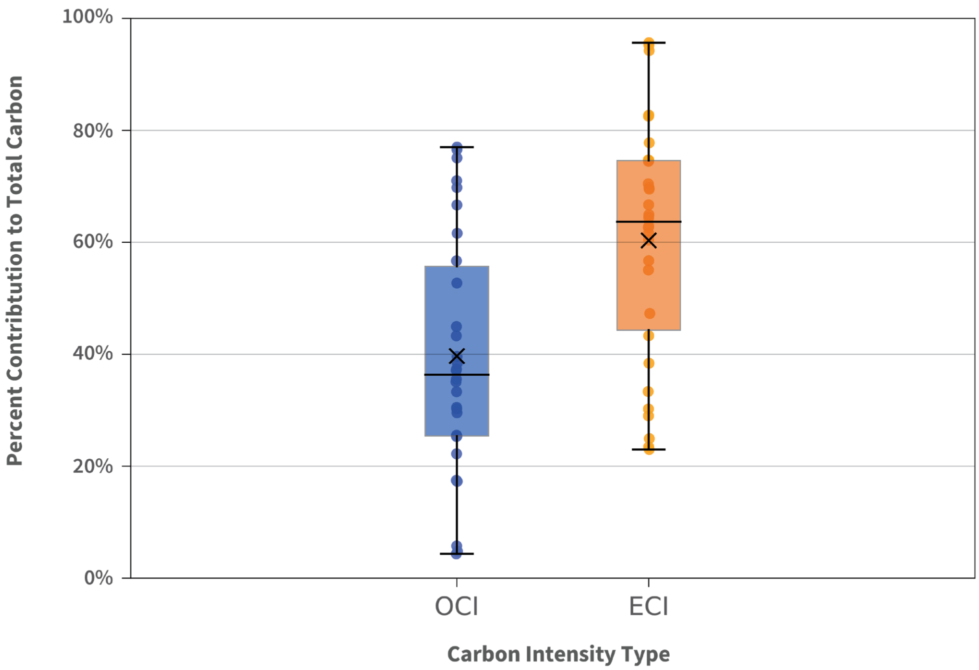

Figure 10. Percentage contribution of operational and embodied carbon to whole life carbon impacts for all buildings. Buildings assessed over a 60-year reference study period. Mean values are shown with a cross (x) and median values with a horizontal solid line within the box plots.

Table 6. Minimum, 1st quartile, median, mean, 3rd quartile, and maximum percentages of ECI and OCI contributions to whole life carbon impacts under a 60-year reference study period. Values in this table are rounded to the nearest percent.

	Min	1st qt	Median	Mean	3rd qt	Max
ECI %	23%	44%	64%	60%	75%	96%
OCI %	4%	25%	36%	40%	56%	77%

4.1.1 The timing of emissions

To illustrate the balance between embodied and operational carbon over time, we compared the impacts of buildings in our dataset in **Figure 11** using median annual emissions (above) and median cumulative emissions for key years (below). Here, results are shown for all buildings (A), all-electric buildings (B), and electric/gas buildings (C). In all groupings, the first major source of emissions is the upfront embodied carbon impacts that occur by the time the buildings have been completed (orange spike at year 0). After the initial construction, embodied carbon (orange) has periodic impacts shown for the replacement of materials and eventual impacts from end-of-life. Annual operational carbon emissions (blue) are seen to slowly decline over time owing to the decarbonization of the electrical grid. When looking at all buildings (A), the annual median OCI started at 16 kg $CO_2e/m^2/yr$ but eventually flattened to 2 kg $CO_2e/m^2/yr$. For all-electric buildings, OCI started at 13 kg $CO_2e/m^2/yr$ and flattened to 2 kg $CO_2e/m^2/yr$. For electric/gas buildings, the effects of decarbonization were less pronounced due to their continued reliance on the combustion of natural gas. For these buildings, median OCI started at 23 kg $CO_2e/m^2/yr$ and flattened to 11 kg $CO_2e/m^2/yr$.

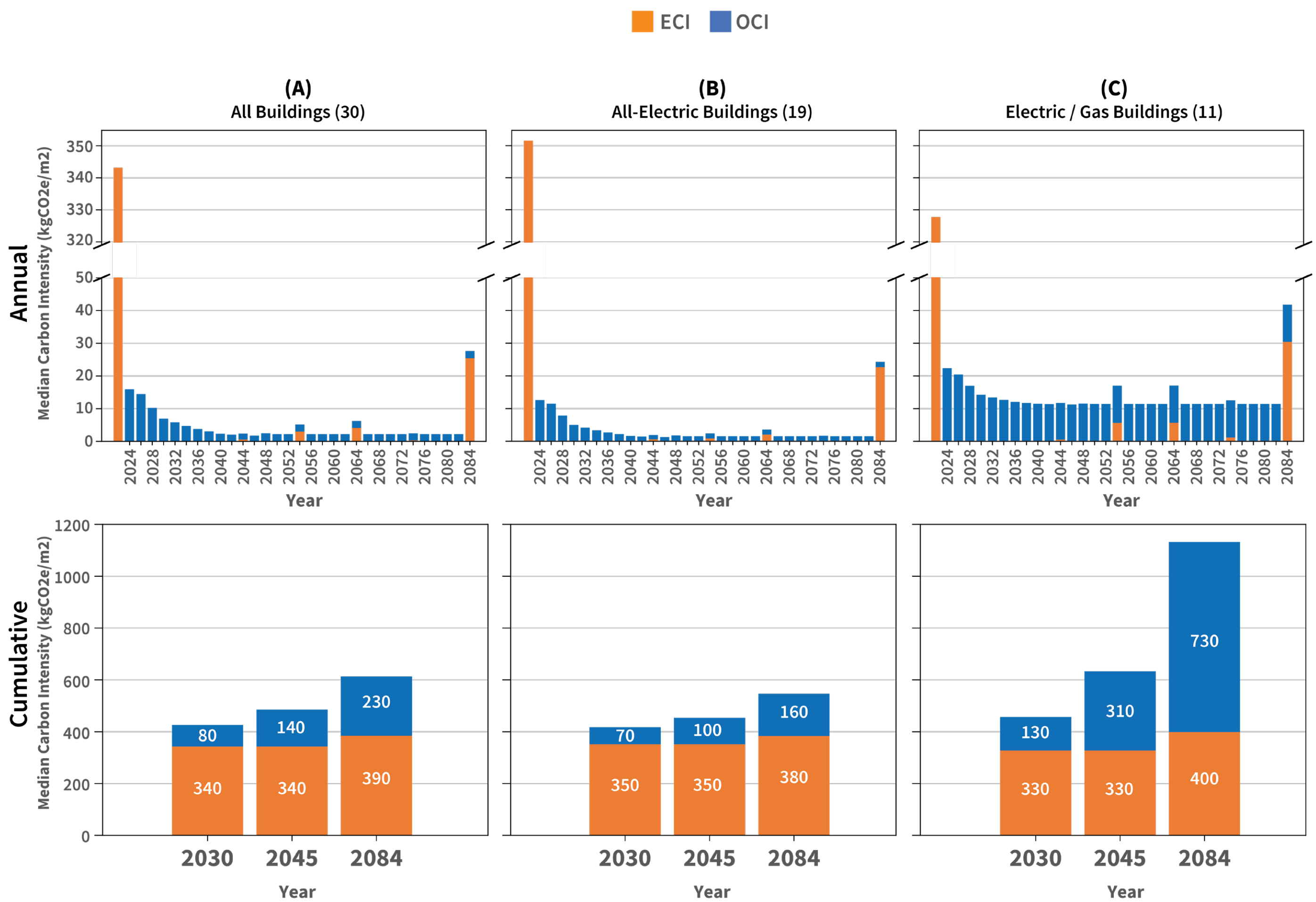

Figure 11. Annual and cumulative embodied carbon intensities (ECIs) and operational carbon intensities (OCIs) by key years. Results are shown as median annual values (above) over a 60-year reference study period and median cumulative values (below) by key years. Buildings are grouped by all 30 buildings (A), the 19 all-electric buildings (B), and the 11 electric/gas buildings (C). Note that the y-axis for annual impacts (above) is shown with a break between 50 and 320 kg CO_2e/m^2.

When looking at the results cumulatively, there was little difference between the groupings by the year 2030 and the median embodied carbon impacts far outweighed those of operational (340 compared to 80 kg CO_2e/m^2 respectively). By the year 2045, the cumulative operational carbon had cumulatively increased in all scenarios but still did not exceed embodied carbon impacts. By 2045, electric/gas buildings showed a notably higher total carbon intensity with a median ECI of 330 and OCI of 310 kg CO_2e/m^2. By the year 2084, large differences between all-electric buildings and electric/gas buildings were visible. The ECI remained larger than OCI for all-electric buildings (380 compared to 160 kg CO_2e/m^2 respectively), but the OCI exceeded the ECI for electric/gas buildings (730 compared to 400 kg CO_2e/m^2 respectively).

In **Figure 12,** the median cumulative ECI (orange line) and OCI (blue line) are shown for all projects in our dataset and compared across a 60-year reference study period. When the lines intersect, the year of occurrence is marked. When looking at all buildings (12A), ECI was larger than OCI by the end of a 60-year study period, with a median ECI of 390 kg CO_2e/m^2 and OCI of 230 kg CO_2e/m^2. When separated by energy use category (12B), embodied carbon impacts far outweighed operational impacts for all-electric buildings. Conversely, by the year 2047, the OCI exceeded those of ECI for electric/gas buildings, and the cumulative OCI for these buildings by the year 2084 was nearly two times greater than ECI.

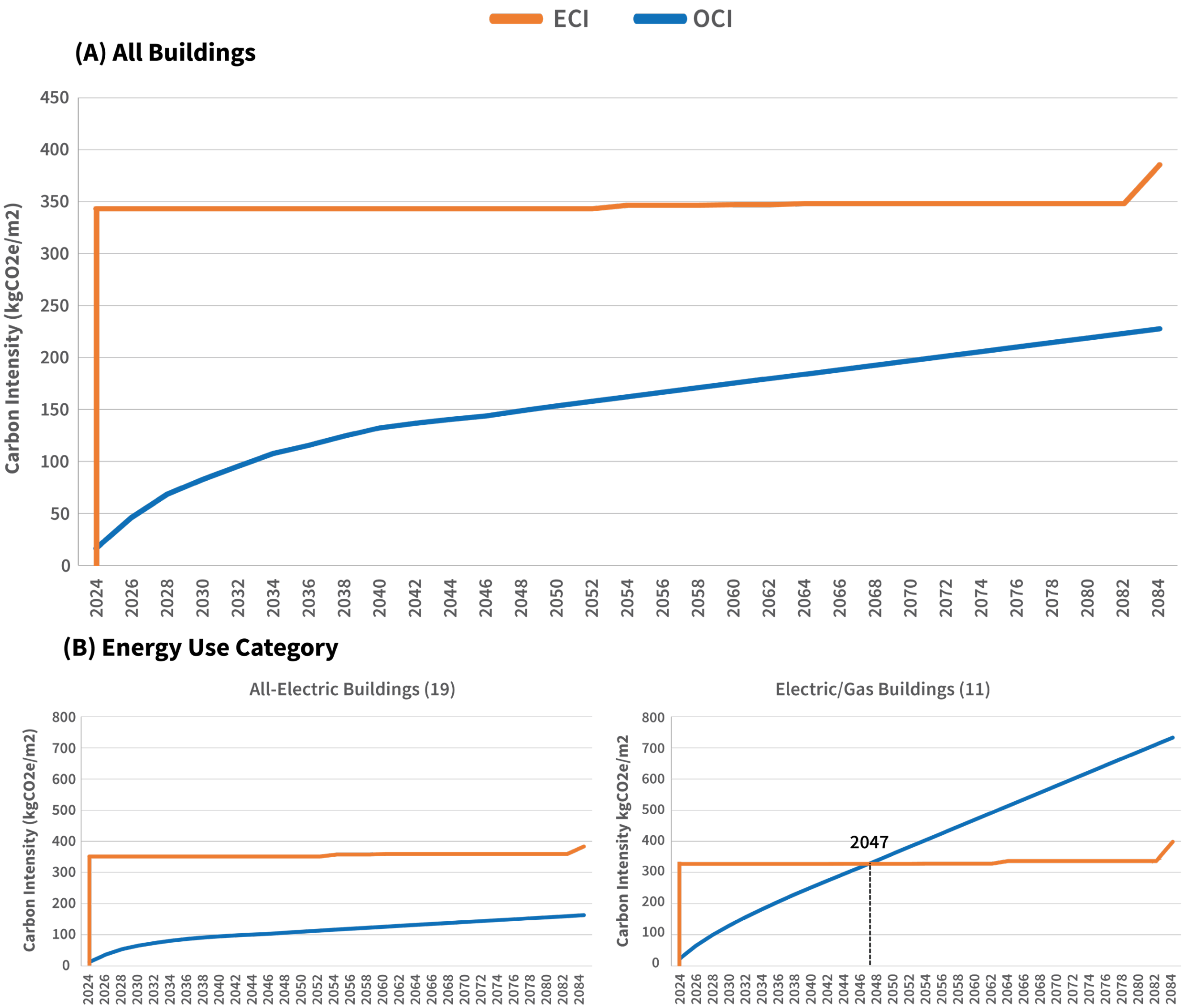

Figure 12. Median cumulative embodied carbon intensities (ECIs) and operational carbon intensities (OCIs). Results are shown for all buildings (A) and separated by energy use category (B) over a 60-year reference study period.

We also explored the cumulative impacts of buildings by their respective building use categories but found no meaningful correlations as the sample sizes were too small. Ultimately, we found the energy use category to be more significant for predicting operational carbon emissions than the building use category. Overall, cumulative operational carbon impacts exceeded embodied carbon impacts for only 9 out of the 30 projects analyzed, all of which were buildings that used natural gas.[11]

11. This specific finding is most graphically evident in Appendix B Section B.1.1.

4.1.2 *Effects of grid decarbonization*

While whole life carbon assessments project emissions into the future, many WLC models use a static emissions profile for grid electricity and other fuels (EN15978:2011, EN15804). However, it is well understood that electricity grids are rapidly decarbonizing and data exists to explore the effects of grid decarbonization (Gagnon et al., 2023) on building emission profiles (BSR/ASHRAE/ICC, 2024; RICS, 2023). This section explores the sensitivity of WLC results relative to choices made related to grid decarbonization scenarios.

Figure 13 illustrates the influence of grid decarbonization on the cumulative carbon emissions of the buildings analyzed across a 60-year reference study period. The base scenario used annual grid carbon intensities from the draft standard ASHRAE/ICC 240P (BSR/ASHRAE/ICC, 2024) as discussed in Section 3.5.5 with emissions factors flattening as we approach 2050. The static grid scenario was based on EPA's eGRID emission factors of 2022 data and represents what would happen if the grid does not change from its present structure and efficiency for California (U.S. EPA, 2024). Additional grid decarbonization scenarios are shown to provide a reasonable estimate of the range of OCIs that would be expected based on current grid decarbonization efforts. These additional grid decarbonization scenarios are the 2022 Cambium Low Natural Gas Costs and 2022 Cambium High Natural Gas Costs scenarios, representing the lower and upper bounds for projected grid decarbonization respectively.

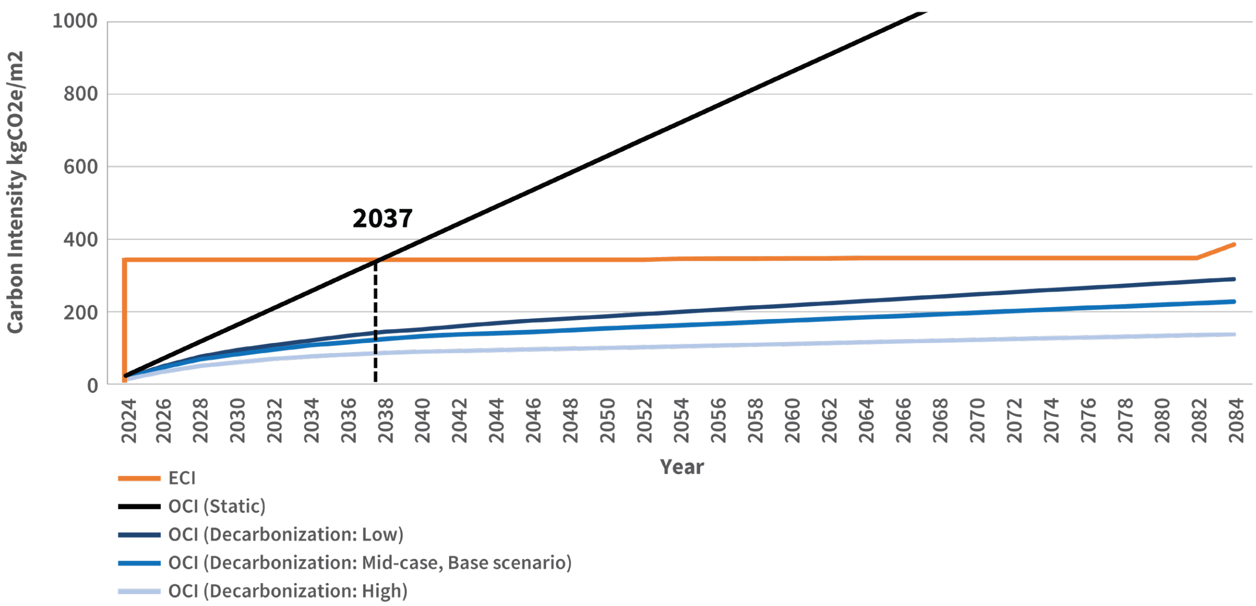

Figure 13. Median cumulative carbon emissions comparing static and decarbonizing grid scenarios. Operational carbon intensity (OCI) is shown for static grid emissions (black line) and high, low, and mid-case grid decarbonization projections (blue lines) over a 60-year reference study period.

Under a static grid scenario, the median OCI exceeded the median ECI around the year 2037. Whereas when grid decarbonization was considered, OCI remained lower than ECI across the entire 60-year reference study period for all scenarios evaluated. It is important to note that the uncertainty associated with different grid scenarios increases the further they are projected into the future and that this study only includes structure and enclosure for embodied carbon impacts. If additional building element scope were included, the dates of equivalence would be farther in the future.

4.2 Operational carbon variability

Figure 14 shows the variability in operational carbon across all projects studied. The range of OCIs after a 60-year reference study period for electric/gas projects was 120-1170 kg CO_2e/m^2, which was significantly larger than the range for all-electric buildings (10-370 kg CO_2e/m^2). Based on the calculation methods used in this study, the all-electric buildings had less variability and lower total operational carbon impacts than those that utilized natural gas. However, the range of OCI for all buildings, especially all-electric buildings, is likely to change based on the demand profile for the building and the time-dependent carbon intensity of the grid network. The relationship between the building demand profile and the time-dependent grid carbon intensity will depend on the decarbonization projection used for the analysis and the granularity of grid carbon intensities. Moving towards higher frequency grid carbon intensities would more accurately represent the different power generation equipment operating at the margin to provide additional power.

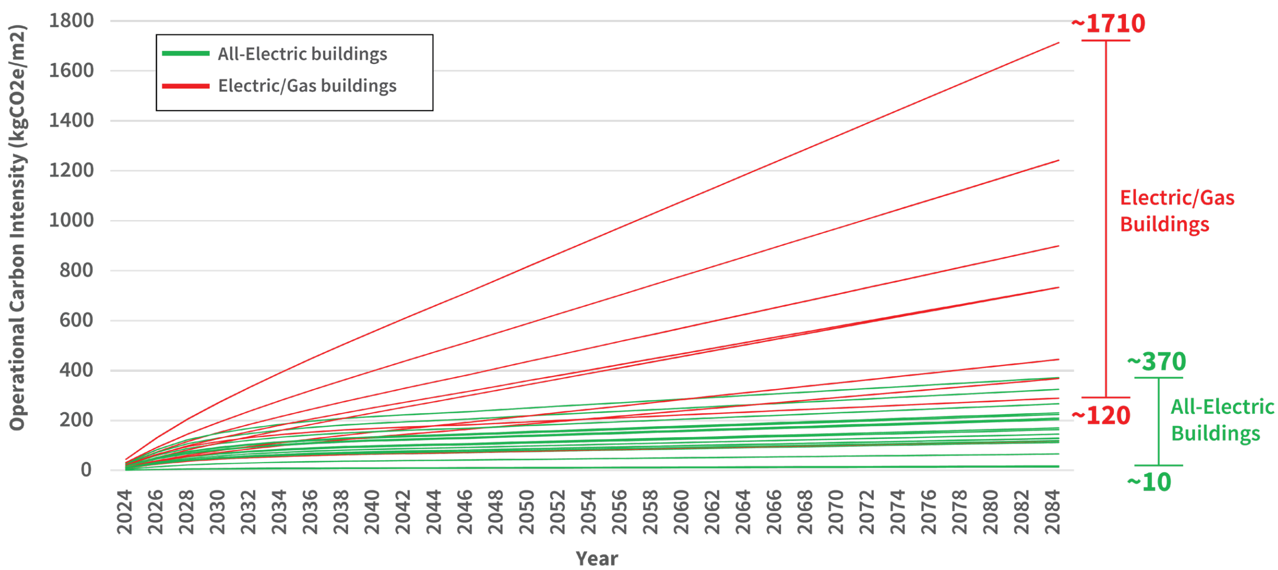

Figure 14. Cumulative operational carbon intensity (OCI) for all buildings by energy use category. OCI is shown for all-electric (green) and electric/gas buildings (red) over a 60-year reference study period.

The proportions of OCI from electricity and natural gas are shown in **Figure 15**. The carbon impacts from using grid electricity remained below 400 kg CO_2e/m^2 for all buildings, regardless of whether they were all-electric or electric/gas buildings. For electric/gas buildings, the impacts from natural gas contributed <1-1450 kg CO_2e/m^2 to the OCI, and these combustion emissions far outweighed those of electricity use for all but two of the buildings (#13 and #26 had very little natural gas consumption).

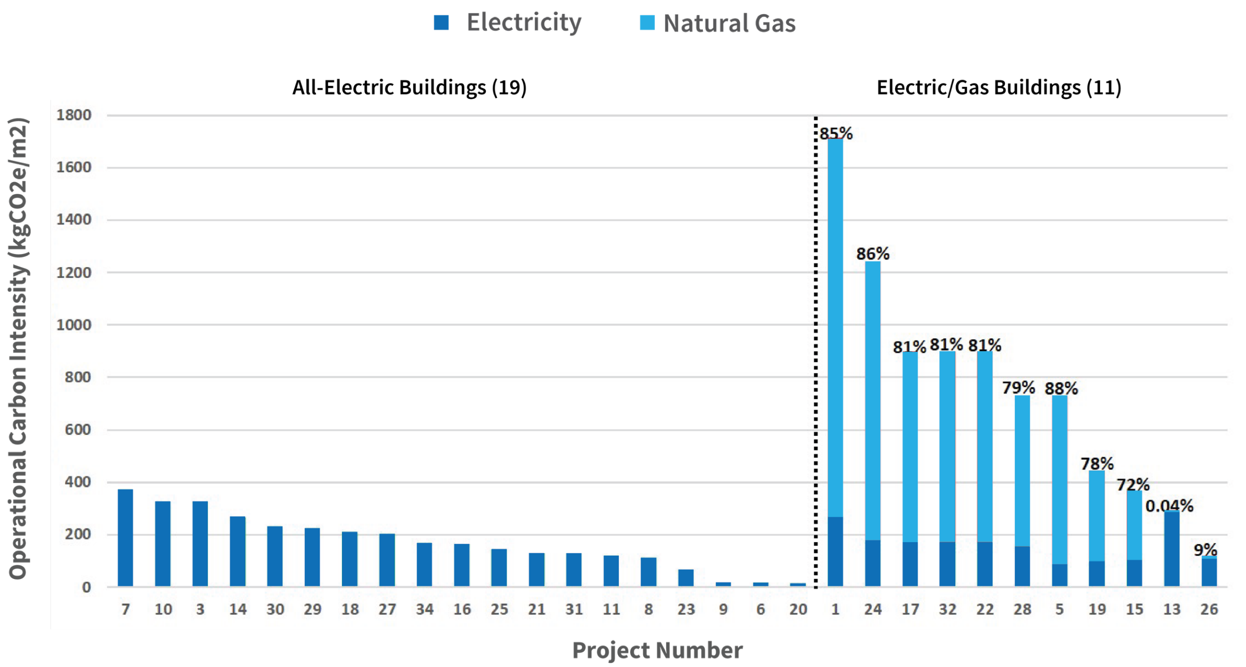

Figure 15. Operational carbon intensity (OCI) contributions from electricity and natural gas for all buildings. Buildings are grouped by energy use category and assessed over a 60-year reference study period. The proportion of natural gas emissions is listed respectively for each building as a percent of operational carbon intensity. Results are in kg CO_2e/m^2.

4.3 Embodied carbon variability

Figure 16 compares ECI for projects based on the LCA tools used for the assessment (A), indication of efforts made to reduce embodied carbon (B), primary building use categories (C), number of stories above grade (D), and primary structural systems of buildings (E). We found very little correlation between embodied carbon intensity and the building categorization systems analyzed. Although differences in the ranges and averages of specific categorizations can be seen, we could not prove that those differences are generalizable. We can neither rule out the possibility that these categorizations are meaningful. A larger data sample and further analysis may prove that many of them are indeed statistically correlated with higher or lower embodied carbon projects.

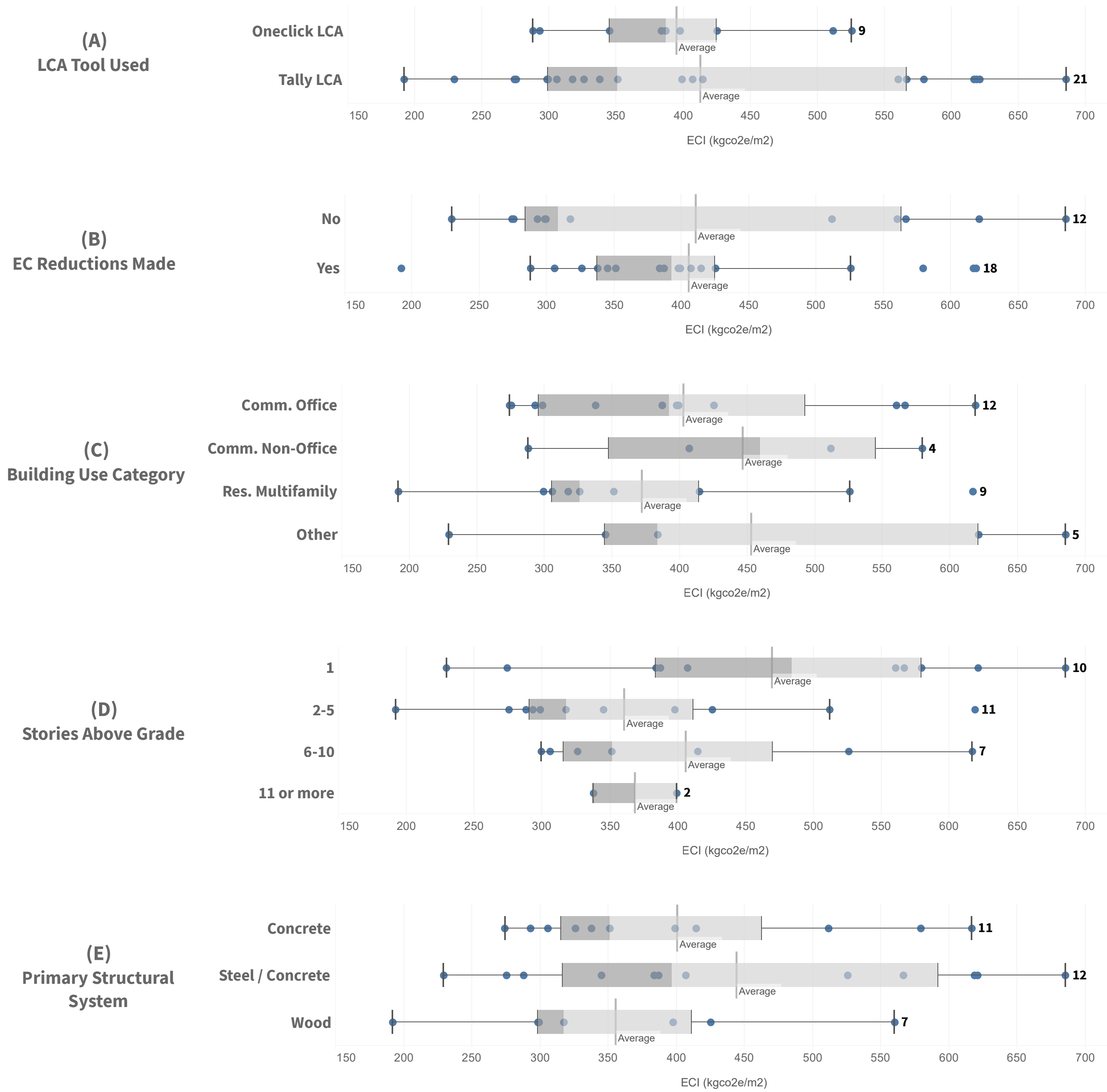

Figure 16. Embodied carbon intensity (ECI) by different LCA or building design attributes. Boxplots are shown based on LCA tools used for the assessment (A), indication of efforts made to reduce embodied carbon (B), primary building use categories (C), number of stories above grade (D), and primary structural systems of buildings (E). The number of data points per boxplot (n) is shown at the right of each. Results are shown for structure and enclosures only assessed over a 60-year reference study period. The average line indicates the mean value whereas the median is indicated by the change in grey shade colors within the boxplot.

4.3.1 The impacts of interiors

In **Figure 17,** the ECI of the 19 buildings that reported the embodied impacts of interiors is shown by looking only at the impacts from their structure and enclosure (above), and their structure, enclosure, and interiors (below). The inclusion of interior construction and finishes increased the embodied carbon intensities of these projects by an average of 65 kg CO_2e/m^2, representing an 18% increase in ECI on average when compared to structure and enclosures only. Interiors were not required to be modeled as part of the data collection requirements, and what was received from data contributors may not account for all elements included under these building element categories. For example, the interiors of an office building may only include the interior finishes on exterior walls and the stair and elevator cores, not the full interior fit-out. Other researchers have found even higher potential embodied carbon impacts of interiors, with ranges between 30-250 kg CO_2e/m^2 (Röck & Sørensen, 2022) and even as high as 130-810 kg CO_2e/m^2 (Huang et al., 2018). Even under our limited scope, this analysis suggests that the impacts of interior elements are significant. Including them in LCA modeling and reporting can be an important consideration for developing more comprehensive assessments and results. This is also a key component when considering ECI in existing buildings that are renovated or retrofitted over time.

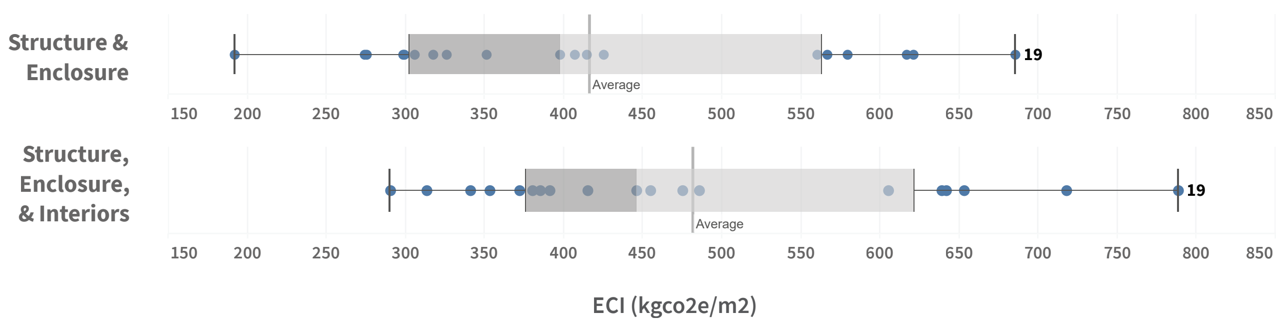

Figure 17. Embodied carbon intensity (ECI) of the 19 projects that included interiors. Results are shown for the same projects looking at structure and enclosure impacts only (above), and structure, enclosure, and interior impacts (below) assessed over a 60-year reference study period.

Figure 18 illustrates the influence of including interior building elements on the ECI of individual buildings for their respective use type categories. The average percentage of increase in ECI is shown for each use type category when comparing between excluding and including interiors. These increases were 14% for commercial offices, 11% for commercial non-office, 25% for residential multi-family, and 10% for other types. While all of these increases are significant, multi-family residential buildings showed the highest impacts from interiors across our dataset.

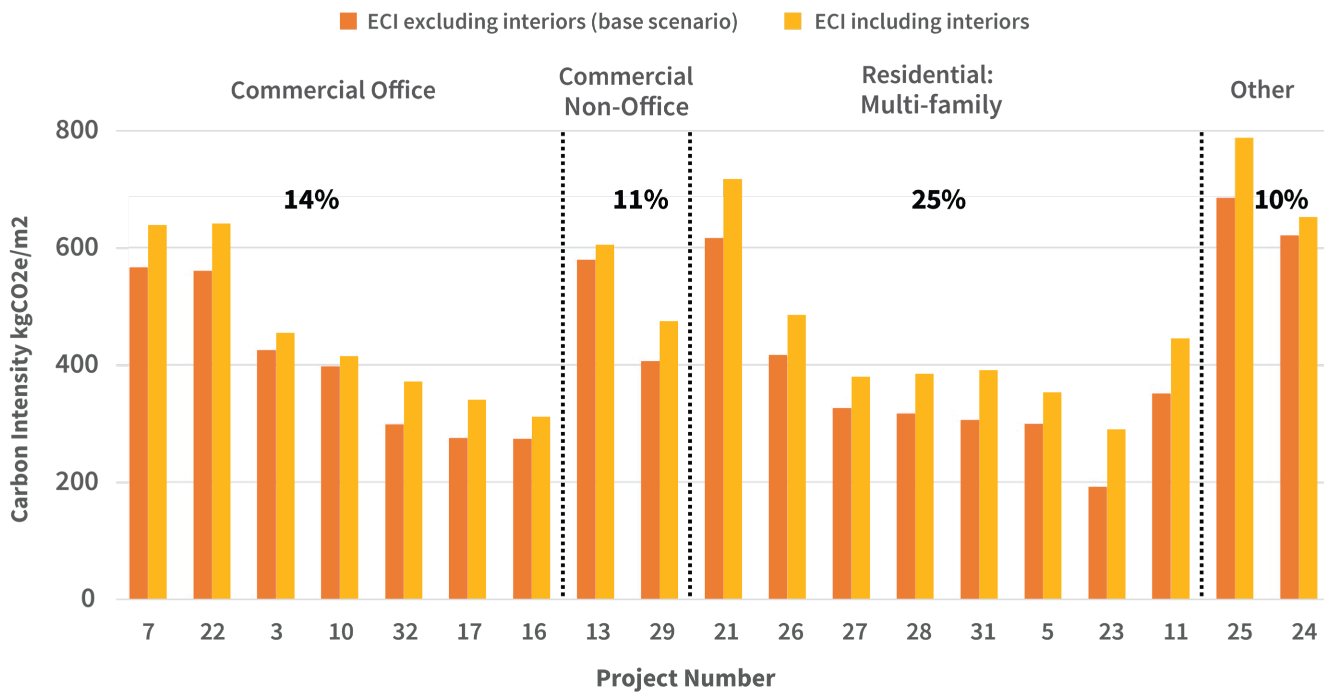

Figure 18. Comparison of embodied carbon intensity (ECI) for the 19 projects that contained interior scope when including and excluding the impacts of those interiors. Results are shown for each building's structure and enclosure impacts only (orange) and structure, enclosure, and interior impacts (yellow) assessed over a 60-year reference study period. Buildings are organized by their use type categories and the average percentage increases in ECI are shown for each type as a result of including interiors.

4.3.2 Embodied carbon contributions

In this section we evaluated the embodied carbon contributions from different life cycle stages, building elements, and material categories.

4.3.2.1 Life cycle stages

Figure 19 illustrates the embodied carbon contribution for each project by life cycle stage and averages across projects with similar physical scopes. Stages A1-A3 were the largest life cycle stage contributors to embodied carbon across all projects, ranging from 150-590 kg CO_2e/m^2 and representing an average of 84% of the embodied carbon impacts of structure and enclosures. While the average carbon impacts from stages A4 and C2-C4 remained similar and relatively small across projects with different scopes, projects that included interiors had notably higher impacts from life cycle stage B4-B5, with an average of 9%, which was three times greater than the average for structure and enclosures only (3%). This is likely due to more frequent replacement of interior materials compared to those of structures and enclosures. It is worth noting that our analysis did not include certain life cycle stages (A5, B1-B3, B5 for some results, and C1, among others) as well as physical scope categories (MEP, sitework, equipment/furnishings, and interior construction and finishes for multiple projects) which would further contribute to carbon impacts beyond A1-A3. Despite the importance and magnitude of A1-A3 impacts, focusing solely on A1-A3 impacts of the structure and enclosure leads to significant gaps in embodied carbon accounting, especially for projects with substantial interior scope.

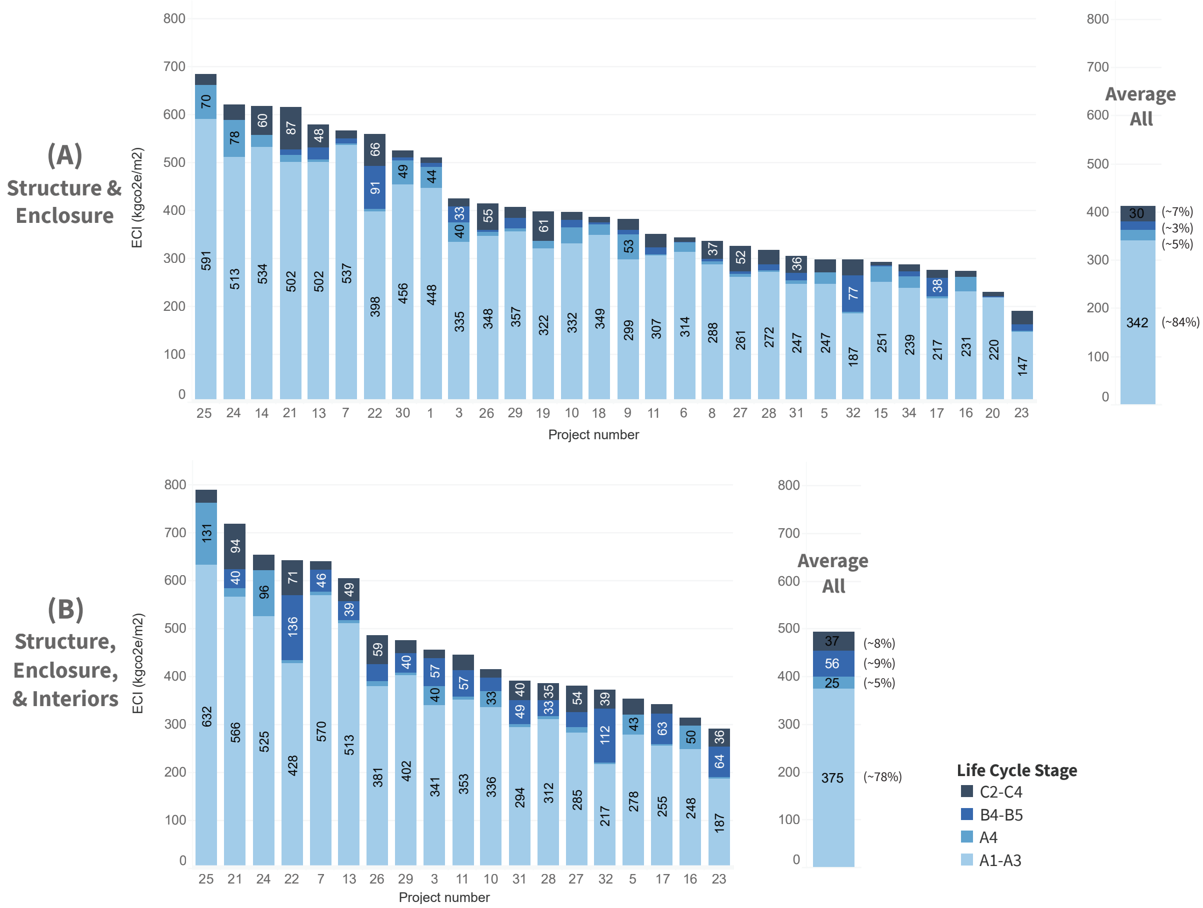

Figure 19. Embodied carbon contributions of life cycle stages. Results are shown for the impacts of structures and enclosures only for all projects (A), and for structure, enclosure, and interiors of the 19 projects that included interiors (B). All values are shown per individual project (left), and the average of the projects (right) assessed over a 60-year reference study period. Results are in kg CO_2e/m^2.

4.3.2.2 Building elements

For this study, we developed a simplified version of building element categories (structure, enclosure, and interiors) based on OmniClass Table 21 (CSI, 2011) and mapped building impacts to those categories using information available from the LCA tool outputs.[13] **Figure 20** shows the embodied carbon contribution of each project by building element category and the average percentages across projects with similar physical scopes. Structural elements were the largest building element contributor to embodied carbon impacts across the projects analyzed, ranging from 130 to 560 kg CO_2e/m^2. They were followed by enclosures ranging from 20-250 kg CO_2e/m^2, and interiors from 20-100 kg CO_2e/m^2 (when interiors were included). The relatively large embodied carbon impacts of structural systems and enclosures are well known and should continue to be an important focus for building decarbonization. However, when included, interior construction and finishes accounted for a significant portion of embodied carbon impacts. Notably, when interiors were included, the relative average percentage of embodied carbon impacts from structures reduced (from 72% to 62%).

13. LCA tool outputs vary in the type of categorization systems used for building elements, as well as their accuracy. The mapping system developed for this study was based on assumptions by the researchers and may not accurately reflect all project impacts or their specific Omniclass categorizations.

This emphasizes the need for expanding the scope of analysis within industry practice and policy development to more fully account for all embodied carbon impacts by including interiors, but also other physical scopes that were not included in this study and are rarely analyzed in industry practices.

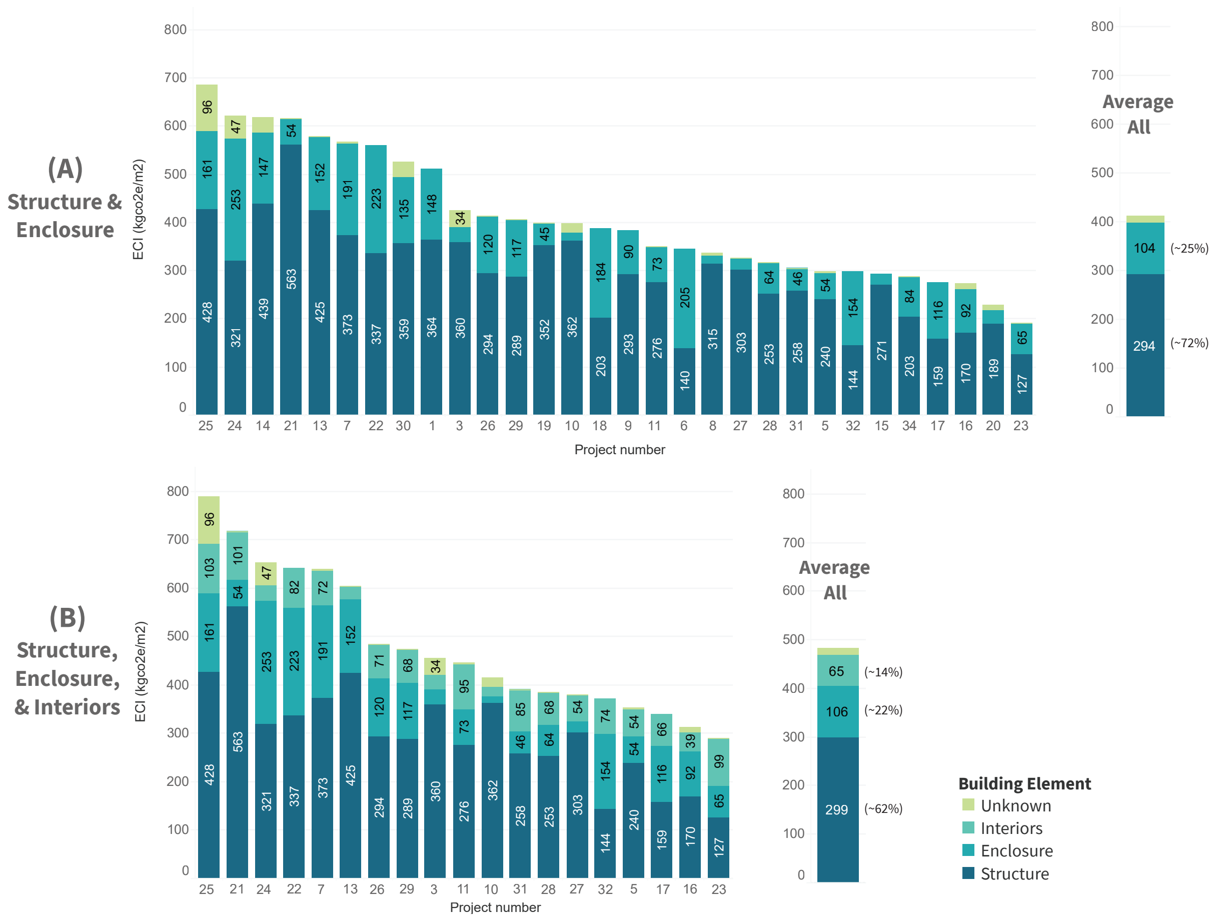

Figure 20. Embodied carbon contribution of building element categories. Results are shown for the impacts of structures and enclosures only for all projects (A), and for structure, enclosure, and interiors of the 19 projects that included interiors (B). All values are shown per individual project (left), and the average of the projects (right) assessed over a 60-year reference study period.

4.3.2.3 Material categories

Figure 21 shows the embodied carbon contribution of each project by CSI Divisions and their averages across projects with different primary structural systems. CSI MasterFormat (CSI, 2011) is a building material categorization system that is frequently used for developing design and construction specifications.

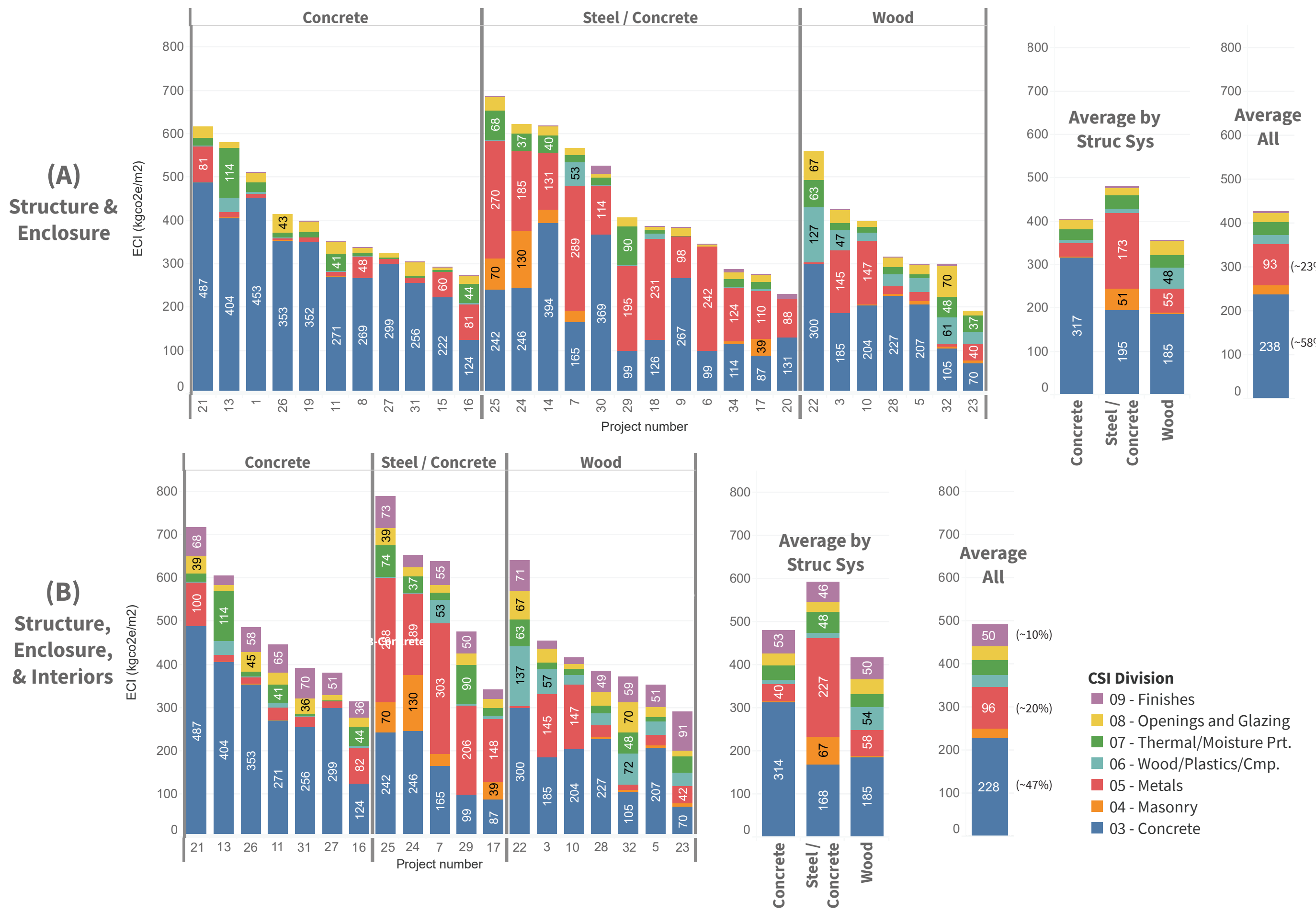

Figure 21. Embodied carbon contribution of CSI Divisions. Results are shown for the impacts of structures and enclosures only for all projects organized by the primary structural system (A), and for structure, enclosure, and interiors of the 19 projects that included interiors (B). All values are shown per individual project (left), and the average of projects (right) assessed over a 60-year reference study period.

When looking at structure and enclosure only **(Figure 21A)**, CSI Division 03-Concrete was the largest contributor to embodied carbon across all projects, ranging from 70-490 kg CO_2e/m^2 with an average of 240 kg CO_2e/m^2 (58% of embodied carbon impacts). For buildings with a primary structural system of reinforced concrete, Division 03-Concrete was a significant contributor, with an average of 320 kg CO_2e/m^2 (79% of structure/enclosure embodied carbon impacts). As opposed to some CSI divisions that may contain multiple types of building materials and products, Division 03 is composed almost entirely of concrete and concrete reinforcing. The second largest contributor was Division 05-Metals, which showed an average of 90 kg CO_2e/m^2 (23%) across all projects.

For steel/concrete hybrid buildings, the average ECI for 03-Concrete and 05-Metals was 200 and 170 kg CO_2e/m^2, respectively. Importantly, 05-Metals contains not just the primary structural steel framing of buildings but also steel decks for concrete floors and metal studs for walls, stairs, and other architectural fabrications. Though there was a significant increase in the ECI contribution of 06-Wood/Plastics/Composites for buildings with a primarily wood structural system (with an average ECI of 50 kg CO_2e/m^2), the main contributing divisions to those buildings were still 03-Concrete and 05-Metals.

When including interior construction and finishes **(Figure 21B)**, the top contributing CSI Divisions remained the same. The most notable difference observed was that projects that included interior scope showed a significant increase in Division 09-Finishes, with an average of 50 kg CO_2e/m^2 (the third largest material division contributor) compared to <5 kg CO_2e/m^2 for structure and enclosure analysis only. Importantly, the inclusion of interior construction and finishes as a physical scope category can increase CSI division contributions beyond Division 09-Finishes. Interior framing, windows, doors, and many other interior construction elements and materials can show up across all CSI divisions as part of the interior scope. As such, small increases in every CSI division were observed for projects that included interiors, and their cumulative effect increased the average ECI by an additional 15 kg CO_2e/m^2 on when compared to structure and enclosures only.

Embodied carbon impacts from Division 03-Concrete and 05-Metals were the most significant material category contributors across our dataset. While addressing the environmental impacts of concrete, steel, and other metals is critical, our analysis shows that focusing solely on these factors can create substantial gaps in carbon accounting and miss out on opportunities for reducing the impacts of other significant material contributors. This was especially true for projects that depend less heavily on steel and concrete as a primary structural system. Improving the completeness of assessments to account for the missing physical scope from this study can alter the relative scale of importance for all of the divisions analyzed here.

5. LIMITATIONS

The findings of this report are not generalizable due to significant limitations of the study. The largest of these included a lack of data to fully quantify and verify all potential whole life carbon impacts of the projects studied and a limited sample size for drawing conclusions. Owing to limitations and barriers of existing LCA data sources, tools, methods, standards, and industry practices, the presented study analyzed only the types of project information, embodied carbon data, and operational energy use information that were readily available from a small subset of design practitioners. Additionally, this study focuses solely on GWP and does not consider other environmental impact categories that could be quantified using LCA.

While perhaps not typical of the entire design industry, the data collected and analyzed here represented common practices for design companies seeking compliance with, or reporting to, various programs like LEED, ILFI, AIA2030, SE2050, and others. As such, the results presented are incomplete and may not be fully comparable. This is not to diminish the credibility of existing modeling and reporting frameworks nor the presented assessments themselves, but instead, to highlight the areas that need to be targeted to improve the overall completeness and comparability of building-scale LCAs for individual practitioners and the industry at large.

Other significant limitations of this study are as follows:

Methods and data quality

- This study did not validate the received embodied carbon and energy use data. Moreover, modeling decisions, material selections, and any other methods used or assumptions made by data contributors were not verified.
- Single values for operational energy use were collected that represented the annual energy use of the buildings. These values did not consider the demand profile of buildings or how these demand profiles align with the carbon intensity of the grid. The alignment of the demand profile with the grid carbon intensity becomes increasingly important as buildings approach net-zero energy.
- The impacts of biogenic carbon were not considered in this study, which, if included, may lead to substantially different results for projects, especially those utilizing wood structural systems.
- Dynamic radiative forcing calculations were not included in our analysis. All models used GWP100, per ISO21930 and ISO21931 Standards, and a conventional study period of 60 years. Furthermore, no discounting was applied for present versus future emissions.

Building element scope

- The level of completeness and resolution to which building elements are included was not verified.
- Building interiors were included in some, but not all, models studied. Sitework, MEP, and furniture/fixtures/equipment were excluded entirely.
- The dataset used in this study lacked information regarding the size of the site versus the size of the building, the type of landscaping and/or site features, the type and volume of refrigerants, and the size and type of any on-site energy generation and/or storage technologies.

Building life cycle stage scope

- No information was collected for construction impact (A5), fugitive emissions and other use impacts (B1), maintenance (B2), repair (B3), operational water use (B7), user activities (B8), or deconstruction/demolition (C1).
- No information was collected to verify the completeness, assumptions, and simplifications made when modeling construction stage transportation (A4), replacement (B4), refurbishment (B5), operational energy use (B6), waste processing (C3), and disposal (C4).
- No details pertaining to any potential benefits or loads occurring outside the system boundary for the assessments were gathered for this study which could inform the impacts and benefits reported in Module D.

6. FUTURE WORK AND RECOMMENDATIONS

The present study illustrates types of LCA data that are readily available from industry practitioners using common modeling practices for various programs like LEED, ILFI, AIA2030, SE2050, and others. The building elements and life cycle stages that are regularly excluded from these practices are important to consider for future research areas that should serve to improve the overall completeness and comparability of assessments. These practices demonstrate more consistent analysis of the embodied carbon impacts for the substructure, superstructure, and enclosure of buildings, but overlook or oversimplify the environmental impacts from many other building elements and life cycle stages. Expanding the scope of the assessments will provide a more holistic view of the true magnitude of environmental impacts that our buildings are responsible for. Additionally, this expanded scope can be used to identify additional means for reducing the environmental impacts of buildings across their full life cycle. Based on the limitations and findings from the present study, several recommendations have been formulated to guide future research and inform design and policy developments.

Biogenic carbon and dynamic radiative forcing

Further work is needed to update and align how GHG emissions are calculated and reported, specifically with regard to biogenic carbon and other potential carbon-storing materials/processes as well as dynamic radiative forcing.

Further work is needed to align how biogenic carbon is considered within background LCI data sources, different assessment tools, and reporting practices. Additionally, further work should be undertaken to investigate the potential benefits of temporary carbon storage from using timber and other biogenic materials in buildings. This should be aligned with recent standards, including EN 15804:2012+A2:2019 (CEN, 2019), which include considerations for how different types of GWP impacts (i.e., fossil, biogenic, land use, and land use change) should be delineated in LCA reporting practices.

Additionally, emerging dynamic LCA methods that consider dynamic radiative forcing impacts can be integrated into WLC assessments in order to evaluate the impacts of time of emission and/or removal in the context of longer-life products such as buildings.

On-site renewables and building energy demand profiles

The scope of the assessment should be broadened to account for the embodied carbon impacts of all on-site energy generation and on-site energy storage technologies that are part of a building (in addition to other scopes identified below) including their replacement, recycling, and end-of-life impacts. The use of on-site energy generation and on-site energy storage technologies elevates the importance of time-of-use grid carbon intensity factors and appropriate granularity of building demand profiles. As such, the operational energy use impacts and the time-of-use grid carbon intensities should be further investigated to determine the appropriate granularity needed from both the consumer-side (building) and the producer-side (grid) to make appropriate net-zero energy and/or net-zero carbon claims for operational energy use (B6).

Physical building element scope

Future work should address current gaps within the physical scope of building-scale assessments, including the lack of information and lack of completeness for the following building elements:

- Interiors
- MEP systems, including on-site energy generation, on-site energy storage, and other forms of energy technologies
- Site impacts
- Furnishings, Fixtures & Equipment (FF&E)

In addition to quantifying the magnitude of environmental impacts for these building elements, it would be advantageous to identify the contributors with the largest impacts and those with the greatest potential for reduction to establish impact reduction strategies that can be implemented during the design process.

Temporal life cycle stage scope

On top of the future work focused on improving the representation of building elements, future work is also required to improve the considerations for life cycle stages that are not regularly considered within current practices. Specifically, information on the following activities and processes should be gathered to improve how the associated life cycle stages are represented in whole life assessments:

- Site preparation, demolition of existing structures, construction stage emissions (including duration and techniques), and construction waste (A5),
- Refrigerant type, leakage, and other fugitive emissions (B1),
- Repair, maintenance, and refurbishment of building elements (B2, B3, B5), and
- End-of-life impacts, particularly deconstruction (C1).

Geographic and typological iterations

This study focused on a small and limited sample of new building projects in the State of California, which is by no means representative of all building typologies in North America, or even California. It is recommended to repeat and expand similar research for other geographies and building typologies not captured here with a larger sample size for each. Additionally, similar studies should be conducted that consider the environmental impacts and payback periods for different retrofit and tenant improvement scenarios as well as single-family residential building types. In future research, we intend to expand on this analysis with a larger data sample and scope, test additional categorization systems, and explore other metrics and forms of analysis for comparing the embodied carbon impacts of buildings.

7. CONCLUSION

This study investigated readily available data from design practitioners to quantify and evaluate the life cycle greenhouse gas emissions of 30 buildings in the State of California. Our goal was to explore the balance between operational and embodied carbon over time. In doing so, we identified gaps and limitations within existing data sources and modeling practices that should be addressed to improve the completeness and comparability of assessments. Although the size of our data sample was small and not representative of all or typical construction, we believe that our analysis is meaningful and can provide researchers, building owners, designers, builders, and policymakers with critical insights into the whole life carbon impacts of these select projects.

Whole life carbon assessment can be a valuable framework for evaluating the embodied and operational carbon impacts of buildings to better understand where and when their emissions occur. In our analysis, on average, the embodied carbon of structure and enclosure alone accounted for a larger share of emissions than operational carbon when grid decarbonization is included. However, the range of operational carbon impacts was broader and heavily influenced by the energy source buildings depended on (electricity vs. natural gas). Embodied carbon impacts remained larger than the operational carbon for every all-electric building studied, whereas, for electric/gas buildings, the operational carbon impacts exceeded those of embodied carbon for 9 out of the 11 buildings. This suggests that transitioning away from combustion energy sources could lead to significant decarbonization for new construction projects in California. Importantly, these findings are heavily influenced and dependent on California's current efforts and goals to achieve a 100% renewable electrical grid by 2045, which must also remain a priority.

No single design parameter or categorization system we analyzed was shown to significantly correlate with embodied carbon intensity. However, we were able to identify several key contributors to embodied carbon impacts that warrant consideration in building design, policy, and research. Of these, the impacts from life cycle stages A1-A3, structural systems of buildings, and concrete and metals material categories were the most substantial. Much has already been written about the importance of reducing the impacts of these top contributors (Birgisdóttir et al., 2016; Birgisdottir et al., 2023; Zimmermann et al., 2021), and they should remain important priorities for the building design industry. We also identified several other significant embodied carbon contributors that warrant consideration, inclusion, and substantial future research in building design, policy, and LCA modeling. These included the impacts from interiors which led to an average increase of 18% in ECI compared to structure and enclosure alone, as well as impacts from life cycle stages beyond A1-A3 (particularly stages B and C) and multiple material categories beyond concrete and metals. We found that variations in embodied carbon contributions across different project types and LCA modeling scopes can be significant, which further emphasizes the need for future research on the impacts of embodied carbon.

Lastly, it is critical to note that our study contained significant gaps in both the physical and temporal scope of the buildings we analyzed. These included impacts from missing life cycle stages, MEP equipment/systems, equipment and furnishings, sitework, and other impacts and considerations such as refrigerants, biogenic carbon, and time-of-use operational impacts, to name a few. Related to our contribution analysis, further research and gap-filling of these could substantially affect the top embodied carbon priorities we identified throughout, as well as our operational and corresponding whole life carbon results. In the future, we intend to expand on this study by working to fill data gaps and conducting additional analyses on the variability of embodied, operational, and whole life carbon impacts. We believe that additional future research on these gaps is crucial for developing more comprehensive and comparable whole life carbon assessments, results, and recommendations for reducing the full life cycle impacts of buildings.

DEFINITIONS

Average Grid Emissions: the impact associated with the entire generation mix used to produce energy for a given time period (total emissions divided by the total amount of energy generated).

Carbon Intensity: Embodied, Operational, and Whole Life: these terms refer to the total GWP of a building normalized by its floor area for the corresponding emission type. They are not standardized terms and are used throughout this report to mean the following:

- **Embodied Carbon Intensity (ECI):** the GWP intensity associated with the embodied emissions of a building expressed as kg CO_2e/m^2. For this report, these values were normalized by gross floor area including parking structures, where applicable.
- **Operational Carbon Intensity (OCI):** the GWP intensity associated with the operational emissions of a building expressed as kg CO_2e/m^2. For this report, these values were normalized by gross floor area excluding parking structures, where applicable.
- **Whole Life Carbon Intensity (WLCI):** the global warming potential intensity associated with all emissions of a building expressed as kg CO_2e/m^2. For this report, these values were the sum of embodied and operational carbon intensities.

Comparability [of LCA results]: the extent to which LCA results can be appropriately compared – a function of (i) the extent to which the objects of assessment are technically and functionally equivalent, and (ii) the extent to which the LCAs use equivalent modeling methods and data sources (so that differences in results are due to differences in actual emissions rather than artifacts of the modeling process).

Embodied Carbon: refers to the greenhouse gas (GHG) emissions associated with the manufacturing, transportation, installation, use, maintenance, and disposal of construction materials.

Energy Use Intensity (EUI): a metric to describe the overall operational energy efficiency of a building. It is typically calculated as the energy consumed by a building in a given year divided by its conditioned floor area.

Global warming potential (GWP): the potential climate change impact of a product or process as measured by an LCA, reported in units (typically kilograms) of carbon dioxide equivalent (CO_2e). In this report, GWP is evaluated over a 100-year time horizon (unless otherwise specified).

GWP benchmark, baseline, threshold, limit, target: These related terms each refer to a static GWP value, used (directly or indirectly) for comparisons. The terms can differ in whether they are descriptive/informative (i.e., they describe "what is" – the current or a future state) or normative (i.e., they explicitly support a policy or other agenda – "what should be"). Their use can also vary in terms of whether they are performance-neutral or represent some particular level of performance (e.g., low, average, or high).

The terms are not always used consistently throughout the industry. This report generally uses these terms to mean the following:

- **Benchmark:** "reference point against which comparisons can be made" (ISO, 2020). Benchmark is the most inclusive term here: benchmarks are more general than baselines in that they could represent low, average, or high performance; usually calculated based on existing product or project data, but could be determined otherwise (e.g., downscaled global carbon budgets). The generic term "reference value" is often used similarly.

- **Baseline:** reference point to be used as a basis for comparison that generally aims to describe current business-as-usual performance; typically derived from representative industry data.
    - Example: The CLF Material Baselines draw upon current industry data to provide average GWP values for a range of product types. Policies and programs can use these baselines to inform limits, targets, etc.
- **Threshold** or **[Regulatory] Limit**: upper acceptable GWP threshold for mandatory compliance (i.e., minimum performance); typically set for a particular policy or program.
    - Example: "The threshold approach defines a maximum GHG emissions intensity for each category of material…" (Lewis et al., 2023)
    - Example: The Buy Clean California Act (BCCA) employs GWP limits for specific materials, where products must fall below the limit to comply.
    - *Some documents use the term* ***"emission standard"*** *or* ***"performance standard"*** *to refer to this concept. Because this report uses the term "standard" frequently to describe a different concept (a document that provides LCA rules and methods), we are avoiding the use of "emission standard" or "performance standard" here to minimize confusion.*
- **Target:** voluntary high-performance (i.e., low GWP) goal to aim towards. Programs/policies may include short-, medium-, and long-term target values (ISO, 2020).
    - Example: Ramboll's EC building benchmarks report calls for "setting targets that are aligned with the 2015 Paris Agreement to support the built environment's transition to a lower-carbon future" (Den et al., 2022).

Life Cycle Assessment (LCA): a systematic set of procedures for compiling and evaluating the inputs and outputs of materials and energy, and the associated environmental impacts directly attributable to a product or process throughout its life cycle. An LCA of a building is often called a WBLCA.

Normalization: refers to the process of adjusting values measured on different scales (in this report, GWP and GFA) to a notionally common scale (in this report, GWP).

Operational Carbon: refers to the greenhouse gas (GHG) emissions associated with the operation of a building, over its full life cycle including activities such as heating, cooling, lighting, and equipment use.

Reference study period: period over which the time-dependent characteristics of the object of assessment are analyzed (CEN, 2011; ISO, 2022).

Scope, Physical and Temporal: The scope of a life cycle assessment defines what is being analyzed, including the object of assessment, reference study period, and system boundary. The system boundary can be broken down into physical and temporal scope.

- **Physical Scope:** the physical elements, components, and/or materials of a building included in the life cycle assessment.

- **Temporal Scope:** the individual life cycle stages and modules included in the life cycle assessment.

Standards: formal documents, typically mandatory, that establish uniform technical criteria, methods, processes, and requirements for WBLCA. They are typically produced by third-party standardization organizations and require the formal consensus of technical experts before publication.

Total Carbon: Another term for "whole life carbon."

Verification / Verified: these terms are used generically throughout this report to refer to the process of recreating, reproducing, and/or ensuring that LCA results are based on appropriate data, calculated consistently and correctly, provide justification of completeness, and conform with applicable WBLCA standards. For example, EN 15978 (CEN, 2011) outlines minimum requirements for the verification of LCA results.

Whole Building Life Cycle Assessment (WBLCA): also referred to as "Building Life Cycle Assessment" - a life cycle assessment (LCA) of an entire building, spanning its full life cycle.

Whole life Carbon (WLC): refers to the greenhouse gas (GHG) emissions resulting from the materials, construction, and use of a building over its entire life cycle, including its demolition and disposal. *Can be framed in terms of GHG Protocol scopes 1-3, EN 15978 (CEN, 2011) or ISO 21931-1 (ISO, 2022).*

Whole life Carbon Assessment (WLCA): a life cycle assessment (LCA) of an entire building, spanning over its full life cycle, evaluating global warming potential only. *This term is usually used to refer to both embodied and operational carbon impacts.*

REFERENCES

ANSI/ASHRAE/IES. (2018). *ANSI/ASHRAE/IES 90.2-2018 Standard: Energy-Efficient Design of Low-Rise Residential Buildings.* https://www.techstreet.com/ashrae/standards/ashrae-90-2-2018?product_id=2030773

ANSI/ASHRAE/IES. (2019). *ANSI/ASHRAE/IES 90.1-2019: Energy Standard for Buildings Except Low-Rise Residential Buildings.* American National Standards Institute (ANSI). https://webstore.ansi.org/standards/ashrae/ansiashraeies902019

Arehart, J. H., Hart, J., Pomponi, F., & D'Amico, B. (2021). *Carbon sequestration and storage in the built environment.* Sustainable Production and Consumption, 27, 1047–1063. https://doi.org/10.1016/j.spc.2021.02.028

Athena Sustainable Materials Institute. (2023). *Impact Estimator for Buildings v5.5: User Manual and Transparency Document.* Athena Sustainable Materials Institute. https://calculatelca.com/wp-content/uploads/2023/12/IE4B_v5.5_User_Guide_Dec_2023.pdf

Birgisdottir, H., Lützkendorf, T., Palaniappan, S., & Passer, A. (2023). *Assessing life cycle related environmental impacts caused by buildings - summary report (Annex 72)*.

Birgisdóttir, H., A., H.-W., Moncaster, A., Rasmussen, F. N., Nehasilova, M., Potting, J., & Soulti, E. (2016). *Evaluation of Embodied Energy and CO 2eq for Building Construction (Annex 57) Subtask 4: Case studies and recommendations for the reduction of embodied energy and embodied greenhouse gas emissions from buildings.* https://www.iea-ebc.org/Data/publications/EBC_Annex_57_ST4_Case_Studies_Recommendations_Appendix.pdf

BSR/ASHRAE/ICC. (2024). *Standard 240P, Evaluating Greenhouse Gas (GHG) and Carbon Emissions in Building Design, Construction and Operation: First Full Publication Public Review Draft.* ASHRAE and International Code Council (ICC).

Buy Clean California Act, 262, California Department of General Services Chapter 816, Assembly Bill (2017). https://www.dgs.ca.gov/PD/Resources/Page-Content/Procurement-Division-Resources-List-Folder/Buy-Clean-California-Act

California Energy Commission. (2022). *Building Energy Benchmarking Program.* https://www.energy.ca.gov/programs-and-topics/programs/building-energy-benchmarking-program

CEN. (2011). *EN 15978:2011: Sustainability of construction works - Assessment of environmental performance of buildings.* European Committee for Standardization (CEN).

CEN. (2019). EN 15804:2012+A2:2019: *Sustainability of construction works - Environmental product declarations - Core rules for the product category of construction products.* https://www.en-standard.eu/bs-en-15804-2012-a2-2019-sustainability-of-construction-works-environmental-product-declarations-core-rules-for-the-product-category-of-construction-products/

CIBSE. (2021). *TM65: Embodied carbon in building services: a calculation methodology (The Chartered Institution of Building Services Engineers (CIBSE))*. The Chartered Institution of Building Services Engineers London. https://www.cibse.org/knowledge/knowledge-items/detail?id=a0q3Y00000IPZOhQAP

CSI. (2011). *Construction Specifications Institute: About OmniClassTM. Omniclass Table 21.* https://www.csiresources.org/standards/omniclass/standards-omniclass-about

Den, X. L., Steinmann, J., Röck, M., H.Birgisdottir, Horup, L. H., Tozan, B., & Sørensen, A. (2022). T*owards embodied carbon benchmarks for buildings in Europe - Summary Report (Ramboll).* Ramboll. https://fs.hubspotusercontent00.net/hubfs/7520151/RMC/Content/EU-ECB-Summary-Report.pdf

DOE2. (2018). *eQUEST: the QUick Energy Simulation Tool.* James J. Hirsch & Associates (JJH) in collaboration with Lawrence Berkeley National Laboratory (LBNL). https://www.doe2.com/equest/

Gagnon, P., Cowiestoll, B., & Schwarz, M. (2023). *Cambium 2022 Scenario Descriptions and Documentation (No. NREL/TP-6A40-84916).* National Renewable Energy Laboratory (NREL). https://www.nrel.gov/docs/fy23osti/84916.pdf

Hitchin, E. R., & Pout, C. H. (2002). *The carbon intensity of electricity: how many kgC per kWhe?* Building Services Engineering Research and Technology, 23(4), 215–222. https://doi.org/10.1191/0143624402bt044oa

Huang, M., Simonen, K., & Ditto, J. (2018). *Life Cycle Assessment (LCA) for Low Carbon Construction: Tenant Improvements in Commercial Office Buildings, Final Report*. Carbon Leadership Forum (CLF). https://carbonleadershipforum.org/wp-content/uploads/2019/05/CLF-TI-LCA-Report.pdf

ICC. (2022). *2022 California Green Building Standards Code, Title 24, Part 11 (CALGreen) with July 2024 Supplement*. International Code Council. https://codes.iccsafe.org/content/CAGBC2022P3

IEA. (2023). *CO2 Emissions in 2022 (International Energy Agency (IEA)). International Energy Agency (IEA).* https://iea.blob.core.windows.net/assets/3c8fa115-35c4-4474-b237-1b00424c8844/CO2Emissionsin2022.pdf

ISO. (2020). *ISO 21678 Sustainability in buildings and civil engineering works — Indicators and benchmarks — Principles, requirements and guidelines.* https://www.iso.org/standard/71344.html

ISO. (2022). *ISO 21931-1:2022 Sustainability in buildings and civil engineering works — Framework for methods of assessment of the environmental, social and economic performance of construction works as a basis for sustainability assessment — Part 1: Buildings.* ISO.

Lewis, M., Waldman, B., Carlisle, S., Benke, B., & Simonen, K. (2023). *Advancing the LCA Ecosystem A Policy-Focused Roadmap for Reducing Embodied Carbon.* Carbon Leadership Forum (CLF). https://carbonleadershipforum.org/advancing-lca-ecosystem/

Office of Governor Gavin Newsom. (2022, September 16). Governor Newsom Signs Sweeping Climate Measures, Ushering in New Era of World-Leading Climate Action. Office of Governor Gavin Newsom. https://www.gov.ca.gov/2022/09/16/governor-newsom-signs-sweeping-climate-measures-ushering-in-new-era-of-world-leading-climate-action/

One Click LCA. (2023). *Comply with EN/ISO standards and 80+ certifications.* Certification and Compliance. https://oneclicklca.com/software/design-construction/

certifications-compliance

Pimm, A. J., Palczewski, J., Barbour, E. R., & Cockerill, T. T. (2021). *Using electricity storage to reduce greenhouse gas emissions.* Applied Energy, 282, 116199. https://doi.org/10.1016/j.apenergy.2020.116199

Röck, M., & Sørensen, A. (2022). *Towards embodied carbon benchmarks for buildings in Europe - #2 Setting the baseline: A bottom-up approach (Ramboll)*. Ramboll. https://fs.hubspotusercontent00.net/hubfs/7520151/RMC/Content/EU-ECB-2-Setting-the-baseline.pdf

Roudsari, M. S., Pak, M., & Adrian Smith + Gordon Gill Architecture. (2013). *Ladybug: A parametric environmental plugin for grasshopper to help designers create an environmentally-conscious design.* Proceedings of the 13th International IBPSA Conference, 3128–3135. https://www.aivc.org/sites/default/files/p_2499.pdf

RICS. (2023). *Whole life carbon assessment for the built environment (2nd Edition, Ed.).* Royal Institute of Chartered Surveyors (RICS). https://www.rics.org/profession-standards/rics-standards-and-guidance/sector-standards/construction-standards/whole-life-carbon-assessment.html

Tally. (2023). *Methods.* https://choosetally.com/methods/

United Nations Environment Programme. (2022). *2022 Global Status Report for Buildings and Construction: Towards a Zero-emission, Efficient and Resilient Buildings and Construction Sector*. United Nations (UN). https://www.unep.org/resources/publication/2022-global-status-report-buildings-and-construction

U.S. Department of Energy. (2011). *Prototype Building Models. Building Energy Codes Program.* https://www.energycodes.gov/prototype-building-models

U.S. DOE. (2017). *EnergyPlusTM (Version 00)*. USDOE Office of Energy Efficiency and Renewable Energy (EERE), Energy Efficiency Office. https://www.osti.gov/biblio/1395882

U.S. EIA. (2021). Commercial Buildings Energy Consumption Survey (CBECS). 2018 CBECS Survey Data. https://www.eia.gov/consumption/commercial/data/2018/

U.S. EPA. (2024). *Emission Factors for Greenhouse Gas Inventories.* U.S. Environmental Protection Agency (U.S. EPA). https://www.epa.gov/system/files/documents/2024-02/ghg-emission-factors-hub-2024.pdf

Zimmermann, R. K., Andersen, C. E., Kanafani, K., & Birgisdóttir, H. (2021). *Build Report 2021 : Whole Life Carbon Assessment of 60 Buildings* (No. 9788793585355; BUILD Report). Department of the Built Environment, Aalborg University Copenhagen. https://build.dk/Pages/Whole-Life-Carbon-Assessment-of-60-buildings.aspx

APPENDIX A. LIFE CYCLE EMISSIONS CALCULATIONS

Calculations for this study were based on the data collected as described in Section 3. After the data collection phase, the project dataset was used to calculate embodied, operational, and whole life carbon impacts, as outlined in Figure A1. This included establishing annual embodied carbon impacts from the LCA results submitted and using emissions factors and grid scenarios to convert operational energy use into operational emissions. Detailed calculations for each emission type are outlined in detail in the following subsections.

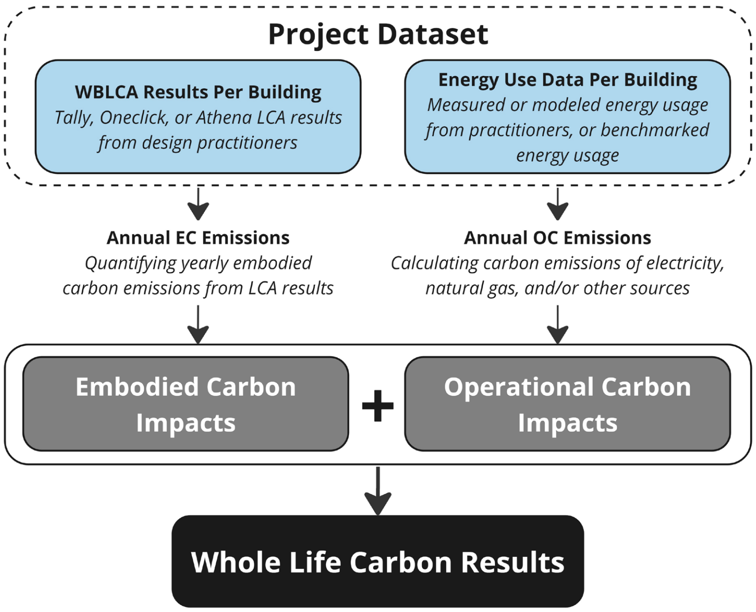

Figure A1. Diagram of the general methodology used in this study to estimate whole life carbon emissions.

A.1 Embodied carbon calculations

The equations and methods for calculating embodied carbon GWP impacts are built into the LCA tools used by this study's data contributors (Tally LCA and One Click LCA). Both of the tools' calculation methodologies for environmental impacts are consistent with international standards such as ISO 14040-14044, ISO 21931:2010, EN 15804:2012, and EN 15978:2011. Importantly, and as outlined in Section 3, while the calculation methods of the tools may be consistent, they contain significant differences that do not result in directly comparable results.

The LCA tools used for this study do not report annual embodied carbon impacts. Instead, embodied carbon GWP profiles in annual format were generated for each project based on the sum of all the materials' impacts at the reference year. To create alignment between Tally LCA and One Click LCA, this calculation was for life cycle modules A-C only. The detailed calculation steps are demonstrated below and were necessary based on the direct outputs from the LCA tools allowed for this study:

- When the reference year of building k =0,

$$EC_{B,k} = sum\ (EC_{B,A1-A3} + EC_{B,A4})\ with\ all\ the\ materials$$

Where:

$EC_{B,k}$= Embodied carbon emissions (kg CO_2e) for building B in year *k*

$EC_{B,A1-A3}$= Embodied carbon emissions (kg CO_2e) of phase A1-A3 for building B in year *k*

$EC_{B,A4}$= Embodied carbon emissions (kg CO_2e) of phase A4 for building B in year *k*

- When the reference year of building 0<k <K (K is the service life of buildings which are all 60 years in this study), $EC_{B,k} =$
$sum\ (EC_{B,B2-B5})with\ the\ materials\ which\ should\ be\ replaced\ at\ the\ reference\ year\ k$

Where:

$$EC_{B,B2-B5} = EC_{B,A1-A3} + EC_{B,A4} + EC_{B,C2-C4}$$

$EC_{B,B2-B5}$= Embodied carbon emissions (kg CO_2e) of phase B2-B5 for building B in year *k*

$EC_{B,C2-C4}$= Embodied carbon emissions (kg CO_2e) of phase C2-C4 for building B in year *k*

- When the reference year of building k =K,

$$EC_{B,k} = sum\ (EC_{B,C2-C4})\ with\ all\ the\ materials$$

The ECI for building B in year k was defined below as discussed in Section 3.3.5:

$$ECI_{B,k} = EC_{B,k}/GFA_i$$

Where:

$ECI_{B,k}$= Embodied carbon intensity (kg CO_2e/m^2) for building B in year *k*

$EC_{B,k}$= Embodied carbon emissions (kg CO_2e) for building B in year *k*

GFA_i= Gross floor area including parking area (m^2)

A.2 Operational carbon calculations

The operational energy use demands of buildings analyzed were generated according to Figure 7 in Section 3.5.1. These final outputs for operational energy consumption included annual electricity (kWh/year) and annual natural gas (kBTU/year). Though annual on-site renewable electricity production (kWh/year) from PV was provided by some data contributors, they were excluded as discussed in Section 3.5.4. None of the projects included any other fossil fuel sources other than natural gas. We then calculated carbon emissions based on the energy consumed from each energy source.

A.2.1 Operational carbon emission from electricity

Operational carbon emissions from electricity for each building were calculated on an annual basis. The annual energy consumption in each building was assumed to remain constant for the duration of the reference study period. The electricity emission factor dataset from draft ASHRAE/ICC 240P (BSR/ASHRAE/ICC, 2024) which was applied here explicitly accounts for decarbonization trends in the electricity sector.

Operational carbon from building electricity use for future years was calculated using:

$$OC_{B,Elec,k} = E_{Elec} \times EF_{Elec,k}$$

Where:

$OC_{B,Elec,k}$ = Operational carbon emissions (kg CO_2e) from electricity used in building B in year *k*

E_{Elec} = Annual electricity consumption (kWh) in buildings excluding any on-site renewable generation (e.g., PV). In Section B2.1, E_{Elec} considering PV benefits should be the annual net electricity consumption that presented any on-site renewable generation, where E_{Elec}= E_{Elec}- E_{Renew}.

$EF_{Elec,k}$ = Emission factor (kg CO_2e/kWh) for grid electricity in year *k* based on the dataset sources which were draft ASHRAE/ICC 240P

The OCI from electricity for building B in year k was defined below as discussed in Section 3.3.5:

$$OCI_{B,Elec,k} = OC_{B,Elec,k}/GFA_{e}$$

Where:

$OCI_{B,Elec,k}$= Operational carbon intensity (kg CO_2e/m^2) from electricity used in building B in year *k.*

$OC_{B,Elec,k}$ = Operational carbon emissions (kg CO_2e) from electricity used in building B in year *k.*

GFA_{e}= Gross floor area excluding parking area (m^2).

A.2.2 Operational carbon emission from natural gas

Operational carbon emissions from natural gas combustion for each building were calculated on an annual basis. The annual energy consumption in each building was assumed to remain constant. The natural gas emission factor datasets from draft ASHRAE/ICC 240P were used which do not account for decarbonization trends in the natural gas sector.

$$OC_{B,Gas,k} = E_{Gas} \times EF_{Gas,k}$$

Where:

$OC_{B,Gas,k}$ = Operational carbon emissions (kg CO_2e) from natural gas in building B in year *k*.

E_{Gas} = is the annual natural gas consumption (kBTU) in the buildings.

$EF_{Gas,k}$ = Emission factor for natural gas (kg CO_2e/kBTU) in year *k* based on the draft ASHRAE/ICC 240P

The OCI from natural gas for building B in year k was defined below as discussed in Section 3.3.5:

$$OCI_{B,Gas,k} = OC_{B,Gas,k}/GFA_{e}$$

Where:

$OCI_{B,Gas,k}$= Operational carbon intensity (kg CO_2e/m^2) from natural gas used in building B in year *k*

$OC_{B,Gas,k}$ = Operational carbon emissions (kg CO_2e) from natural gas in building B in year *k*.

GFA_{e}= Gross floor area excluding parking area (m^2).

A.2.3 Total operational carbon emission

$$OC_{B,Total,k} = OC_{B,Elec,k} + OC_{B,Gas,k}$$

Where:

$OC_{B,Total,k}$ = Total operational carbon emissions (kg CO_2e) from electricity excluding any renewable generation and natural gas for building *B* in year *k.*

$OC_{B,Elec,k}$ = Operational carbon emissions (kg CO_2e) from electricity excluding any renewable generation used for building *B* in year *k.* In Section B2.1, $OC_{B,Elec,k}$ considering PV benefits should be the annual operational carbon emission from net electricity consumption

$OC_{B,Gas,k}$ = Operational carbon emissions (kg CO_2e) from natural gas for building *B* in year *k.*

The total OCI from electricity and natural gas for building B in year k was defined below as discussed in Section 3.3.5:

$$OCI_{B,Total,k} = OC_{B,Total,k}/GFA_{\ e}$$

Where:

$OCI_{B,Total,k}$= Total operational carbon intensity (kg CO_2e/m^2) from electricity and natural gas used in building B in year *k.*

$OC_{B,Total,k}$ = Total operational carbon emissions (kg CO_2e) from electricity excluding any renewable generation and natural gas for building *B* in year *k.*

$GFA_{\ e}$= Gross floor area excluding parking area (m^2).

A.3 Whole life carbon calculations

Whole life carbon was the sum of embodied carbon and operational carbon at year k.

$$WLC_{B,k} = OC_{B,Total,k} + EC_{\ B,k}$$

Where:

$WLC_{B,k}$= whole life carbon (kg CO_2e) for building *B* in year *k*

$OC_{B,Total,k}$= Total operational carbon emissions (kg CO_2e) from electricity excluding any renewable generation and natural gas for building *B* in year *k.* In Section B2.1, $OC_{B,Elec,k}$ considering PV benefits should be the annual operational carbon emission from net electricity consumption

$EC_{\ B,k}$= Embodied carbon emissions (kg CO_2e) for building *B* in year *k*

The WLCI for building B in year k was defined below as discussed in Section 3.3.5:

$$WLCI_{B,k} = OCI_{B,Total,k} + ECI_{\ B,k}$$

Where:

$WLCI_{B,k}$= The whole life carbon intensity (kg CO_2e/m^2) for building B in year *k.*

$OCI_{B,Total,k}$= Total operational carbon intensity (kg CO_2e/m^2) from electricity and natural gas used for building B in year *k.*

$ECI_{\ B,k}$= Embodied carbon intensity (kg CO_2e/m^2) for building B in year *k*

APPENDIX B. ADDITIONAL ANALYSIS

This appendix provides additional analysis, figures, and other explorations of the data collected. In Section B.1, additional analysis is shown using the same methodology from the main body of this report. In Section B.2, we explored the variability of our results and findings based on changes to this methodology.

B.1 Additional figures and analysis

B.1.1 Embodied and operational carbon

Figure B1 demonstrates the distribution of 30 projects based on the building use types and energy use categories. The x-axis and y-axis are OCI and ECI, respectively. The points below the diagonal line indicate projects whose OCI exceeded ECI over the reference study period (only 9 total). Overall, ECI and OCI did not show a strong correlation based on the data collected for this study. The main reasons for this may include the small size of our dataset; the lack of physical elements included in the LCAs for mechanical, electrical, and plumbing equipment; or inconsistencies between embodied and operational carbon modeling. Exploring the tradeoffs between ECI and OCI could offer insights into the most effective reduction strategies for individual projects, but additional data and research are needed to better understand their relationship.

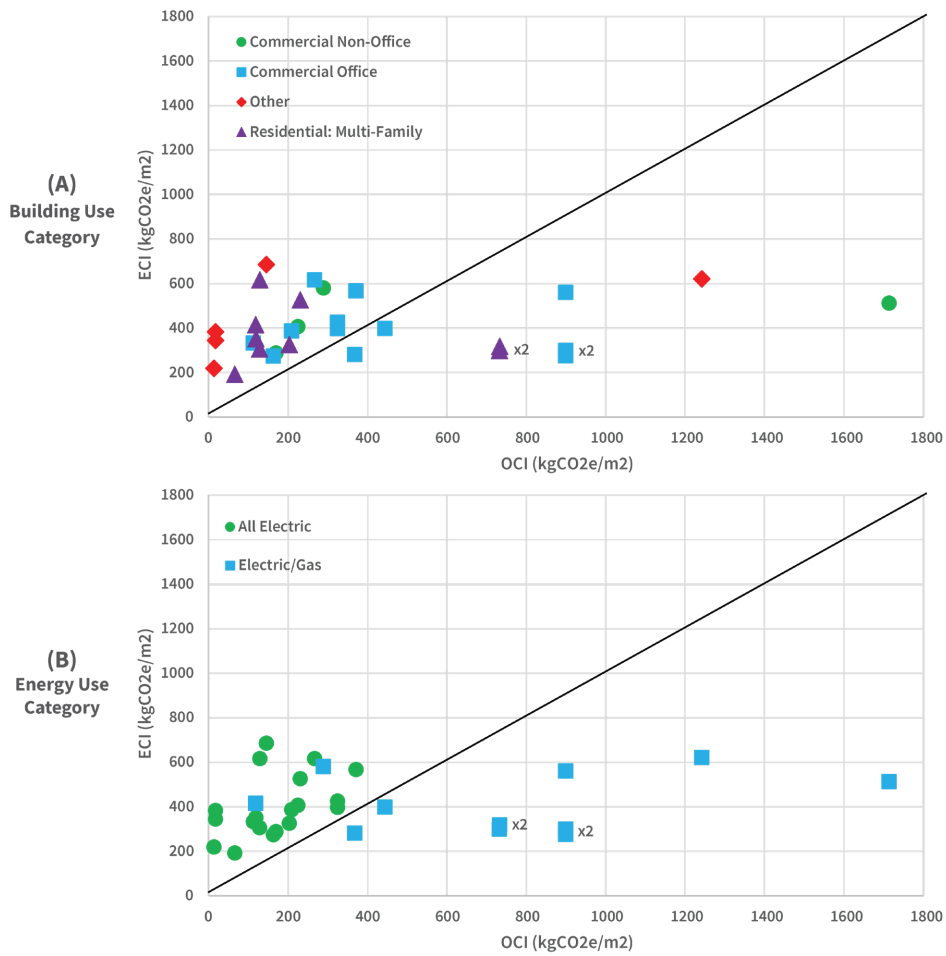

Figure B1. Embodied carbon intensity (ECI) and operational carbon intensity (OCI) under different building categorizations. Results are shown for all buildings by building use category (A) and energy use category (B) as symbols. Points above the diagonal line indicate projects whose ECIs were larger than OCIs at and, below the line, projects whose OCIs were greater.

Figure B2 illustrates the relationship between site energy use intensity (EUI) and OCI under different energy use categories. The all-electric projects tended to produce lower carbon emissions and their relationship with site EUI and OCI was linear. For projects that included combustion but had a limited reliance on natural gas (two points in red), their emissions closely aligned with the trend of all-electric buildings. Furthermore, several all-electric and nearly all-electric buildings were able to consume more energy and still emit fewer carbon emissions than projects that depended more heavily on natural gas (see 9 orange/yellow outliers). Ultimately, we found that reducing total energy consumption is, and should remain, an important decarbonization strategy. But we also found that reducing or eliminating combustion fuel sources alone could lead to significant decarbonization. It is important to note that these findings are based on the assumption that grid decarbonization trends continue in the State of California.

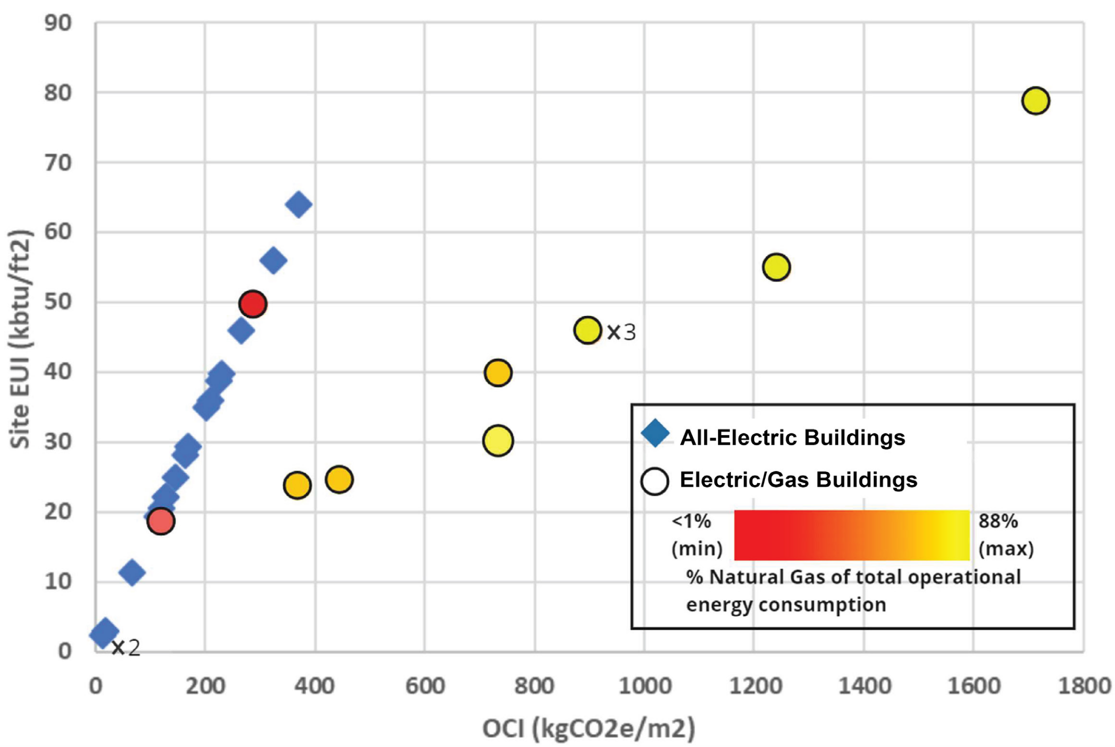

Figure B2. Operational carbon intensity (OCI) compared to site energy use intensity (EUI). OCIs (x-axis) and EUIs (y-axis) are shown for every building analyzed using a 60-year reference study period. Symbols reflect the energy use category of buildings, with electric/gas buildings colored on a gradient of their percentage of total energy consumption that came from natural gas combustion (<1% and 88% being the minimum and maximum values in our dataset).

B.1.2 Embodied, operational, and whole life carbon values

In **Figure B3**, OCI, ECI, and WLCI are shown for different building use types: commercial office (12 buildings), commercial non-office (4 buildings), multi-family residential (9 buildings), and other (5 buildings). **Table B1** lists the values for the 1st quartile, 3rd quartile, median, and mean of ECI, OCI, and WLCI (for building use types). Sample sizes for building use categories were too small to draw any significant conclusions regarding correlation with embodied, operational, or whole life carbon intensity.

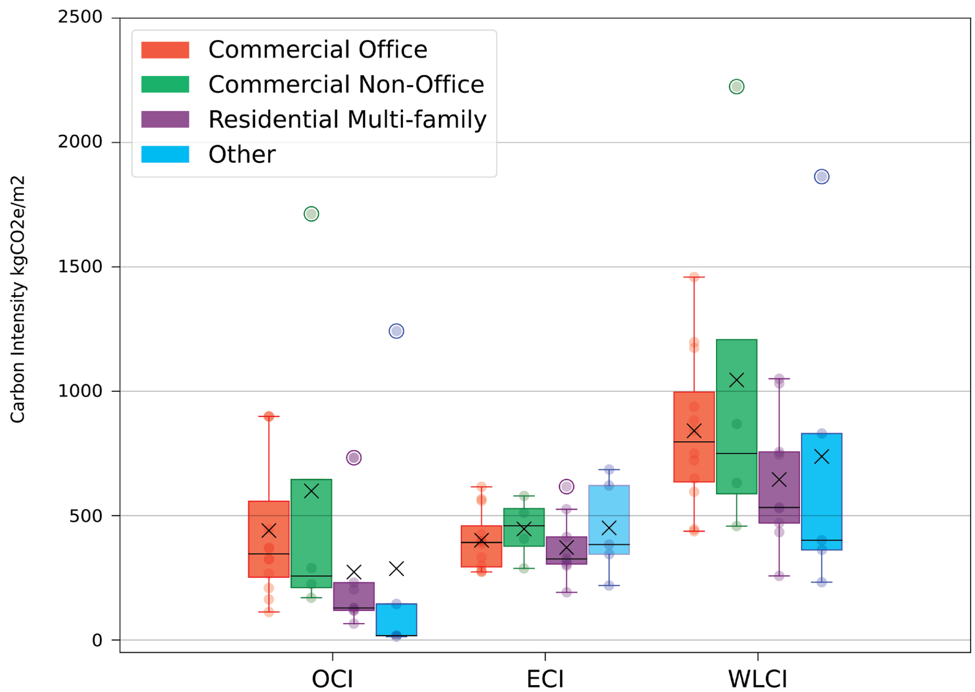

Figure B3. Embodied carbon intensity (ECI), operational carbon intensity (OCI), and whole life carbon intensity (WLCI) boxplots of all buildings. Results are categorized by building use type: Commercial office buildings; Commercial buildings other than offices; Residential multi-family buildings; and Other use types and assessed using a 60-year reference study period.

Table B1. 1st quartile, 3rd quartile, median, and mean of ECI, OCI, and WLCI for building use types. Values in this table were rounded to the nearest 10 units as a significant integer.

Metric	Statistic	Commercial office (n=12)	Commercial non-office (n=4)	Residential multi-family (n=9)	Others (n=5)	All buildings (n=30)
OCI (kg CO_2e/m^2)	1st quartile	250	210	120	20	130
	median	350	260	130	20	230
	3rd quartile	560	650	230	150	430
	mean	440	600	270	290	390
ECI (kg CO_2e/m^2)	1st quartile	290	380	300	340	300
	median	390	460	330	380	390
	3rd quartile	460	530	410	620	520
	mean	400	450	370	450	410
WLCI (kg CO_2e/m^2)	1st quartile	640	590	470	360	460
	median	800	750	530	400	730
	3rd quartile	1000	1200	760	830	920
	mean	840	1050	650	740	790

Figure B4 shows the variations in OCI, ECI, and WLCI based on the different operational energy use categories. The two categories were all-electric (19 buildings) and electric/gas (11 buildings). **Table B2** lists the values for the 1st quartile, 3rd quartile, median, and mean of ECI, OCI, and WLCI (for energy use categories). Electric/gas buildings had notably higher mean and median OCIs than all-electric buildings, but their ECIs were similar. The larger WLCI of electric/gas buildings is thus largely attributable to their increase in OCI.

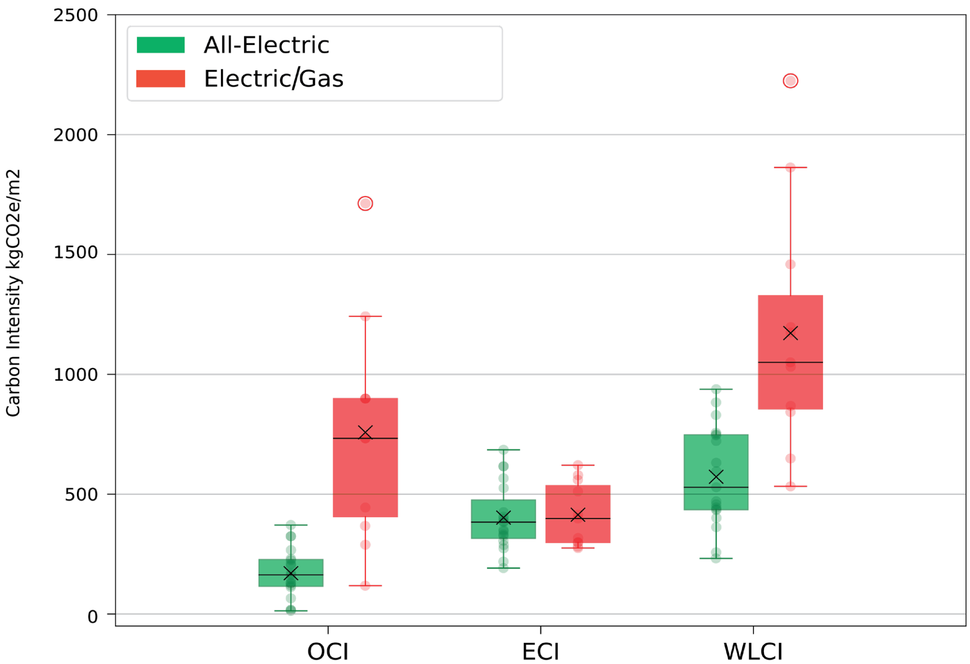

Figure B4. Embodied carbon intensity (ECI), operational carbon intensity (OCI), and whole life carbon intensity (WLCI) boxplots of all buildings by energy use type. Results are shown for All electric projects (green, n=19) and electric/gas projects (red, n=11) using a 60-year reference study period.

Table B2. 1st quartile, 3rd quartile, median, and mean of ECI, OCI, and WLCI for energy use categories. Values in this table were rounded to the nearest 10 units as a significant integer.

Metric	Statistic	All-Electric (n=19)	Electric/Gas (n=11)	All buildings (n=30)
OCI (kg CO_2e/m^2)	1st quartile	120	410	130
	median	160	730	230
	3rd quartile	230	900	430
	mean	170	760	390
ECI (kg CO_2e/m^2)	1st quartile	320	300	300
	median	380	400	390
	3rd quartile	480	540	520
	mean	400	410	410
WLCI (kg CO_2e/m^2)	1st quartile	440	860	460
	median	530	1050	730
	3rd quartile	750	1330	920
	mean	570	1170	790

B.2 Methodological variability

B.2.1 The potential benefits of photovoltaics

Thirteen (13) projects from our dataset contained PVs (including 10 out of 19 all-electric buildings and 3 out of 11 electric/gas buildings). The amount of PV generation varied across projects, ranging from 8% to 100% of the project's mean annual grid electricity demand. **Figure B5** compares the median cumulative OCI and ECI for the buildings that had PVs (13) and did not have PVs (17). For the buildings that had PV (B5A), OCI is shown assuming 100% grid offset benefits of PV (black line) and with 0% of the benefits of PV (blue line, base scenario). Large differences existed in the two OCIs across the 60-year reference study period. However, they were both far below the median ECI (orange line). Assuming 100% of the potential benefits of PVs is an oversimplification that does not consider the difference in demand and generation profiles for the buildings nor the time-dependent carbon intensity for the electricity grid and can lead to a substantial underestimation of OCI. For the buildings that did not have any PV (B5B), ECI and OCI also did not intersect even by the end of the 60-year study period. We found that including PV or other renewable energy sources could significantly decrease operational carbon impacts, but additional research is required to consider the actual time-of-use impacts for both PV generation and electrical grid conditions.

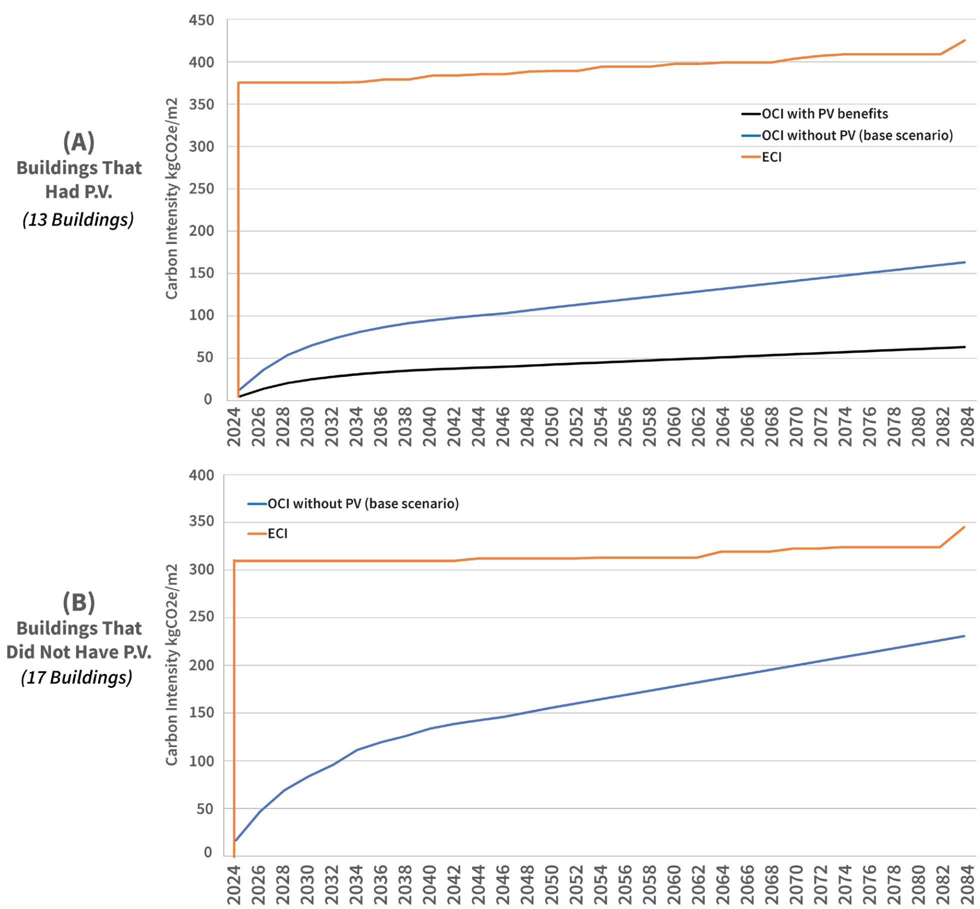

Figure B5. Median cumulative embodied carbon intensity (ECI) and operational carbon intensity (OCI) comparing the potential benefits of photovoltaics (PVs). Results are shown over a 60-year reference study period for the 13 buildings that had photovoltaics (A) while including PV generation (black line) and excluding PV generation (blue line, base scenario). The buildings that did not have photovoltaics are shown below (B).

B.2.2 *Variability based on DOE prototype buildings*

Several of the buildings analyzed were designed or constructed prior to current state energy codes in California. To test and compare the energy demand profiles and corresponding OCIs that were used throughout the main body of this report, we also quantified the energy demands of all the buildings using DOE Prototype Buildings Models (U.S. Department of Energy, 2011) based on 2019 ASHRAE 90.1 (ANSI/ASHRAE/IES, 2019) for all 30 buildings, to approximate their energy demands under more modern energy code requirements. **Figure B6** shows the variability of median cumulative OCIs for the base scenario used in this report, which excludes PV (blue line), includes PV (black line), and a scenario where DOE prototype model reference values were used for operational energy use (green line). Notably, the DOE prototypes did not include renewable energy production. OCI with PV (black line) had the lowest OCI (170 kg CO2e/m2), followed respectively by the base scenario (230 kg CO2e/m2) and DOE prototypes (270 kg CO2e/m2). First, this analysis shows that neither of the two alternative methodological scenarios for operational carbon caused median OCI to exceed ECI. Secondly, the analysis indicates that the median operational energy demands that were used throughout this report varied more substantially based on the inclusion or exclusion of PV than they did from the source of energy use information (in this case, from DOE prototype reference models under ASHRAE 2019.1).

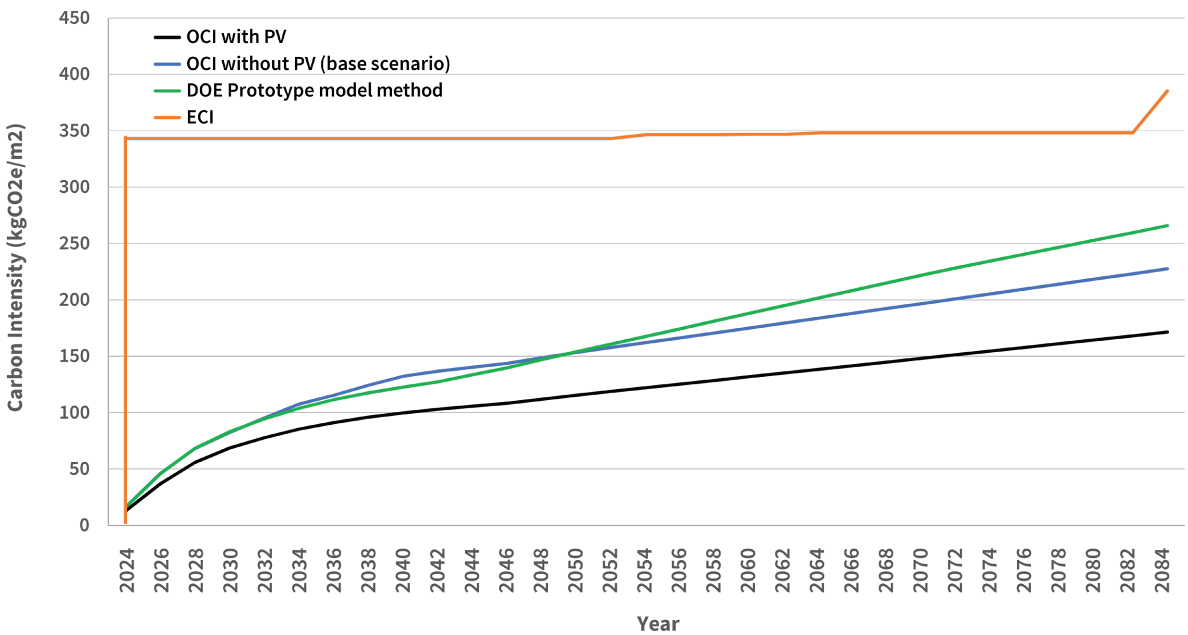

Figure B6. Median cumulative embodied carbon intensity (ECI) and operational carbon intensity (OCI) comparing operational energy use quantification methods. Results are shown over a 60-year reference study period comparing the OCI of our base scenario (blue line), OCI with PV (black line), and OCI by DOE prototype method (green line).

Figure B7 compares the OCI between our base scenario and DOE prototype models for individual buildings grouped by their use type categories. As noted above, the median difference between our base scenario and the DOE prototype models was not particularly significant. However, when looking at individual buildings, considerable OCI differences existed. Some of the most significant were buildings #1, #17, #22, #24, and #32, which did not have directly comparable DOE models, so the use of proxies or averages between different use types was required. Multi-family residential buildings tended to show the largest difference between the two methods; which suggests, generally, that these buildings may use less energy (or less carbon-intensive energy) than predicted by equivalent DOE prototypes. Other factors that can contribute to different results between these two scenarios include the operational energy data source from data contributors (measured vs. modeled), the accuracy of the energy modeling methods used, and general variation between how buildings are modeled to perform versus how they actually perform when they are built and operated. More research is required to determine the cause of these differences.

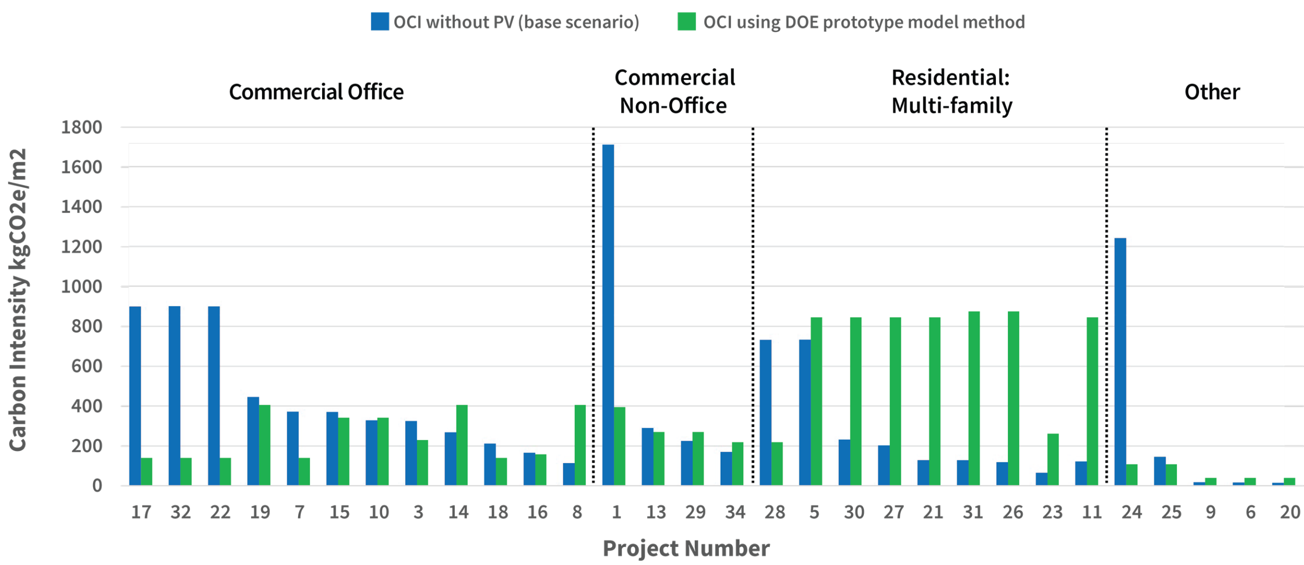

Figure B7. Operational carbon intensity (OCI) comparisons between base scenario and DOE prototype model method for all individual buildings. Results are shown for a 60-year reference study period and buildings are grouped by use types. Results are in kg CO_2e/m^2.

B.2.3 Floor area normalization comparisons

Embodied carbon intensities in this report were displayed as kg CO2e/m2 and normalized using total gross floor area (GFA). Where applicable, this GFA included the floor area of attached parking structures (surface parking lots were excluded). Generally speaking, this approach results in lower ECI values for projects with parking structures than would otherwise be the case if normalized to gross internal floor area only (excluding parking areas). While the total carbon emissions will remain the same under either method, normalizing to different floor area metrics will result in different carbon intensity values, which is an important consideration for those looking to use the ECI, OCI, or WLCI to create targets, limits, or other performance or comparison indicators. Methods for normalizing OCI can also vary but are often done using the conditioned floor area of the building since it typically comprises the area of the building that uses the actual operational energy. In this study, we used gross floor area excluding parking as a proxy for conditioned floor area, which was not collected, to quantify and normalize operational carbon.

Figure B8 explores the influence of the three different floor area normalization methods on ECI, OCI, and WLCI. Six (6) of the projects from our dataset included attached or integrated parking components (building numbers 5, 10, 13, 15, 23, and 28). These parking components ranged in size from 27% to 278% of the project's respective floor area excluding parking, meaning that some of the parking components were larger than the actual areas dedicated to primary uses of the buildings. Three scenarios for normalization were explored:

- For the base scenario (which was used for the results in the main body of this study), ECI was normalized using gross floor area including parking area, OCI using gross floor area excluding parking area, and WLCI was the sum of the two.
- In scenario 2, all carbon intensities are normalized using gross floor area excluding parking.
- In scenario 3, all carbon intensities are normalized by gross floor area including parking.

For ECI, the base scenario and scenario 3 were the same, but scenario 2 caused substantial increases in ECI (between 29% and 278%). This is due to the embodied carbon impacts being normalized over a smaller floor area than when including parking. For OCI, the base scenario and scenario 2 were the same, but scenario 3 caused significant decreases in OCI (21%-74%) due to normalizing the same impacts over a larger floor area. For WLCI, scenario 2 always showed increases (8%-186%) and scenario 3 always showed decreases (5%-34%). We found that the chosen method of floor area normalization can cause huge variations in carbon intensities. All of these differences were directly correlated with the relative size of the parking components compared to the building area, excluding parking, for each respective project. Floor area normalization methods are an important consideration for those looking to report and/or regulate carbon impacts using carbon intensities. Currently, there is no clear consensus among existing standards, guidelines, or policy requirements for floor area normalization methods, and future harmonization, guidelines, and clear definitions are needed.

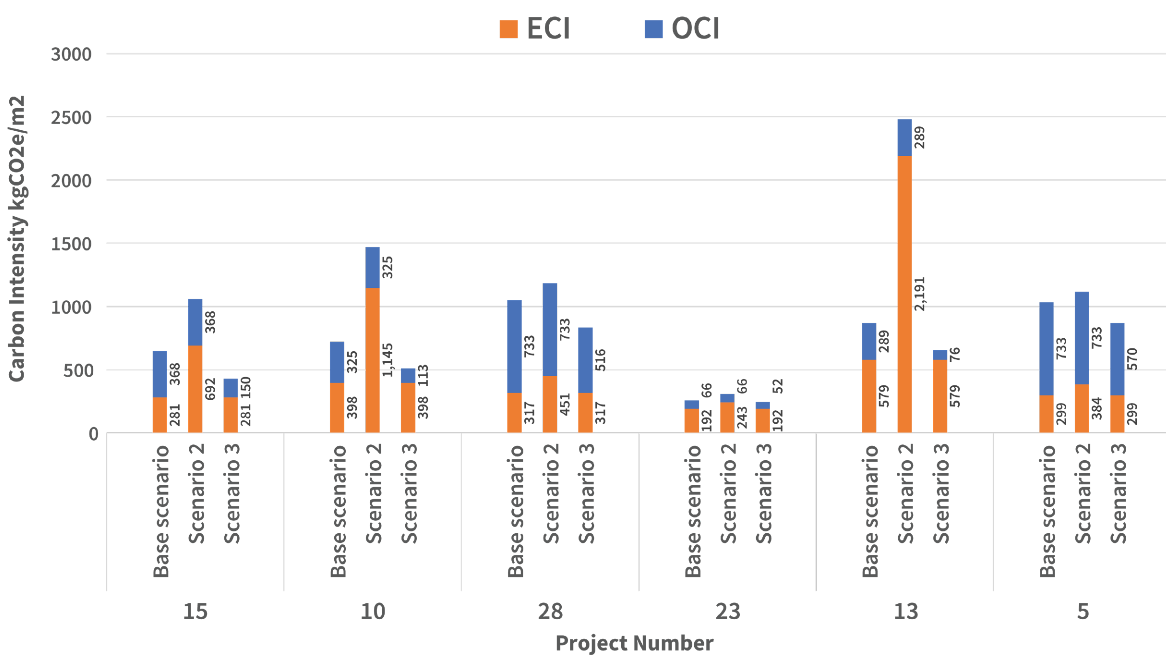

Figure B8. Comparison of embodied carbon intensity (ECI), operational carbon intensity (OCI), and whole life carbon intensity (WLCI) among different floor area normalization methods for projects that had parking components. Results are shown for base scenario (ECI including parking area, OCI excluding parking area), scenario 2 (ECI/OCI excluding parking area), and scenario 3 (ECI/OCI including parking area) over a 60-year reference study period.

B.2.4 GWP20 and GWP100

Global Warming Potential is quantified over a defined time horizon. Different greenhouse gases, however, have different effective life spans in the atmosphere. Most commonly, a 100-year time horizon is used to quantify GWP (GWP100); this includes the embodied carbon values currently reported in EPDs. However, there are concerns that GWP100 underrepresents the impact caused by short-lived greenhouse gases (including methane and hydrofluorocarbons, among others) (Ocko et al., 2017). GWP20 is argued to more accurately represent the impact of these short-lived pollutants and highlight the near-term implications of different climate policies. To address this, GWP can be reported at both 100-year and 20-year time horizons (GWP100 and GWP20, respectively) to provide a more holistic view of the impacts that occur in the short-term (20-year) as well as in the longer term (100-year) time horizons. This dual perspective on climate change would mitigate concerns that focusing on long-term pollutants would overlook and minimize the impact of short-lived pollutants on our climate (Fesenfeld et al., 2018). It is important to note that GWP cannot be combined across different time horizons (i.e., GWP20 values should not be combined with GWP100 values, or vice versa). Therefore, to compare embodied and operational carbon and combine these into a metric that represents the whole life carbon impacts for a building, GWP100 was used throughout the main body of this report.

In **Figure B9**, we evaluated the operational carbon impacts based on GWP20 for both all-electric buildings and electric/gas buildings. First, these charts show that GWP20 resulted in higher operational carbon emissions. For both energy use types, GWP20 emission values increased the OCI by 21% on average compared to GWP100 values at the end of building service life. This increase was particularly important for electric/gas projects and caused OCI to surpass ECI 5 years earlier than under GWP100 within the reference study period. GWP20 values are not currently available for the embodied impacts of materials. However, it is anticipated that the GWP20 embodied carbon impacts will be higher for materials that rely on high consumption of fossil fuels throughout their supply chain. Future work should be conducted to incorporate GWP20 into EPDs to enable the reporting of climate change impacts on both a 20-year and 100-year time horizon.

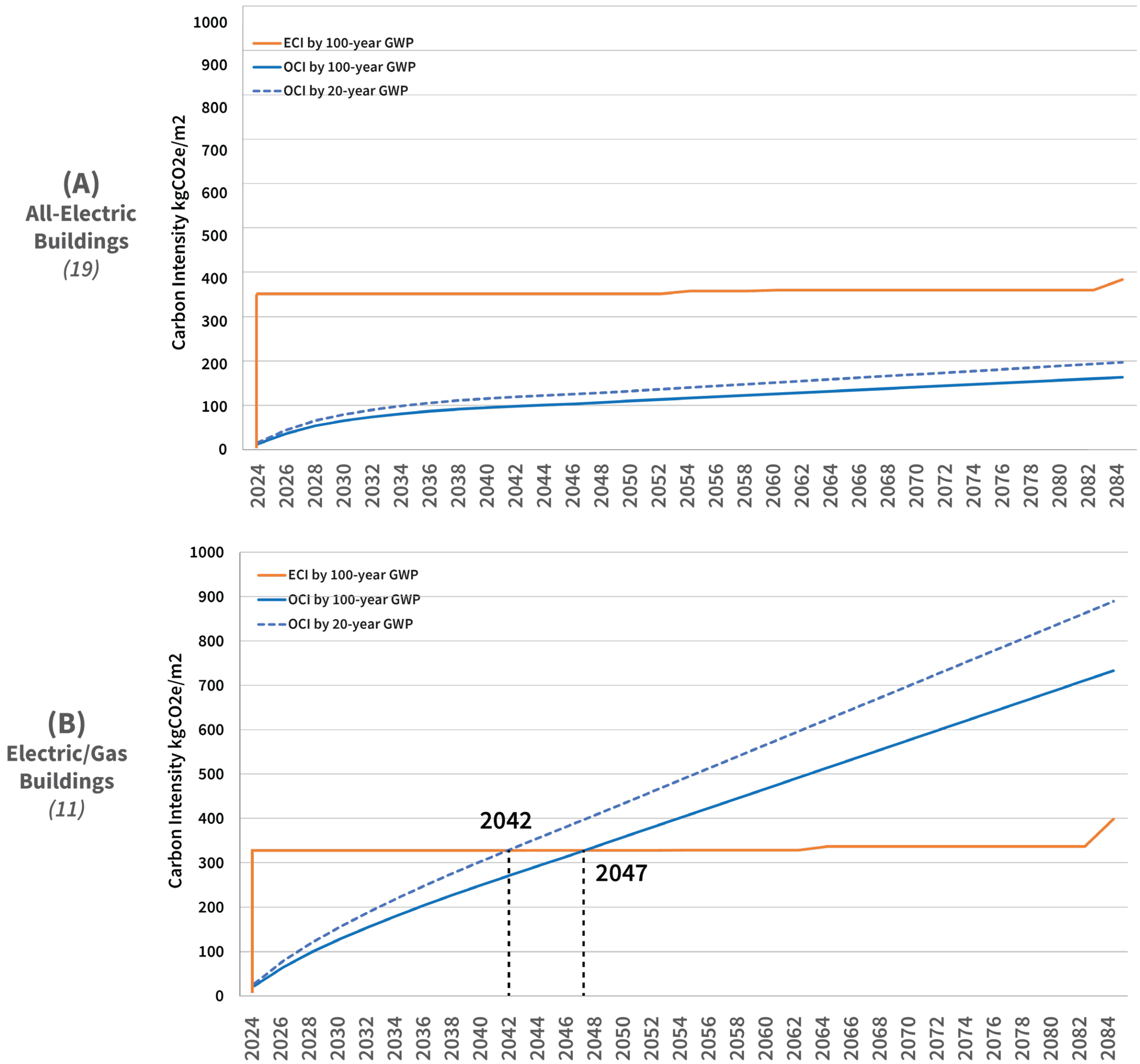

Figure B9. Comparison of median cumulative operational carbon intensity (OCI) using GWP100 and GWP20. Results are shown over a 60-year reference study period for all-electric buildings (A) and electric/gas buildings (B). Embodied carbon was measured using GWP100 (orange line); operational carbon was measured and compared using GWP100 (solid blue line) and GWP20 (dashed blue line) respectively.

Appendix B references

ANSI/ASHRAE/IES. (2019). *ANSI/ASHRAE/IES 90.1-2019: Energy Standard for Buildings Except Low-Rise Residential Buildings. American National Standards Institute (ANSI)*. https://webstore.ansi.org/standards/ashrae/ansiashraeies902019

Fesenfeld, L. P., Schmidt, T. S., & Schrode, A. (2018). *Climate policy for short- and long-lived pollutants.* Nature Climate Change, 8(11), 933–936. https://doi.org/10.1038/s41558-018-0328-1

Ocko, I. B., Hamburg, S. P., Jacob, D. J., Keith, D. W., Keohane, N. O., Oppenheimer, M., Roy-Mayhew, J. D., Schrag, D. P., & Pacala, S. W. (2017). *Unmask temporal trade-offs in climate policy debates.* Science, 356(6337), 492–493. https://doi.org/10.1126/science.aaj2350

U.S. Department of Energy. (2011). *Prototype Building Models. Building Energy Codes Program.* https://www.energycodes.gov/prototype-building-models

APPENDIX C. DATA COLLECTION USER GUIDE

Appendix C references the CLF WBLCA Benchmark Study (v2) Data Collection User Guide v1.0. This document provided requirements and guidance for data contributors who submitted data to this study. It includes project requirements, embodied carbon modeling and reporting requirements, operational energy use requirements, and data entry guidance.

Citation:

Carbon Leadership Forum. (2024). *CLF WBLCA Benchmark Study (v2) Data Collection User Guide v1.0.* Carbon Leadership Forum. Seattle, WA. https://hdl.handle.net/1773/51285

This document is also available at https://carbonleadershipforum.org/clf-wblca-v2/

APPENDIX D. DATA COLLECTION DATA ENTRY TEMPLATE

Appendix D references the CLF WBLCA Benchmark Study (v2) Data Entry Template v1.0. This document is an Excel spreadsheet that was used to collect data for the study. It is made up of three tabs for participant data, project data, and energy data and includes dropdowns, syntax, and other requirements for consistent data entry.

Citation:

Carbon Leadership Forum. (2024). *CLF WBLCA Benchmark Study (v2) Data Entry Template v1.0.* Carbon Leadership Forum. Seattle, WA. https://hdl.handle.net/1773/51286

This document is also available at https://carbonleadershipforum.org/clf-wblca-v2/

CLF Carbon Leadership Forum

CBE CENTER FOR THE BUILT ENVIRONMENT