Massachusetts 100-Home Embodied Carbon Study

Final Report

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SUBMITTED TO:

Massachusetts Clean Energy Center

SUBMITTED BY:

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Acknowledgements and Call to Action

The Massachusetts 100-Home Embodied Carbon Study Team comprises the Northeast Home Energy Rating System (NEHERS) Alliance, Stephens & Company, Builders for Climate Action, Ekotrope, and NMR Group, Inc.

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Cover Image

- Permission to use image "Ask me about Embodied Carbon" hat courtesy Stacy Smedley – Founder, Building Transparency.

Take Action

It is our humble pleasure to present the findings of this Massachusetts 100-Home Embodied Carbon Study. We hope this report serves as both a resource and a call to action. Please consider sharing it within your networks and incorporating embodied carbon analysis into your own work—whether you are a designer, builder, rater, policymaker, or advocate.

The Funders

The Study Team

Glossary of Terms

This section defines the key terms that are relevant to this study's findings.

Greenhouse Gas (GHG) Emissions. GHG emissions refer to gases that trap heat in the atmosphere and contribute to global warming. These include carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and fluorinated gases (e.g., hydrofluorocarbons, perfluorocarbons, etc.).[1] GHG emissions are typically expressed in terms of carbon dioxide equivalent (CO_2e), calculated by multiplying the amount of each gas by its global warming potential (GWP) compared to CO_2.

Global Warming Potential (GWP). GWP is a measure of how much heat a GHG traps in the atmosphere over a specified period of time (commonly 100 years for building lifecycle analysis), relative to CO_2. In the context of materials, GWP values are often expressed in kilograms of CO_2e per functional unit (e.g., kg CO_2e per square meter, cubic meter, or kilogram of material) for specific lifecycle stages.

Environmental Product Declarations (EPDs). EPDs are documents developed by manufacturing companies in accordance with International Organization for Standardization (ISO) standards to disclose a product's environmental impact, including the embodied carbon emissions (ECE) across its lifecycle stages. The Building Emissions Accounting for Materials (BEAM) estimator tool[2], used for this study, relies on EPDs to quantify the embodied carbon from stages A1–A3 of the building lifecycle. [3]

Embodied Carbon Emissions (ECEs). ECEs refer to the GHG emissions associated with the production, construction, maintenance, and disposal of building materials. This study focuses on the production stages A1–A3 (Figure 2), which include extraction, transport, and manufacturing, using material-specific or industry-average EPDs and associated GWP factors, as estimated through the BEAM Estimator tool.

Gross ECE. Gross ECE reflects the total embodied carbon materials associated with A1–A3 of the building lifecycle *prior to accounting for any biogenic carbon storage*. This metric is essential for quantifying the cradle-to-gate carbon footprint of building materials and serves as the foundation for calculating net emissions when biogenic storage is considered.

Carbon Storage from Biogenic Materials. Biogenic materials, such as those derived from agricultural residues, forestry byproducts, and recycling streams, store carbon that was removed from the atmosphere via photosynthesis when the biological feedstocks were grown. When included in a building product, these materials may result in net-negative emissions during stages A1–A3, depending on the quantity of biogenic carbon stored versus emitted. This study does not include carbon storage from virgin timber products, due to ongoing uncertainty in accounting methods and concerns related to forestry practices.

Net ECE. Net ECE accounts for both the gross ECE and any biogenic carbon storage. This value may be positive or negative, depending on the balance of emissions and storage in a product.

Embodied Carbon Assessment. This refers to the process used to estimate the embodied carbon associated with buildings. Embodied carbon assessments result in an estimate of gross ECE, carbon storage from biogenic materials, and the net ECE.

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1 https://www.epa.gov/ghgemissions/overview-greenhouse-gases
2 https://www.buildersforclimateaction.org/beam-estimator.html
3 https://www.epa.gov/system/files/documents/2024-11/epd_basics_how_why_to_develop.pdf

Operational Energy Consumption. This refers to the annual energy consumption of a building under normal operating conditions, including all end-uses, such as heating, cooling, domestic hot water production, ventilation, and plug loads from appliances and miscellaneous equipment.

- Electric consumption is expressed in kilowatt-hours per year (kWh/year).
- Fossil fuel consumption (e.g., natural gas, propane, fuel oil) is commonly expressed in therms per year, gallons per year, or cubic feet per year depending on the fuel type.

In this report, to enable consistent cross-fuel comparisons, all energy consumption figures are converted and presented in thousands of British Thermal Units (MBtus) per year. Expressing energy consumption in MBtu provides a fuel-neutral metric, allowing aggregation of different fuel types into a single energy-use value and facilitating analysis of total building energy demand and the associated carbon emissions.

Operational Carbon Emissions (OCE). OCEs are calculated based on the annual operational energy consumption of a home and are the carbon emissions associated with the specific fuel used at the home:

- On-site combustion (e.g., natural gas, propane) is evaluated using direct CO_2e emission factors.
- Electricity consumption is assessed using grid-based emissions factors from the electric generation mix. This study uses long-run marginal emission rates from the National Renewable Energy Laboratory's (NREL) Cambium datasets.

The report distinguishes between operational carbon emissions (OCE) and embodied carbon emissions (ECE) to help define and clarify the total carbon profile of the home.

Energy Use Intensity (EUI). EUI is a key metric that provides insight into how efficiently a given building assembly uses energy relative to its floor area, and enables comparison between buildings of varied sizes and types. EUI measures the annual operational energy consumption of a building, normalized by its size. It is typically expressed in units such as kBtu per square foot per year (kBtu/ft^2/year) or kWh or kBtu per square meter per year (kWh or kBtu/m^2/year). Lower EUI values generally indicate higher energy efficiency. **Note:** In this report, EUIs are expressed as per ft^2 of conditioned floor area to benchmark against other sources that show EUI.

Operational Carbon Intensity (OCI). This metric represents the GHG emissions produced through the operation of a building, normalized by floor area, expressed in units such as pounds (lbs) CO_2e/ft^2 or kg CO_2e/m^2. OCI reflects both the building's energy efficiency and the carbon intensity of its energy sources, providing a critical measure of the building's climate impact during use.

Embodied Carbon Intensity (ECI). This metric quantifies the embodied carbon emissions associated with building materials per unit of floor area. It is calculated by dividing the net material emissions (lbs. or kg CO_2e), or ECE, by the building's floor area, resulting in lbs. CO_2e/ft^2 or kg CO_2e/m^2. ECI shows how carbon-intensive the materials in a building assembly are when normalized by building size. It is a useful metric for comparing design choices, material selections, and building typologies. **Note:** In this report, ECI is expressed using conditioned floor area per square meter, to maintain comparability with other assessments of embodied carbon emissions and operational emissions.

User Defined Reference Home (UDRH). A program incentivizing above-code or other high-performance new construction thresholds will determine unit savings by comparing a participating home's efficiency to a baseline comprised of typical efficiency values found in non-participant homes, which is referred to in energy modeling software as the UDRH. The characteristics of the UDRH are based on periodic studies of the new construction market in the relevant program territory.

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Executive Summary

This study is the product of a multiyear collaboration between the Northeast Home Energy Rating System (NEHERS) Alliance, Stephens & Company, Ekotrope, Builders for Climate Action, and NMR Group (hereafter referred to as “the study team”).

The primary goals were to:

1. Explore the feasibility of adding embodied carbon analysis to typical operational energy assessments conducted on residential buildings by HERS® Raters.
2. Use these augmented energy assessments to explore the feasibility of establishing baseline values for embodied carbon emissions generated by residential new construction in Massachusetts.

Operational emissions refer to the amount of carbon generated by normal building operations, including heating, cooling, lighting, etc. Normally, residential building energy assessments, like the HERS® Index Score, do capture these emissions. Emissions associated with the production, transport, and disposal of the building materials themselves are not included in an operational emissions analysis. These emissions—called embodied carbon emissions—begin to accrue long before a building is constructed or fully operational and represent an unrealized opportunity to capture up-front carbon reductions across all building types. This study focuses on emissions associated with the extraction, transportation to factory, and manufacturing of construction materials (A1–A3 or most “cradle-to-gate” emissions). The study excludes downstream stages such as construction (A4–A5), maintenance (B1–B5), and end-of-life (C1–C4) emissions due to limited data availability and high uncertainty about the quality of available data.

This study is based on an analysis of building construction and mechanical equipment data collected by HERS® Raters at 100 newly constructed single-family homes in Massachusetts. To generate estimates of embodied carbon emissions, the study team took the following steps with the on-site data:

- The study team generated operational energy assessments with Ekotrope, a RESNET®-accredited energy modeling tool widely used by HERS® Raters.
- Those assessments were converted into operational carbon emissions using the National Renewable Energy Laboratory (NREL) Cambium dataset.[4]
- The team developed an integration worksheet to assist transferring data on building materials from Ekotrope into the Building Emissions Accounting for Materials (BEAM) estimator tool, developed by Builders for Climate Action.
- Participating HERS® Raters received training to use the integration sheet and to collect additional information from building plans required for embodied carbon assessment, which did not require any extra site visits.
- The team combined Mechanical, Electrical and Plumbing (MEP) system data collected at the homes and captured in Ekotrope with MEP system embodied carbon estimates used in the RESNET® 1550 draft standard[5]
- All homes followed the projected assessment pathway set by the RESNET® 1550 draft standard, and the team produced embodied carbon estimates with the BEAM calculator.

[4] This dataset is the basis of the HERS® CO_2 Index, which the study team utilizes later in our analysis of the on-site data.

[5] Table 10.1.5 here: PDS02-RESNETICC1550_webcmnt.docx

Key Findings & Recommendations

This section describes key findings from the study team's analysis of operational and embodied carbon data collected during onsite assessments, followed by recommendations for policymakers and program administrators. The study included a HERS® Rater participant feedback survey, and key takeaways are addressed in this section. (Refer to Appendix B for more details.) The team intends for these findings and recommendations to be accessible and to highlight practical considerations for advancing low-embodied carbon practices across the residential construction market. These insights are not exhaustive, nor are they prescriptive; instead, they offer a starting point to inform future program design, policy development, and industry best practices.

Embodied Carbon Emissions

Key Finding 1: Embodied Carbon Emissions (ECEs) Make up a Large Portion of a Building's Overall Carbon Emissions

- ECEs can account for as much as 32% of a building's overall carbon emissions over a 25-year period (Figure 26), with operational emissions contributing an average of 5.5 tons CO_2e annually (Figure 28). This statistic underscores the fact that operational carbon emissions (OCEs) can no longer be considered in isolation. Both operational and embodied emissions must be considered because, as operational performance improves, embodied carbon plays a proportionally larger role in reaching the ambitious climate goals set forth by the state of Massachusetts.
- The 100 homes in this study's sample accounted for a total of 5,555 net tons of CO_2e, or an average of 55.5 tons of CO_2e in net embodied carbon emissions (ECEs) per home. The total emissions are equivalent to a gas-powered vehicle driving 14 million miles. In 2024, Massachusetts built 11,390 new homes. Using the average ECE of 55.5 tons of CO_2e, those homes combined to emit an estimated 632,145 tons of CO_2e[6].
- Single-family detached homes with two or more stories had higher average net ECE (59.2 tons CO_2e) than one-story detached homes (52.8 tons CO_2e), duplexes (45 tons CO_2e), or townhomes (39 tons CO_2e). The three home categories with lower net ECEs had limited sample sizes, collectively representing about 30% of the study sample.

Key Finding 2: Mechanical, Electrical, and Plumbing (MEP) Systems Contribute to Gross ECE

- This study is the first ever to incorporate the embodied carbon impacts of MEP systems as part of a broader study of ECE in new residential buildings. The study found that MEP systems contribute an average of 10 tons of CO_2e per house, or 18% of gross ECE in new single-family construction. This finding demonstrates the significant contribution of MEP systems to ECE in new homes.

6 https://www.resnet.us/wp-content/uploads/2025-Data-Trends-Report-of-HERS-Rated-Homes_final.pdf

Key Finding 3: Material Substitution Offers Immediate Carbon Reduction Potential

- This study shows that three product categories make up 68% of all gross ECE in new homes: concrete (39%), MEP systems (18%[7]), and insulation (11%).
- Biogenic (carbon-storing) materials were not widely present within the sampled homes; biogenic materials reduced total gross embodied emissions by only 1.6%.
  - Cellulose, fiber cement siding, and wood fiber boards were the most utilized biogenic carbon-storing materials.
  - Use of these materials can provide immediate emission savings without compromising building performance.

Recommendations

- **Address knowledge gaps and expand market uptake of low-carbon and carbon-storing materials.** Aggressive stretch codes and successful new construction programs have made Massachusetts a leader in building highly energy efficient new residential buildings, but much potential remains to educate the market on the use of low-ECE and carbon-storing materials. Massachusetts is positioned to be a leader in embodied carbon assessments and tracking due to its high incidence of HERS® ratings in new homes and recent policy shifts, such as the limited inclusion of embodied carbon in the 2023 Massachusetts Stretch Code[8] for concrete and insulation. Adding MEP to the Stretch Code would be a next logical step. Existing training and education infrastructure like those sponsored by Mass Save® (e.g., codes and standards compliance support and training on electrified new construction) or Built Environment Plus are promising gateways to expose market actors to low-carbon and carbon-storing solutions and help the market look beyond operational carbon.
- **Create embodied carbon reduction incentives for utility programs and code pathways.** Utility program administrators, like Mass Save, and code enforcement agencies must continue to explore how to create incentives for reducing embodied carbon, which could include reporting requirements, embodied carbon credits, incentive tiers, or defining a User Defined Reference Home (UDRH) based on overall combined carbon emissions or on carbon use intensity. Programs could use the Embodied Carbon Intensity metric to incentivize designers and builders to balance overall carbon footprint with material choices in pursuit of project design goals. Financial incentives will help to increase market uptake and drive transformation in the way designers and builders conceptualize project carbon footprints.
- **Refine and expand embodied carbon data tool capabilities and material databases.** Material emissions datasets, particularly for MEP systems, must be expanded to improve accuracy and usability. Additional support for software integration would also allow for streamlined and scaled embodied carbon assessments.

[7] The breakdown within the broader MEP system category was 12% of emissions from mechanical equipment, 2% for electric equipment, and 4% for plumbing equipment

[8] The embodied carbon credit provides a three-point reduction in the HERS® score of a home for using low GWP concrete or low-GWP insulation materials. MA 2025 Residential Stretch code and Specialized Opt-in code (IECC 2021 with MA amendments) DOER Final Draft 12-17-24, section R406.5.2

Cumulative Operational and Embodied Carbon Emissions

Key Finding 4: Embodied Carbon Reduction Potential Exists Across All Home Types, Even Those Considered "High-Performance" Under Prevailing Operational Efficiency Paradigms.

- Embodied carbon intensity did not vary significantly across home type, energy performance (HERS® scores), or Carbon Index ratings. This demonstrates that there are opportunities to lower embodied carbon across all home types, even those that perform well above code.
- High upfront embodied carbon creates an emissions spike that even high-performing homes may need many years to balance out, highlighting the importance of seizing opportunities to reduce embodied carbon before construction begins. Example homes in the study's sample had similar overall carbon emissions over a 25-year forecast period despite major differences in operational energy efficiency because the homes with greater operational efficiency generated more embodied carbon emissions prior to construction.

Key Finding 5: All Electric Homes and Attached Townhomes Had Lower Total Carbon Emissions.

- All electric homes outperformed fossil fuel and mixed fuel homes in both operational and total estimated emissions.
  - On average, all electric homes exhibited 60% lower total 25-year carbon emissions (including both operational and embodied emissions) than fossil fuel-only homes, and 52% lower emissions compared to mixed fuel homes.
  - Electric homes produced the lowest amount of operational carbon emissions (57.7 tons), while fossil fuel homes produced the highest (180.6 tons). This difference is amplified by the anticipation that the electric grid will become cleaner over time.
- Townhomes had the lowest cumulative carbon emissions within the study's sample. Over 25 years of forecasted operation, townhomes show 26% lower MEP system ECE, 32% lower building enclosure ECE, and 38% lower OCE than the overall sample averages.

Recommendations

- **Align embodied carbon metrics with broader climate policy targets**. To maximize impact, policymakers and program administrators should integrate embodied carbon data into state and local climate action plans, carbon tracking systems, and emissions reduction targets. Considering the entire building lifecycle is crucial to achieve net-zero carbon.
- **Develop resources and guidance that are accessible to an array of market actors.** Most builders and contractors have room to grow their understanding and comfort with low-carbon building solutions, even those who build what the market currently characterizes as "high-performance" homes. Program administrators and building efficiency organizations should prioritize clear, accessible guidance to help both high-performance and conventional builders utilize low-carbon options that will reduce upfront carbon emissions without impacting performance. Early intervention in projects is key, and these market actors need to understand how the suggested material substitutions may affect cost.

HERS® Raters & Embodied Carbon Assessment Workflow

Key Finding 6: HERS® Raters Are Well-Positioned to Support Embodied Carbon Assessments with Modest Additional Effort.

- Most of the data needed for embodied carbon assessments using the BEAM Estimator app already exist in the energy modeling files that HERS® Raters produce. Each home is unique, and the assumed overlap of data varies from 60% to 70%[9].
- This study demonstrated the feasibility of a semi-automated workflow between Ekotrope and the BEAM Estimator, streamlining the embodied carbon assessment process.

Key Finding 7: Raters Adapted Well to the Additional Workload, and It Did Not Reduce Their Likelihood of Recommending Low-Embodied Carbon Materials in the Future.

- On average, after completing 5 to 10 projects, participants reduced completion time from 3.5 hours to 2.7 hours—a 23% decrease.
- HERS® Raters identified the following key factors that added to their workflow when assessing embodied carbon: time constraints, scope expansion (assessing anything beyond the thermal boundary, examining materials in more detail, and gathering additional data), and software integration.
- Nearly all (10 of 12) participants stated they were Somewhat Likely, Likely, or Very Likely to recommend low-embodied carbon assemblies to builders and homeowners for future projects. Some respondents noted that decisions to pursue low-embodied carbon projects will likely fall to the builder and Rater, who must value-engineer the greatest combined reduction of emissions for the lowest cost.

Key Finding 8: Raters View Incentives and Education as Key to Encouraging Low-Carbon Material Choices.

- Respondents highlighted financial utility program incentives, rebates, and HERS® score credits as important drivers to increase low-embodied carbon emission projects.
- Some Raters noted that education will encourage other stakeholders to adopt low-carbon emitting material choices, emphasizing that training and guidance can build confidence in using alternative materials.

[9] ±20% due to homes subjected to variation depending on the complexity of the home, materials used, and level of detail the assessment aims to capture.

Recommendations

- Track the market response to and evolution of RESNET® Standard 1550 to adopt ECE into codes.
- **Provide targeted technical training for HERS® Raters and building professionals.** Expanding the pool of HERS® Raters with the awareness and training to address embodied carbon in their work is a key step in expanding awareness and uptake among builders and designers. HERS® Raters have been essential conduits between energy-efficiency programs and those same market actors for years; that general structure can be leveraged here. Continued and expanded training for HERS® Raters is also critical for accurate and consistent assessments as this effort is scaled up.
- **Invest in software integration between energy and carbon modeling tools.** Automating the transfer of data between tools like Ekotrope and BEAM can significantly reduce the time, cost, and error associated with manual data entry.

Considerations for Future Research

1 **The state of Massachusetts should continue to obtain data regularly regarding embodied and operational carbon emissions of homes to help build a more robust baseline and characterize the market for low-carbon and carbon-storing materials.**

While this study aimed for diversity of home types, broader sampling strategies could ensure greater alignment with the characteristics of the overall residential new construction market across Massachusetts and neighboring regions. Increasing the sample sizes would support additional analyses such as ECE outcomes by code version or a more robust examination of ECE outcomes by home typology. Additional research opportunities include collecting data on the incidence of low-carbon or carbon-storing materials.

2 **Leverage the study data for deeper analysis.**

This is the first embodied and operational carbon benchmarking study in Massachusetts, and the dataset generated by this study offers a valuable resource for future research.

Further efforts building on this research should include:

- Sensitivity analyses for material substitutions
- Incremental cost comparisons
- Training content development
- Modeling for alternative climate scenarios or policy proposals
- The development of a UDRH or a reference home for an Embodied Carbon Index
- Expanded sample sizes and regional representation
- Longitudinal tracking of new construction emissions

3 **Address embodied carbon in existing buildings, including low-embodied carbon renovations and building reuse.**

Large numbers of existing residential structures continue to be renovated or demolished, even as new construction comes online. Updating the operational efficiency of existing housing stock is a huge component of meeting state climate goals. These updates include improvements to the efficiency of the building shell and electrification of its mechanical systems. Future research should focus on post-construction embodied carbon lifecycle phases to inform program or policy interventions that address embodied carbon emissions from existing home upgrades. The market needs greater clarity on how upfront embodied carbon emissions from existing building upgrades compare to operational energy savings realized from those upgrades. Market actors need more guidance on how to effectively implement low-carbon solutions in existing homes, which can be more complicated than designing a new project for their use. Addressing end-of-life (C1–C4) or beyond the lifecycle (D) emissions could help expand incentives and establish policy requirements around demolition, disposal, or reuse of existing buildings.

Introduction

The state of Massachusetts has set ambitious climate targets through legislation, such as the **Global Warming Solutions Act** (GWSA) of 2008[10], which mandates statewide greenhouse gas (GHG) emission limits and sector-specific sublimits to achieve a net-zero economy by 2050, and the **2021 Climate Law**, *An Act Creating a Next-Generation Roadmap for Massachusetts Climate Policy*[11]. These legislative frameworks, combined with efforts from public agencies, grassroots initiatives, industry organizations, and evolving building codes, have emphasized the need for practical tools that help stakeholders identify and reduce GHG impacts across sectors. The study team developed this study in the context of these drivers with the goal of enhancing technical and workforce capabilities and advancing our understanding of the full carbon impacts of residential new construction.

The study team secured funding from the Massachusetts Clean Energy Center (MassCEC), with additional support from National Grid and Eversource, to conduct this study in 2024.

1. The first phase of this project was to create an integration worksheet to help transport Application Programming Interface (API) data from the Ekotrope energy modeling software to the BEAM Estimator.
2. The second phase was to train HERS® Raters on how to use the integration worksheet to transfer data from Ekotrope into BEAM.
3. The third and final phase was to conduct an analysis of both the operational and embodied carbon emissions from 100 newly constructed homes in Massachusetts.

This report provides quantitative and qualitative results from this study, including an overview of current carbon performance in new, single-family homes and potential strategies to support deeper decarbonization of the residential building sector.

Study Background

In response to data from a 2017 study showing that nearly half of global carbon emissions came from either building operations (28%) or the production and distribution of building materials (21%),[12] the Northeast Home Energy Rating System (NEHERS) Alliance formed an Embodied Carbon Working Group in the spring of 2020. The purpose of the group was to:

1. Advocate for the development of a RESNET® Standard on Embodied Carbon.
2. Explore the potential role of HERS® Raters in collecting the data needed to support embodied carbon tracking in the U.S. residential building sector.

The use of high embodied carbon materials can unintentionally offset the benefit of operational emissions reductions from energy-efficiency programs and new building codes, so the study team aimed to encourage the building industry to consider both operational and embodied carbon emissions. The group set out to explore the role that the HERS® Rater could play in capturing the “low-hanging fruit” of embodied carbon savings—emissions that enter the atmosphere before a home is built or occupied.

[10] https://malegislature.gov/Laws/SessionLaws/Acts/2008/Chapter298
[11] https://malegislature.gov/Laws/SessionLaws/Acts/2021/Chapter8
[12] https://nehers.org/Data/Sites/1/media/training/webinars/presentations/embodied-carbon-2020.pdf

There were no formal code mechanisms to report embodied carbon when this effort began. Newly formed committees (e.g., within ASHRAE 90.2) had not yet adopted consistent methodology for measuring and reporting ECE. Meanwhile, the availability of tools like EC3 and databases such as those maintained by the Carbon Leadership Forum were expanding rapidly,[13, 14] yet these tools were primarily focused on the commercial sector. Grassroots initiatives, including those spearheaded by Builders for Climate Action and New Frameworks, began highlighting the importance of embodied carbon in residential construction—which comprises nearly 50% of new floor area in the U.S.[15]—and interest was growing among developers, design teams, and homeowners in that sector.

NEHERS began advocating for the development of a RESNET® standard to create a common definition for measuring embodied carbon. By the end of 2022, support was growing among industry stakeholders across North America. In 2022, NEHERS formally submitted a recommendation for such a standard to RESNET®. On July 11, 2023, the RESNET® Board of Directors approved the formation of Standard Development Committee 1550. A technical working group for Standard 1550, comprised of 35 subject matter experts, including HERS® Raters, architects, energy and embodied carbon modeling software developers, residential builders (including large-volume production builders), and building materials manufacturers.[16] At the time of this report's publication, the proposed standard was undergoing a final round of public review and comment.[17]

NEHERS recognized that HERS® Raters were already collecting many key data points required for embodied carbon assessments. An estimated 60% to 90% of the data that Raters already collected for a HERS® rating could inform such embodied carbon assessments, with variation based on the home's overall design features. NEHERS leveraged this overlap and supplemented it with a list of targeted material-specific inputs to help Raters provide comprehensive carbon profiles of homes, inclusive of both operational and embodied carbon.

The NEHERS study team proposed this project as the first attempt to prove that a certified HERS® Rater can simultaneously assess embodied carbon and operational carbon. The team designed this effort to lay the groundwork for future software development, training curriculums, and quality assurance processes to advance embodied carbon emissions assessments, which had not previously existed for residential embodied carbon tracking. This effort also helps to establish a residential baseline for embodied carbon in Massachusetts.

Combining the HERS® Rater workflow with an embodied carbon assessment was a natural fit for Massachusetts due to the fact that 88%[18] of new homes in the state receive a HERS® rating—20% higher than any other state in the country. The widespread adoption of HERS® ratings in Massachusetts has led to a knowledgeable and experienced HERS® Rater workforce eager to lead new initiatives and metrics like Embodied Carbon Reporting.

13 https://carbonleadershipforum.org/
14 https://www.buildingtransparency.org/tools/ec3/
15 https://www.researchgate.net/publication/340738973_Achieving_Net_Zero_Embodied_Carbon_in_Structural_Materials_by_2050
16 The 1550 committee is chaired by Chris Magwood and Tracy Huynh of RMI, along with Brian Shanks of Beazer Homes.
17 https://www.resnet.us/about/standards/minhers/draft-pds-01-resnet-1550-embodied-carbon/
18 https://www.resnet.us/wp-content/uploads/2025-Data-Trends-Report-of-HERS-Rated-Homes_final.pdf

Study Objectives

The team designed this study to explore the feasibility of incorporating an embodied carbon assessment into the existing workflow of residential energy modeling commonly undertaken by HERS® Raters. Currently, operational energy can be assessed in multiple ways, including through RESNET® HERS® Index scores, the Carbon Index, and energy metrics such as total energy consumption and energy use intensity (EUI). This study investigated how to evolve those existing processes to support assessments of both operational and embodied carbon in practical applications. Just as HERS® Raters can help provide value engineering through operational efficiency solutions, the study team envisioned applying this same value engineering to reduce the embodied carbon emissions of home-building projects. This study focuses on emissions associated with the extraction, transportation to factory, and manufacturing of construction materials (A1–A3 or "cradle-to-gate" emissions). The study excludes downstream stages, such as construction (A4–A5), maintenance (B1–B5), and end-of-life (C1–C4) emissions due to limited data availability and high uncertainty about the quality of available data.

The study team structured its analysis around the following key research questions. The research questions cover a variety of discrete topics but support a broader goal to integrate embodied carbon assessments into standard residential energy measurements. This effort will support a more holistic approach to carbon accounting in the built environment.

- What is the range of embodied carbon emissions and emissions intensities of selected new homes in Massachusetts?
- What are the percentages of embodied carbon emissions associated with major material categories used in new homes in Massachusetts?
- Which assemblies, material choices, or number of stories contribute most to total embodied carbon emissions?
- What are the operational carbon emissions modeled for the selected homes, based on their energy use and energy source?
- What is the total carbon footprint, both operational and embodied, associated with constructing and operating a new single-family home, for both the first year of operation and 25-year time horizon (2025–2050)?
- What is the relationship between upfront embodied carbon emissions and accumulated operational emissions over time?
- What additional time, effort, or costs do HERS® Raters require to integrate embodied carbon assessments into their workflow?
- What structural or process-related barriers are there to making embodied carbon assessments a mainstream component of residential energy rating practices?

Methodology

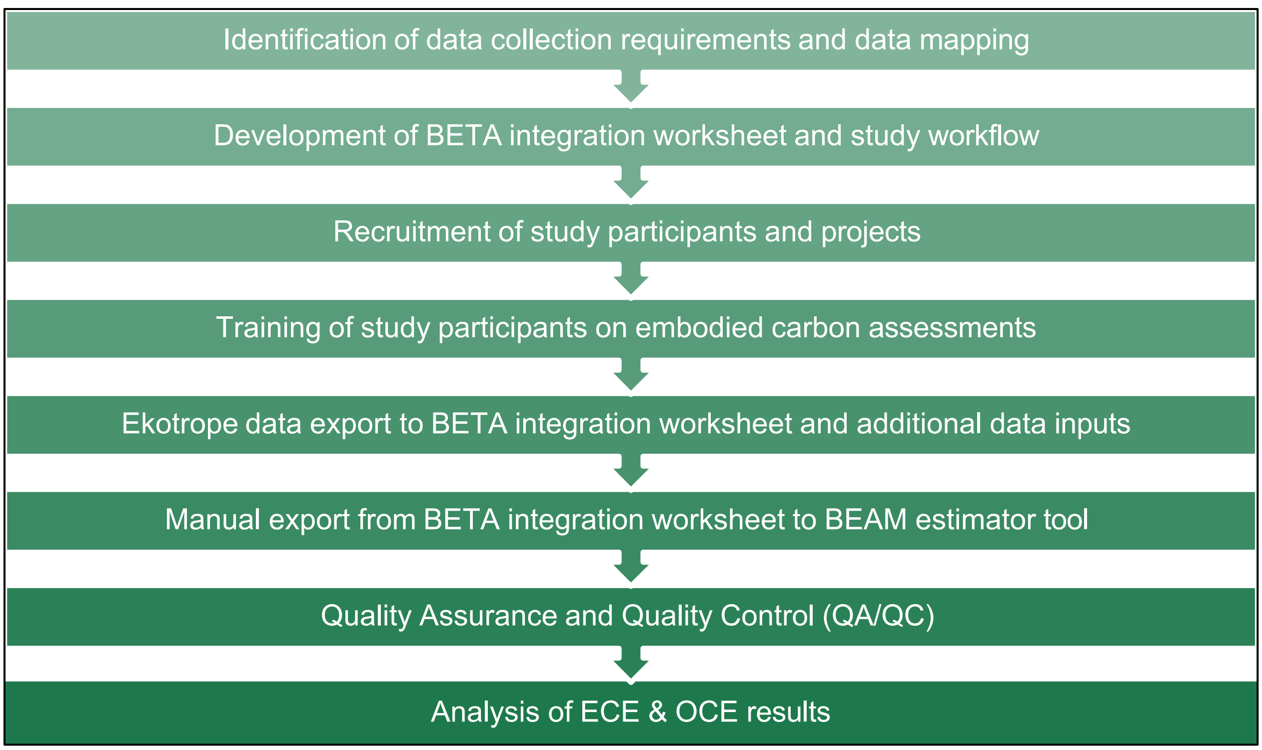
This section outlines the study's methods to examine embodied and operational carbon emissions in 100 newly constructed single-family homes (defined as homes with one to four units to match the definition used by the Mass Save residential new construction program) in Massachusetts. This study expanded upon conventional HERS® ratings by:

1. Identifying supplemental data collection methods for embodied carbon assessments
2. Incorporating outputs from Ekotrope energy modeling software into the BEAM estimator tool to quantify material-related embodied carbon emissions
3. Establishing protocols to provide consistent data integration

The study team accessed volumetric building assembly data and details on MEP system types, which helped them to analyze the energy model-derived operational energy consumption of homes, the associated grid emissions, and embodied carbon emissions estimates.

Recruiting and training HERS® Raters on embodied carbon assessment procedures was crucial for collecting data for analysis and the training process was part of the study scope. The study team conducted follow-up surveys with those Raters to understand their experience and gather feedback to scale up these data collection efforts. A detailed methodology is provided in Appendix A.

Figure 1: Study Methodology



Study Design and Participant Selection

The study team recruited certified HERS® Raters who were then trained to perform embodied carbon assessments. They were asked to identify recently completed single-family homes that had existing energy models and sufficient documentation to assess embodied carbon emissions in the home (e.g., construction drawings, specifications, mechanical equipment details). The team screened these projects to ensure they had sufficient data to support an embodied carbon assessment. The study did not require Raters to perform any additional site visits. For each home included in the sample, certified HERS® assessments were registered with RESNET® after the completion of construction.

While not randomly selected, the team chose homes to reflect diverse real-world construction practices, system types, and design choices. This approach grounded data collection and assessment processes in actual market conditions while keeping them aligned with study objectives.

Embodied Carbon Assessment

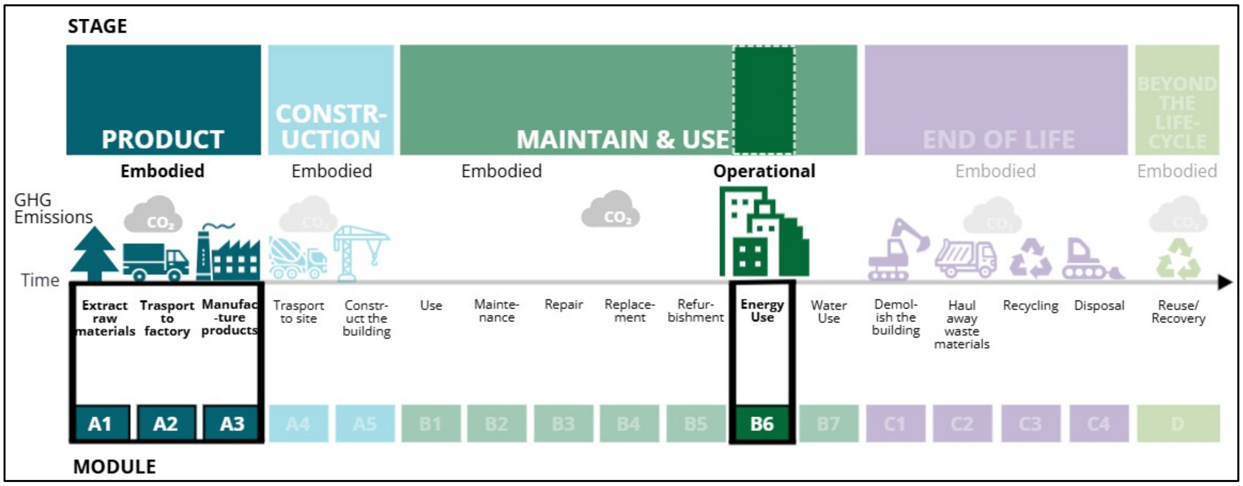
The study team generated embodied carbon estimates with the BEAM estimator tool, developed by Builders for Climate Action. BEAM focuses on the product phase of the lifecycle to calculate cradle-to-gate greenhouse gas (GHG) emissions found in environmental product declarations (EPDs) of building materials. BEAM creates carbon footprint estimations for whole buildings based on data inputs of material quantity takeoffs. Users can derive dimensions and other supplementary information from energy models. For materials with no product-specific EPD, BEAM uses industry-average EPDs for the material category for cradle-to-gate results or peer-reviewed lifecycle assessments.

Figure 2 illustrates the full lifecycle stages of a building—from raw material extraction through end-of-life disposal or re-use—and the GHG emissions associated with each stage.[19] While most lifecycle stages contribute to a building's overall embodied carbon footprint, only two modules (B6 and B7) account for emissions from the building's operational phase. This study specifically focuses on two of the lifecycle stages:

- **Product Stage (A1–A3):** Emissions associated with the extraction, transportation to factory, and manufacturing of construction materials
- **Operational Energy Use (B6):** Emissions resulting from the energy used to operate the home during its lifespan

[19] https://www.researchgate.net/figure/Life-cycle-stages-from-BS-EN-159782011-Sustainability-of-construction-works-Assessment_fig1_259841782

Figure 2: Building Lifecycle Emissions



The A1–A3 or "cradle-to-gate" scope is used in BEAM and in this report. Other lifecycle stages, such as construction (A4–A5), maintenance and use (B1–B5), including water use (B7), end-of-life (C1–C4), and beyond the lifecycle (D), are not included in this study due to limited data availability and high uncertainty about the quality of available data.

Major building assemblies included in the analysis were:

- Foundations (concrete, reinforcement, insulation)
- Footings and slab
- Floors
- Roofs (trusses, sheathing, insulation, roofing materials)
- Garage
- Exterior walls (framing, sheathing, cladding, insulation)
- Windows and glass doors
- Interior walls, partitions, and finishes
- Ceilings
- Structural elements
- Party walls
- Mechanical, electrical, and plumbing (MEP) systems

Home energy ratings capture many of these items. However, an embodied carbon assessment requires data on building assemblies outside the thermal and pressure envelope that may not be needed for an energy audit—for example, the walls and floor of an unconditioned basement, or the roof of a home with an unconditioned, vented attic. Additional examples include interior walls between conditioned rooms and any insulation that may be in those walls for noise dampening.

Estimates for MEP systems use the default values created for use in RESNET's draft Standard 1550. This study is the first ever to incorporate the embodied carbon impacts of MEP systems in residential buildings as part of an embodied carbon assessment. The team did not assess refrigerant leakage impacts in this study because they were not required in the 1550 draft standard at the time of this study.

Operational Carbon Assessment

The team modeled operational energy use with Ekotrope, a RESNET®-accredited software tool commonly used by HERS® Raters in Massachusetts. Ekotrope models generate annual energy estimates by fuel type and end-use (e.g., heating, cooling, water heating).

To convert energy use into carbon emissions, the study used regional emission factors based on the 2024 National Renewable Energy Laboratory (NREL) Cambium dataset for the ISO New England grid. This is the same methodology used in the RESNET® Carbon Index Calculation. The team applied these forecasted annual marginal emissions rates to annual energy use from 2025 to 2050 to estimate emissions over time.

The study team converted fossil fuel use (natural gas, propane) using site-level emission factors. The analysis does not include upstream methane leakage or pipeline emissions, which could underrepresent the total climate impact of fossil fuel use.

Emission Metrics and Time Horizon

The study used two key embodied carbon metrics:

- Embodied Carbon Emissions (ECE): total upfront emissions, net (with biogenic carbon storage), and gross (without biogenic carbon storage).
- Embodied Carbon Intensity (ECI): ECE normalized by square meters of conditioned floor area (kg CO_2e/m^2 CFA), allowing for comparison across homes of varied sizes.

The study examined emissions across two primary periods:

- First-year, to understand initial carbon impacts
  - ECE: upfront, material-related emissions released prior to building occupancy.
- Over a 25-year projection, to analyze cumulative emissions through 2050.
- Operational Carbon Emissions: ongoing emissions from building operations over time.

Workflow Integration and Training

Embedding embodied carbon assessments into the HERS® Rater workflow was a primary goal. To support this, the study team:

- Developed a step-by-step workflow aligned with Rater practices.
- Piloted a BETA integration worksheet between Ekotrope and BEAM to automate data transfer and reduce manual entry.
- Delivered targeted training to participating HERS® Raters on embodied carbon principles, workflow execution, and quality control.

Raters followed a consistent procedure for each home, and study administrators conducted QA/QC reviews to ensure completeness and consistency across assessments. These efforts helped identify where process refinements or future tool improvements could support broader industry adoption.

Embodied Carbon Emissions from Building Materials

The following section presents estimates of gross and net embodied carbon emissions. This section analyzes Embodied Carbon Emissions (ECE) in several ways, including:

- **Gross ECE**—the total embodied carbon material emissions before accounting for any biogenic carbon storage.
- **Net ECE**—both the gross ECE and any biogenic carbon storage.
- **Embodied Carbon Intensity (ECI)**—expressed as kilograms of CO_2e per square meter of *conditioned floor area (kg CO_2e/m^2 CFA)*. Square meters are used here to align with industry practices for reporting embodied carbon intensities and to allow for comparisons to other studies, which often use the same metric for embodied carbon intensities.
- **MEP (Mechanical, Electrical, Plumbing) ECE**—presented separately from building assembly emissions.

Throughout this report, the team expresses ECE results in metric tons of CO_2e (t CO_2e).

The team explored further analysis to find which material categories contribute most significantly to total ECE. Further investigations of embodied carbon emissions are presented by home fuel use, primary heating equipment, and foundation type in the appendices of this report (Appendix D, Appendix E, and Appendix F).

Embodied Carbon Emissions Results

This subsection presents the results for total home ECE, which includes the building enclosure and MEP systems.

Biogenic, or carbon-storing, materials were not widely used across the sampled homes. Among the homes where biogenic materials were present, cellulose insulation and fiber cement siding were the most common. Accounting for carbon storage reduces the average ECE of the total sample from a gross ECE of 56.4 tons CO_2e to a net ECE of 55.5 tons, a modest decrease of only 1.6% (Figure 3 and Figure 4).

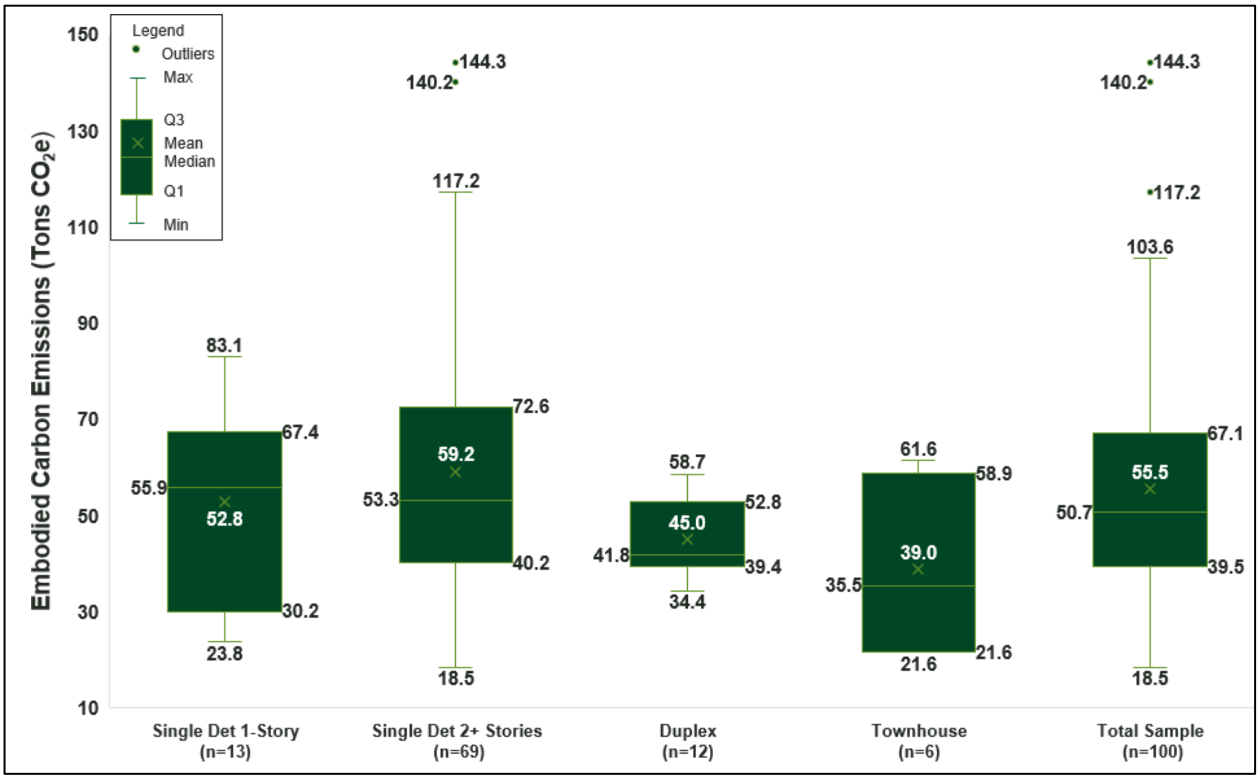
The average overall net ECE among sampled homes was 55.5 tons of CO_2e, which could be a starting point for setting an ECE benchmark for the state of Massachusetts.

The category of single-family detached homes of two or more stories, which make up nearly 70% of the sample, contained the homes with both the highest and lowest net ECE in the study—with the highest ECE home responsible for 155% of the emissions of the lowest ECE home. The home with the highest total gross ECE was an extremely large residence at over 8,400 ft^2 and produced 144.3 tons of CO_2e. It featured a walkout basement with significant quantities of poured concrete, extensive use of open-cell spray foam insulation in the walls, roof, and floor, and it utilized a ducted distribution system with a propane furnace for heating and an air-source heat pump for cooling.

Conversely, the home with the lowest net ECE registered just 18.5 tons of CO_2e. This was a small home, under 700 ft², with an enclosed crawlspace containing minimal poured concrete, fiberglass batt insulation in the walls and floor, open-cell spray foam in the roof, and a single air-source heat pump serving both heating and cooling.

These stark differences underscore how design decisions, home size, and material choices can dramatically influence the overall net ECE of a home.

Figure 3: Net ECE Statistics By Home Type (Tons CO_2e)



MEP systems represented 18% of total home ECE emissions, on average. Attached single-family typologies (duplexes and townhomes) had lower ECE than detached single-family homes. Single-family homes with more than two stories had the highest average ECE, at 59.3 net tons of CO_2e. This represents a 9% increase over one-story detached homes, 23% increase over duplexes, and 53% increase over townhomes (Figure 4).

Both gross and net emissions are shown in Figure 4. The similarity of these numbers demonstrates the limited presence of materials with biogenic storage properties among homes in the sample.

Figure 4: Average Embodied Emissions by Home Type (Tons CO_2e)

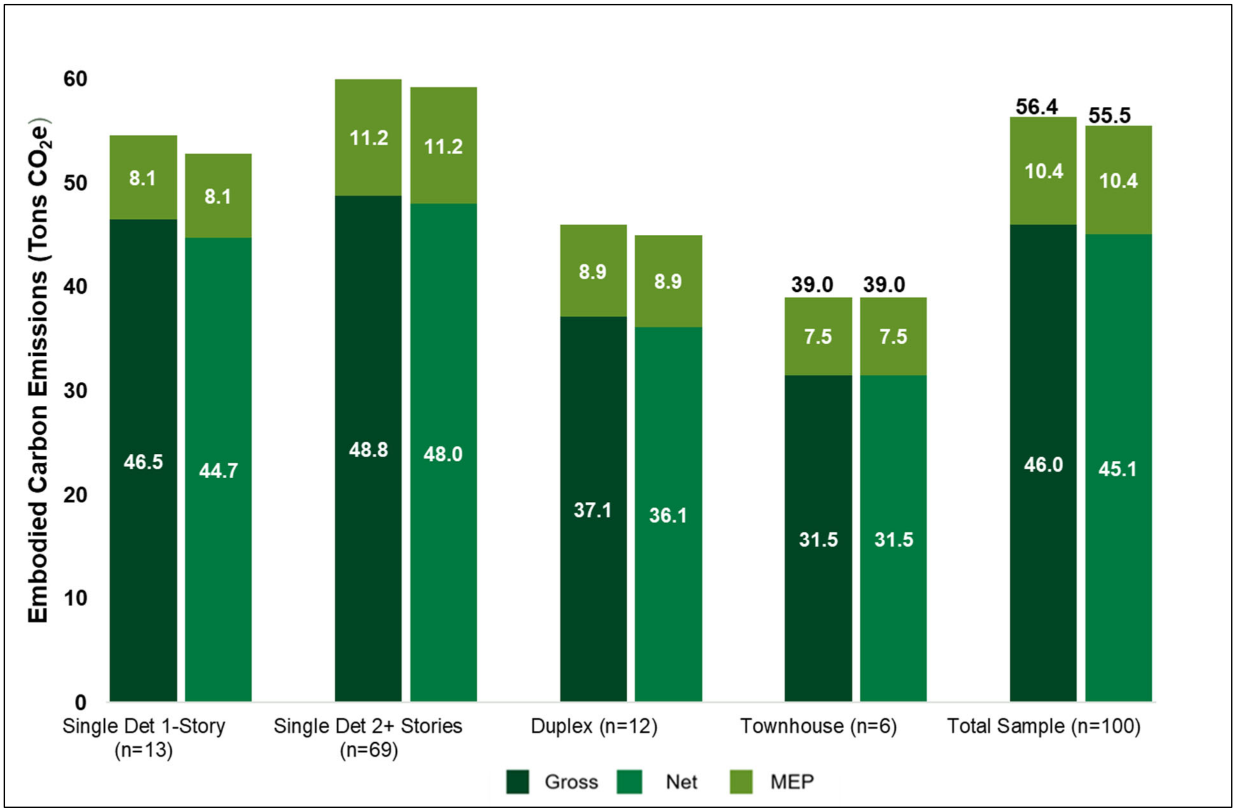


Table 1 provides a breakdown of how various building components in single-family homes contribute to overall home ECE. Concrete is among the largest contributors to embodied carbon emissions among building materials, especially in small residential construction where steel is uncommon. As the table shows, concrete assemblies like foundation walls, slab floors, and footings are the largest source of ECE among construction components. These numbers further reinforce the importance of addressing concrete in new construction, either by switching to low-carbon concrete alternatives or by limiting its use—for example, by favoring designs without full-height basements. Mechanical equipment is the next largest ECE contributor among discrete building components.

Table 1: ECE Contributions of Residential Building Components (Tons of CO_2e)

Assembly	Single Det 1-Story	Single Det 2+ Stories	Duplex	Townhouse	Statewide
	Percentage of ECE				
n-value	*13*	*69*	*12*	*6*	*100*
Foundation Walls	23%	20%	18%	19%	20%
Footings & Slabs	21%	17%	27%	22%	20%
Floors	6%	9%	5%	6%	8%
Roof	9%	7%	6%	8%	7%
Garage[1]	11%	6%	8%	6%	7%
Exterior Walls	4%	7%	5%	6%	5%
Windows	4%	7%	5%	5%	5%
Interior Walls	4%	4%	4%	5%	4%
Ceiling	1%	2%	1%	1%	2%
Structural Elements	2%	3%	<1%	2%	3%
Party Walls	--	--	1%	1%	<1%
Mechanical Equipment	11%	12%	13%	13%	12%
Electrical Equipment	2%	3%	2%	2%	2%
Plumbing Equipment	3%	3%	4%	4%	4%
Total ECE (%)	**100%**	**100%**	**100%**	**100%**	**100%**

[1] Garage category includes various assembly categories required for a garage.
* Totals may not equal sum of column or row due to rounding.

Embodied Carbon Intensity (ECI)

Embodied carbon intensity (ECI) normalizes net ECE by building area and is expressed in kilograms of CO_2e per square meter (kg CO_2e/m^2) of conditioned floor area (CFA). This metric lets the study team compare the carbon intensity of varied-sized buildings. It is a similar concept to energy use intensity, which focuses on operational energy consumption, and is sometimes referred to as the "miles-per-gallon" metric for a building. In this subsection, *total ECI is inclusive of embodied carbon emissions from building assemblies and MEP systems.*

> *The average home ECI of 226.8 kg CO_2e/m^2 provides a possible carbon intensity benchmark for single-family homes in Massachusetts.*

The average ECI across homes in the sample is 226.8 kg CO_2e/m^2 of CFA (Figure 5). Detached single-family homes of two or more stories, which have higher per-home ECE than other building typologies, had the lowest ECI among building typologies. This finding highlights the importance of using different metrics to quantify embodied carbon to prevent a distortion of magnitude that can occur when looking *only* at the intensity per unit of floor area. This may mask the importance of driving down *overall* ECE generated by a home. Policy and programmatic interventions should encourage lower ECI construction while also rewarding lower overall emissions and incentivizing builders to use low-carbon materials and less materials overall. Alternative carbon intensity metrics based on occupancy (e.g., number of bedrooms or estimated inhabitants) could provide another lens into building carbon intensity.

Figure 5: Net ECI per Conditioned Floor Area by Home Type (kg CO_2e/m^2)
(Includes Building Enclosure and MEP)

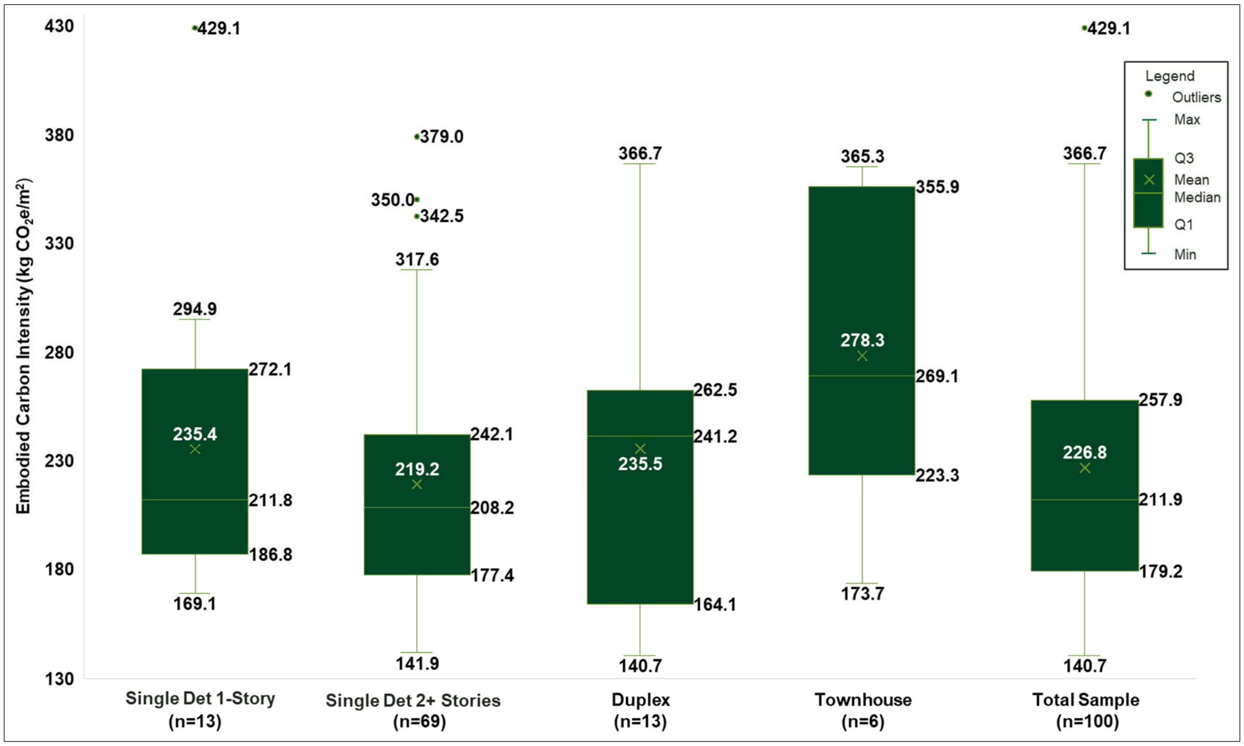
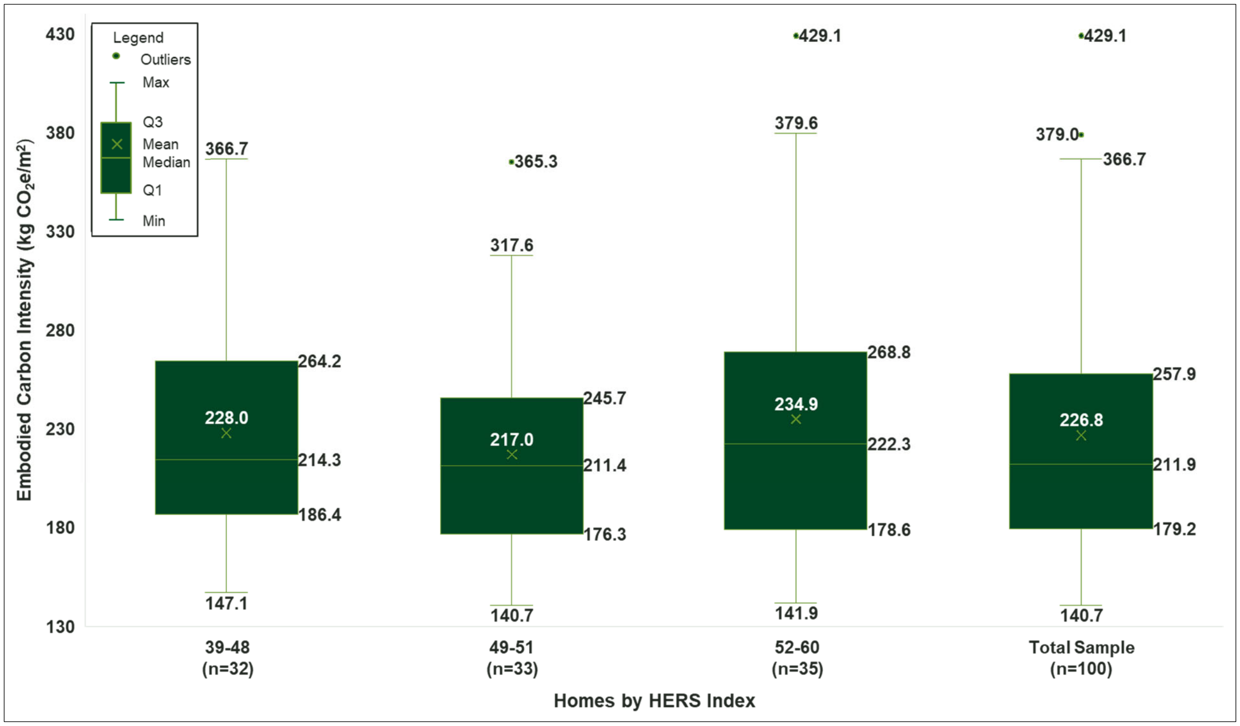


Figure 6 displays the ECI by HERS® Index score. The HERS® Index represents the home's energy performance. It is calculated against a 2006 International Energy Conservation Code (IECC) reference home. A higher HERS® score represents a home with lower energy performance; a home with a low score indicates a high-performance home[20]. The lowest HERS® score amongst the sample set is 39, while the highest is 60. Figure 6 organizes homes into three HERS® Index bins for ease of comparison.

Better or worse HERS® Index scores do not correlate to lower or higher ECI. While it is important to decrease the operational energy consumption and associated emissions to improve home energy performance, these results underscore that *high-performance buildings are currently just as carbon intensive than less energy-efficient homes*. This indicates that both conventional and high-performance building stakeholders are missing opportunities to further reduce embodied carbon and a building's overall carbon footprint.

[20] A HERS® Index score of 100 represents a home built to meet the energy efficiency requirements of the 2006 International Energy Conservation Code (IECC) https://www.hersindex.com/hers-index/what-is-the-hers-index/

Figure 6: Net ECI per Conditioned Floor Area by HERS® Index (kg CO_2e/m^2) (Includes Building Enclosure and MEP)



Previous Embodied Carbon Benchmarking Studies

Builders for Climate Action conducted embodied carbon benchmarking studies in Canada using the BEAM estimator tool[21]. Canada has a commitment under the Paris Agreement to reduce GHG emissions by 40%–45% below 2005 levels by 2030 and become net zero by 2050. Previous studies measured the embodied carbon of multiple new home typologies in the region. **Note:** To align the results of this Massachusetts study to other studies of embodied carbon, the ECE of MEP systems in Massachusetts homes is excluded from comparisons. MEP was not included in the ECE reporting from other studies. Homes in the Massachusetts study had a total net average building assembly ECE of 46.1 tons of CO_2e, which ranges from 7%–40% higher than average home results from the three Canadian embodied carbon studies. Massachusetts can leverage these benchmarks from this study and previous studies to help inform decision-making for future embodied carbon legislation. Figure 7 illustrates the net ECE results of the Massachusetts study alongside the previous embodied carbon benchmarking studies.

[21] Builders for Climate Action Previous Embodied Carbon Studies https://www.buildersforclimateaction.org/our-work.html

Figure 7: Total Net ECE Benchmarks from Previous Studies
(Tons CO_2e, Excluding MEPs)

	Mass n=100	Vancouver n=13	Nelson n=34	Toronto n=503
TOTAL ECE	4,608	559	978	20,122
AVERAGE ECE	46.1	43.0	28.8	39.3
MAX ECE	123.2	140.1	63.6	827.1
MIN ECE	13.6	10.5	5.9	9.5

The Massachusetts study found similar carbon intensity results to the comparison studies in Toronto and Vancouver (Figure 8).

Figure 8: ECI Benchmarks from Previous Studies
(kg CO_2e/m^2 CFA, Excluding MEPs)

	Mass n=100	Vancouver n=13	Nelson n=34	Toronto n=503
AVERAGE ECI	185	193	150	191
MAX ECI	356	357	309	561
MIN ECI	109	138	72	116

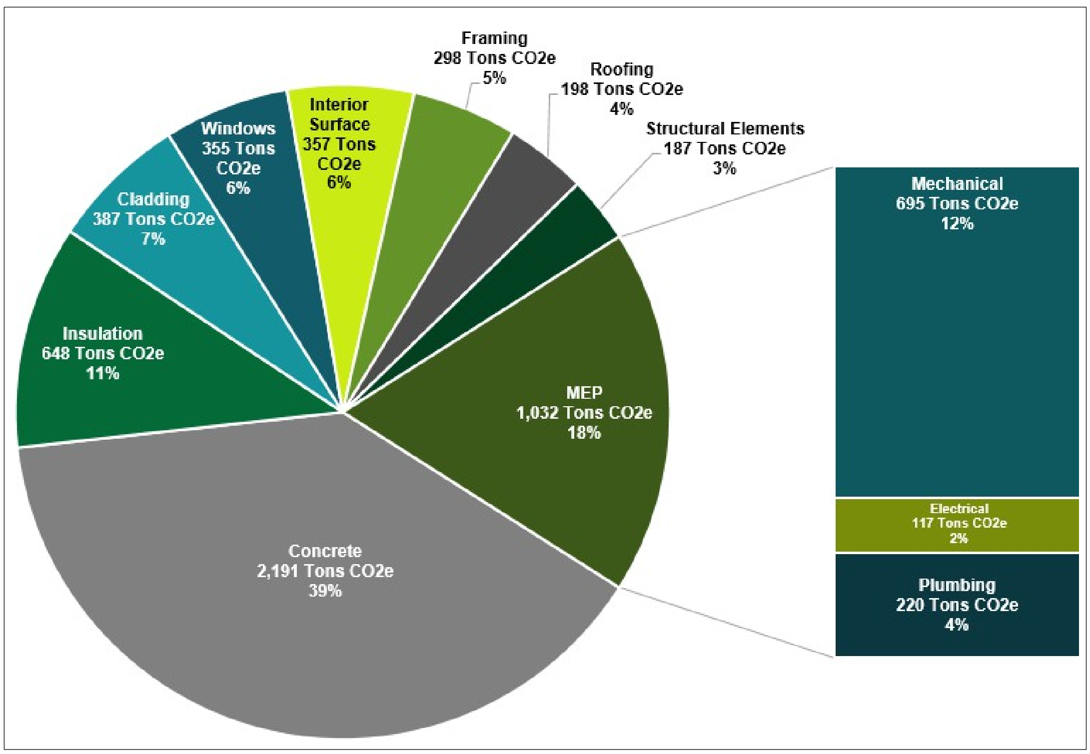
Material Emissions and Intensities by Material Category

This subsection explores the distribution of ECE across various material categories within the sampled homes, identifying which materials contribute most significantly to ECE. Figure 9 presents the *gross* material emissions by category before accounting for any carbon storage effects. Figure 9 includes emissions associated with the MEP systems and depicts both the gross emissions contribution from each category across all 100 homes, and the percentage that material category makes up overall.

Three material categories collectively account for approximately 62% of gross material emissions in the sample: concrete (39%), mechanical (not including electrical and plumbing) systems (12%), and insulation (11%). Concrete emerges as the dominant source of embodied emissions, largely driven by foundation, slabs, and structural components. This study assumed that all homes used the baseline National Ready Mix Concrete Association (NRMCA) average mix, and that the majority of the sample used 3001–4000 psi (Figure 10). A lower GWP concrete mix would have significantly cut the ECE of each home.

As discussed in *Limitations and Sources of Uncertainty*, one data gap is the underreporting of insulation within interior or "party" walls and floors. Available project documentation and the data gathered for the HERS® Rating itself could not adequately capture insulation in these assemblies. Although such insulation is common practice—not for thermal efficiency but for soundproofing—its omission likely leads to an underestimation of insulation-related emissions and may consequently understate the overall ECE of the homes, depending on material selection.

Figure 9: Gross Material Emissions by Category (Tons CO_2e)



Product categories contributing most significantly to ECE offer several alternatives that can reduce emissions. The following options are available for concrete, insulation, and cladding. Adjustments within these categories allow stakeholders to lower total emissions.

Concrete, the largest contributor to ECE in sampled homes, represented 39% of overall embodied emissions. Figure 10 shows the difference of GWP between concrete mixes within three psi brackets. Based on building data, a majority of the sample used 3001–4000 psi standard mix in concrete assemblies. The GWP of this concrete category is 46% higher than the lowest GWP concrete mix. Using an alternative lower GWP mix could significantly decrease the overall embodied emissions.

Figure 10: Global Warming Potential of Concrete Materials (kg CO_2e)

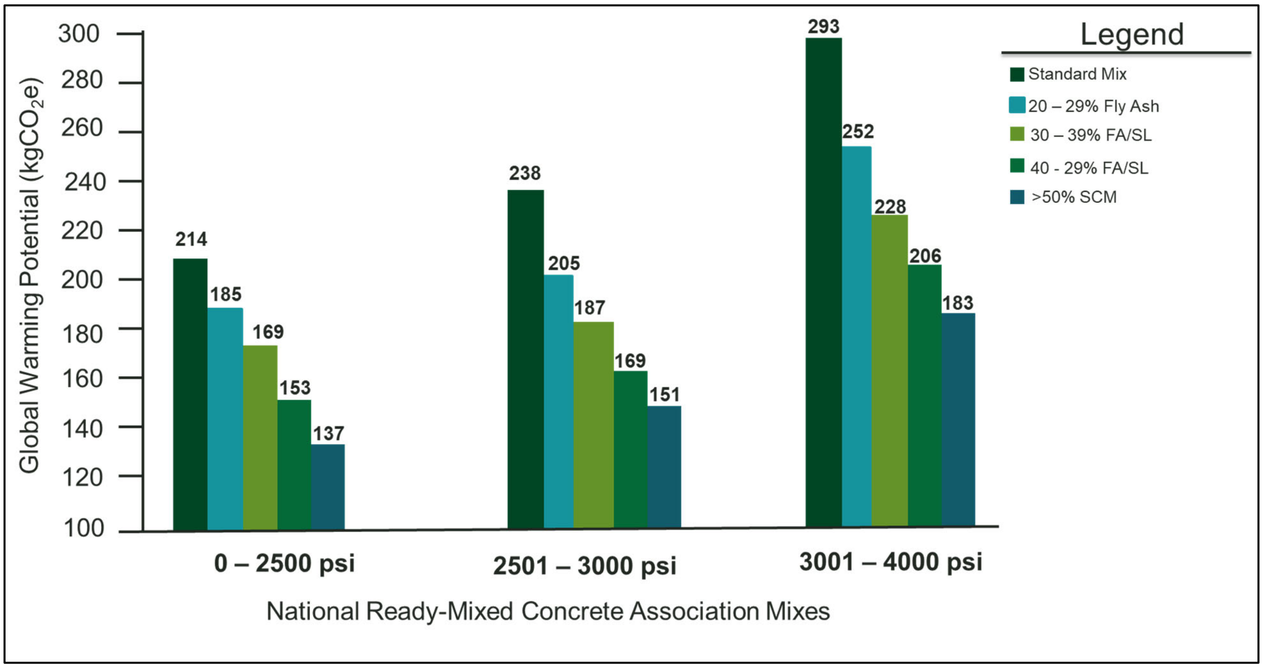


Figure 11 illustrates the embodied carbon associated with various insulation products. XPS foam board exhibits the highest GWP at 9,948 ($kgCO_2e/1,000\ ft^2$), followed by closed-cell spray foam at 4,306 ($kgCO_2e/1,000\ ft^2$). In contrast, bio-based and cellulose-based insulations such as wood fiber board and dense-pack cellulose show net carbon storage. This indicates the potential to achieve negative embodied emissions in buildings if using these materials more frequently for insulation.

Figure 11: Global Warming Potential of Insulation Materials (kg $CO_2e/1000\ ft^2$)

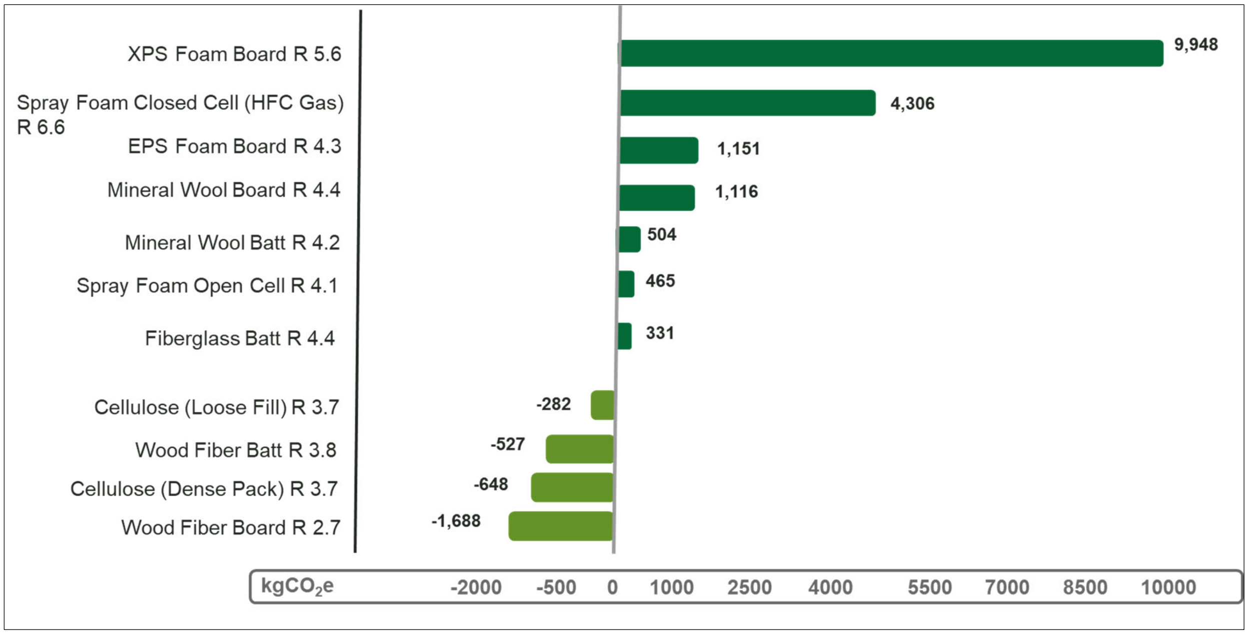
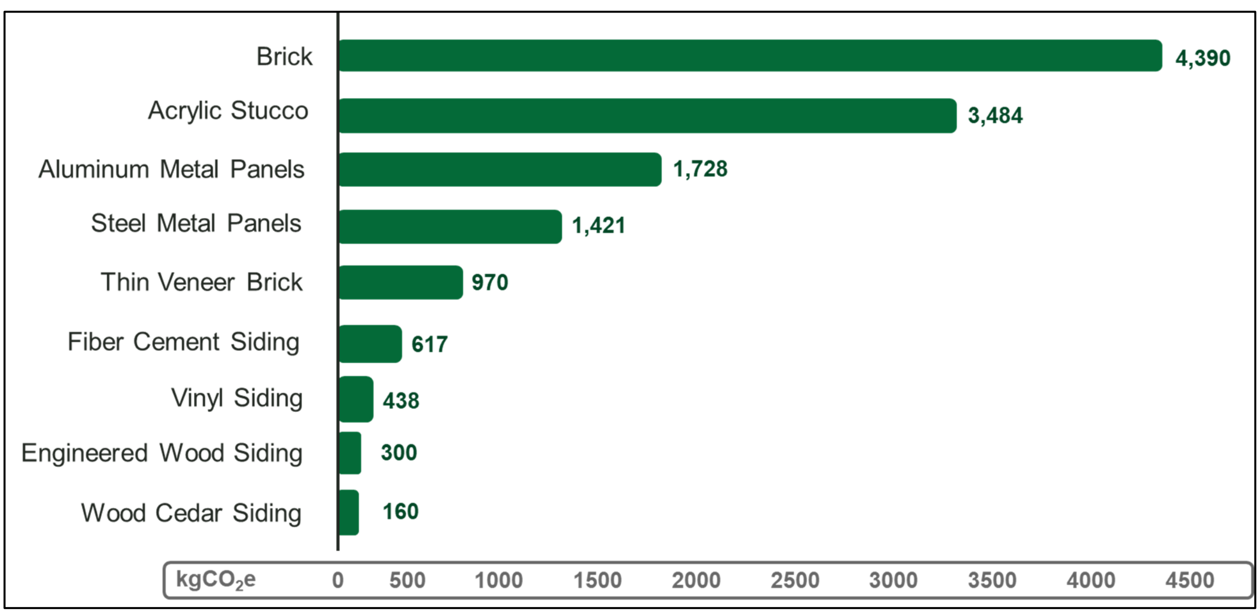


Figure 12 compares the embodied carbon of common cladding materials. Brick and acrylic stucco have the highest global warming potential, at approximately 4,390 and 3,484 (kg $CO_2e/1,000\ ft^2$). In contrast, engineered wood siding (300 kg $CO_2e/1,000\ ft^2$) and wood cedar siding (160 kg $CO_2e/1,000\ ft^2$) have much lower emissions, highlighting substantial variation in cladding materials' emissions intensity.

Figure 12: Global Warming Potential of Cladding Materials (kg $CO_2e/1000\ ft^2$)



Mechanical, Electrical, and Plumbing (MEP) Systems

Mechanical, electrical, and plumbing (MEP) systems contribute to a home's embodied carbon footprint due to the quantity and complexity of manufactured components, the carbon intensity of materials used (e.g., metals, plastics), the energy distribution infrastructure, and the presence of systems with high GWP refrigerants[22]. An often-overlooked contributor to MEP system emissions is the relatively short lifespan of building systems and equipment, which require multiple replacements over a building's life; this study did not account for MEP replacements. This study quantified MEP-related ECE using methodology aligned with the RESNET® draft Standard 1550, which defines system boundaries and unit-level embodied carbon values for residential heating, ventilation, and cooling (HVAC) and domestic hot water equipment.

Statewide, MEP systems contributed more than 10 metric tons of CO_2e, or 18% of total net ECE in sampled homes (Figure 13). Within the broader MEP category, mechanical systems contributed the most ECE, accounting for 12%, followed by plumbing at 4%, and electrical at 2%. Combined, MEP systems were the second largest contributor of ECE in the sample, behind concrete. (Figure 9).

There is substantial variation in the relative contribution of MEP systems to total ECE across homes in the sample, as demonstrated by the homes with the largest and smallest ECE footprints:

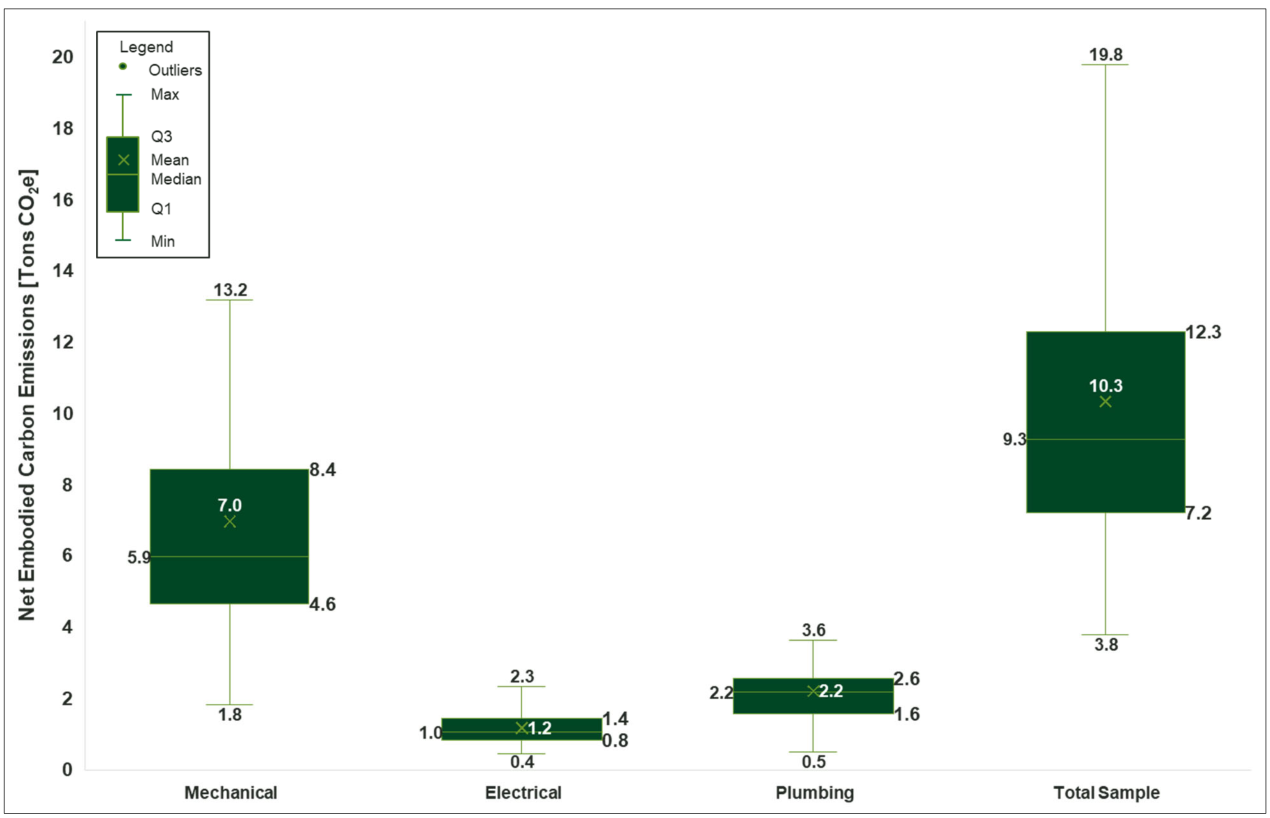
- In the home with the highest ECE (144.3 tons CO_2e):
- MEP components accounted for nearly 21 tons of ECE, representing 15% of the home's total gross ECE, which is lower than the sample average.
  - Concrete and insulation contributed to a combined 51% of total home ECE.
  - This home included a propane furnace and a secondary air-source heat pump system (used for cooling), which utilized an expansive duct distribution system that served a large, conditioned area over 5,000 ft^2.
- In the home with the lowest total gross ECE (18.5 tons):
  - MEP components contributed just under five tons of ECE, or 27% of the home's total ECE.
  - The combination of concrete (37%) and insulation (12%) in this home contributed a similar percentage of overall home ECE (49%) to the high ECE home described above.
  - This home utilized an air-source heat pump for both heating and cooling.

[22] As discussed in the detailed methodology and *Limitations and Sources of Uncertainty* sections of this report, emissions associated with refrigerants were not captured in this study's methods for estimating MEP emissions.

Total ECE from MEP systems can vary significantly based on system complexity, mechanical system type and capacity, redundancy (e.g., dual fuel systems or multiple systems), and distribution strategy.

- **Mechanical ECE.** Mechanical systems were the dominant driver of MEP-related ECE, averaging 7.0 tons CO_2e, or 11.5% of net ECE per home. This category encompasses primary space conditioning equipment, ductwork, air handlers, and associated components. Ductless air-source heat pumps had notably lower ECE, likely due to reduced distribution components, whereas furnaces and boilers added emissions associated with heat exchangers, burners, venting components, and in some cases, storage. However, this study did not specifically investigate how the amount of duct work impacted overall MEP emission estimates.
- **Plumbing ECE.** Plumbing system ECE averaged 2.2 tons CO_2e, or 3% of net ECE per home, and is derived from a combination of water heaters, piping systems (copper, PEX, CPVC), bathroom and kitchen fixtures, and their related installation and distribution components.
- **Electrical ECE.** Electrical systems contributed to the lowest share of MEP-related ECE, averaging 1.2 tons of CO_2e, or 2% of net ECE per home. This includes branch circuit wiring, electrical panels, circuit breakers, junction boxes, and other service equipment. Homes with larger CFA or higher electrical loads can require more extensive electrical infrastructure, increasing ECE.

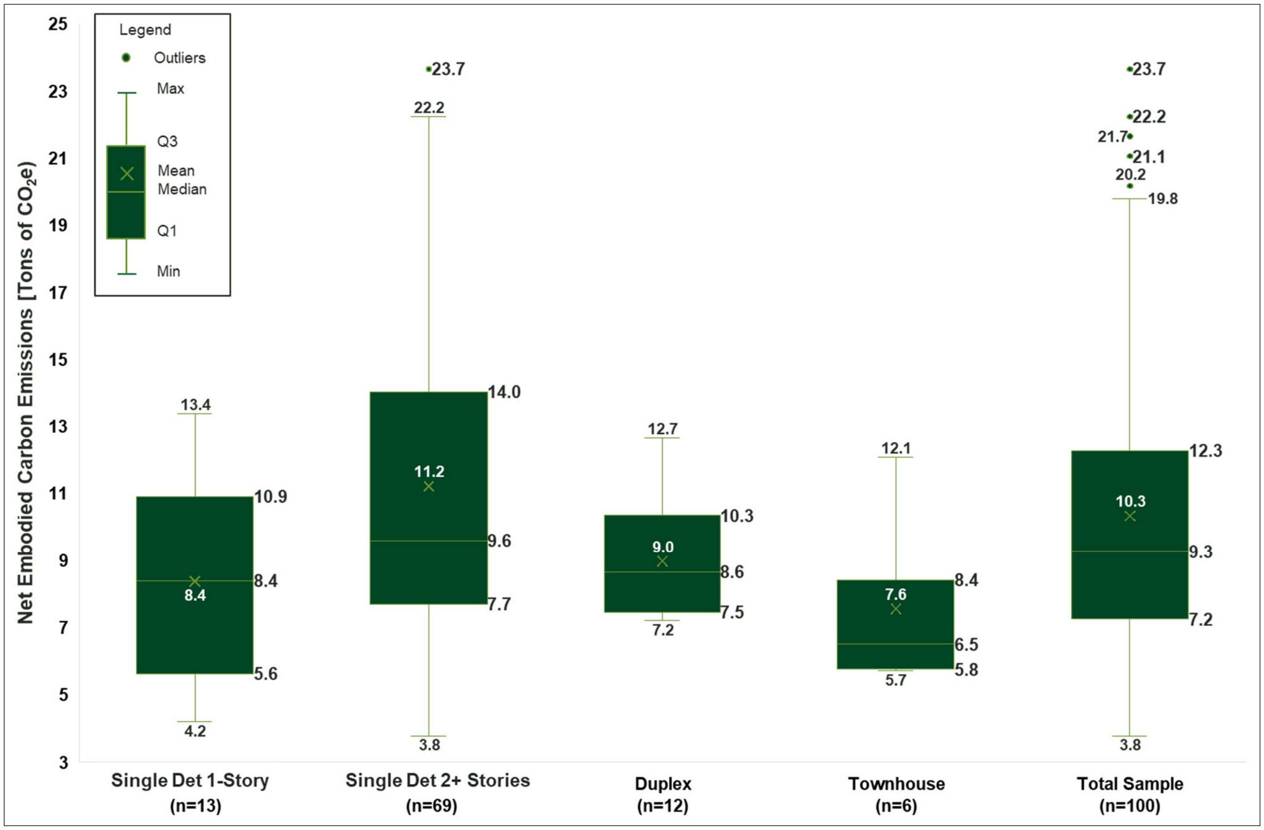
Figure 13: Net ECE for MEP System Components (Tons CO_2e)



* Maximum outliers were removed from this chart due to figure distortion.

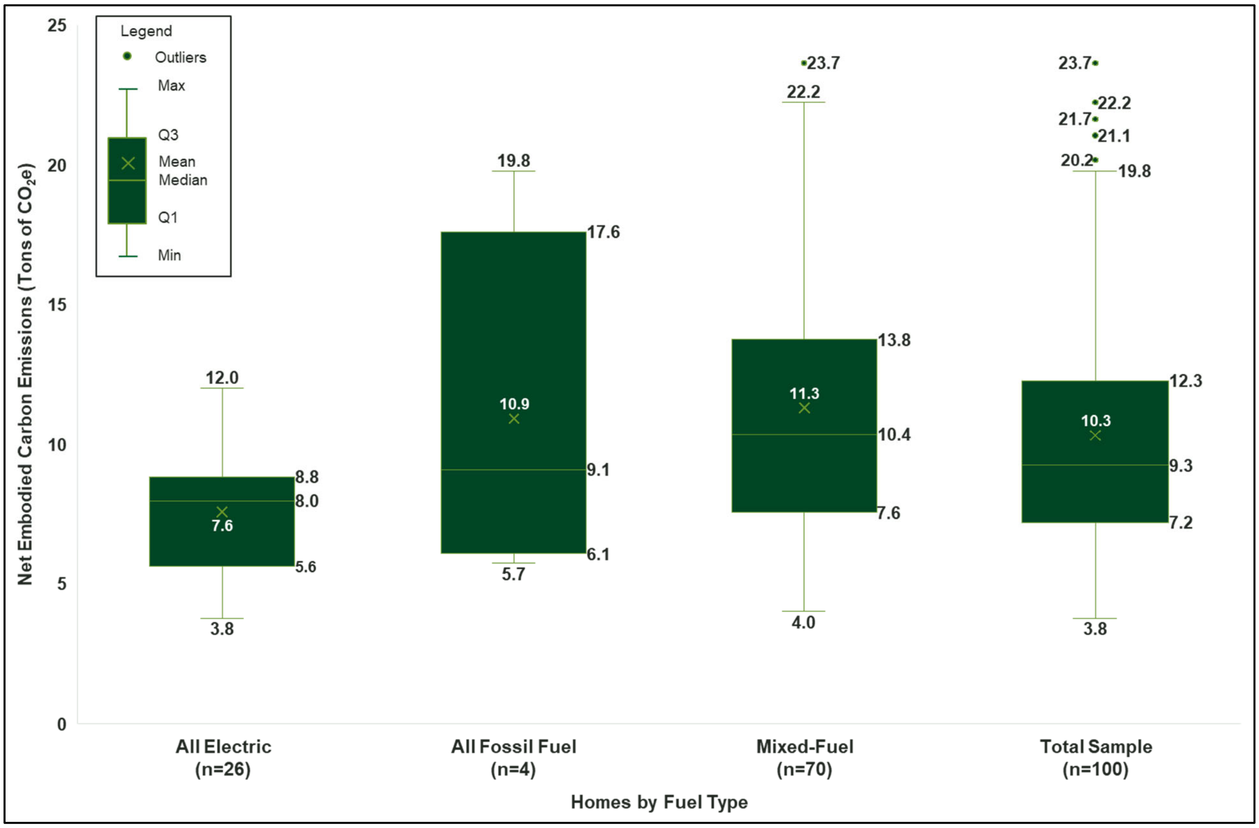
Single-family homes with two or more stories have the widest range of ECE associated with MEP systems.

Figure 14: Average ECE from MEP Systems by Home Type (Tons CO_2e)



Generally, systems that require less materials (e.g., piping, cabinets, ductwork) to operate effectively will help reduce overall ECE. The comparison of all electric and mixed fuel homes is shown in Figure 15. All electric homes had noticeably less ECE (7.6 tons) than mixed fuel homes (11.3 tons). The results illustrate the decarbonization co-benefits of electrification. Electrification not only reduces operational CO_2e emissions by eliminating on-site combustion but also has potential to reduce ECE emissions associated with the infrastructure and distribution systems common to fossil fuel equipment. This dual benefit strengthens the argument for all electric residential design in regions working toward decarbonizing the building sector to meet climate goals.

Figure 15: Average MEP System ECE by Fuel Type (Tons CO_2e)



These findings highlight the importance of accounting for MEP systems when attempting accurate whole-building embodied carbon assessments. MEP systems can represent a substantial share of a home's ECE. In this sample, it accounts for nearly 20% of average net ECE. This is the first study in North America that includes the share of embodied carbon produced by MEP systems when addressing whole-home ECE benchmarking.

Operational Carbon Emissions

This section details findings related to operational energy use, which includes the emissions generated from fossil fuels and emissions from the grid associated with electricity generation and consumption. These values are derived from Ekotrope outputs for the 100 sample homes. This data is analyzed by factors like home type, foundation type, fossil fuel usage, primary heating type, and water heating type to highlight the most crucial factors in operational carbon emissions.

HERS® Ratings and Carbon Index Scores

Figure 16 summarizes HERS® rating statistics for the sample. Duplexes have the lowest mean HERS® rating (48.8). Overall, average and median home energy performance, regardless of the type of fuel used or the type of home, is similar.

Figure 16: HERS® Rating by Home Type

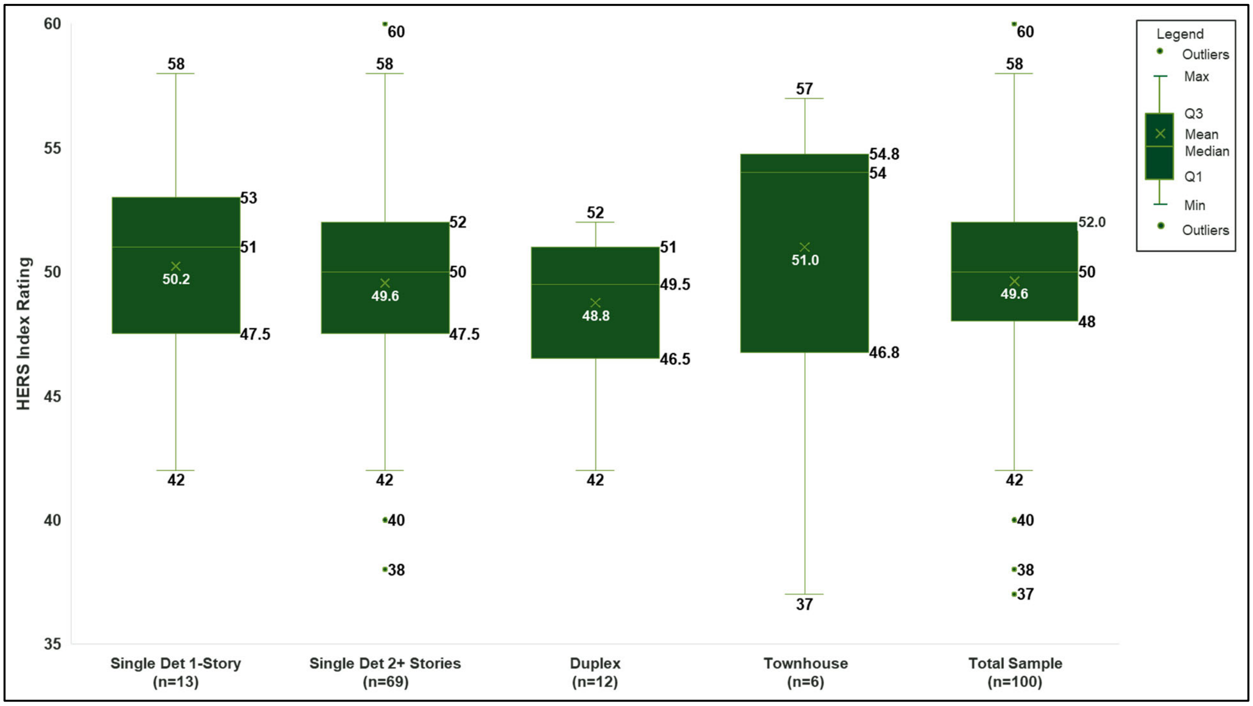
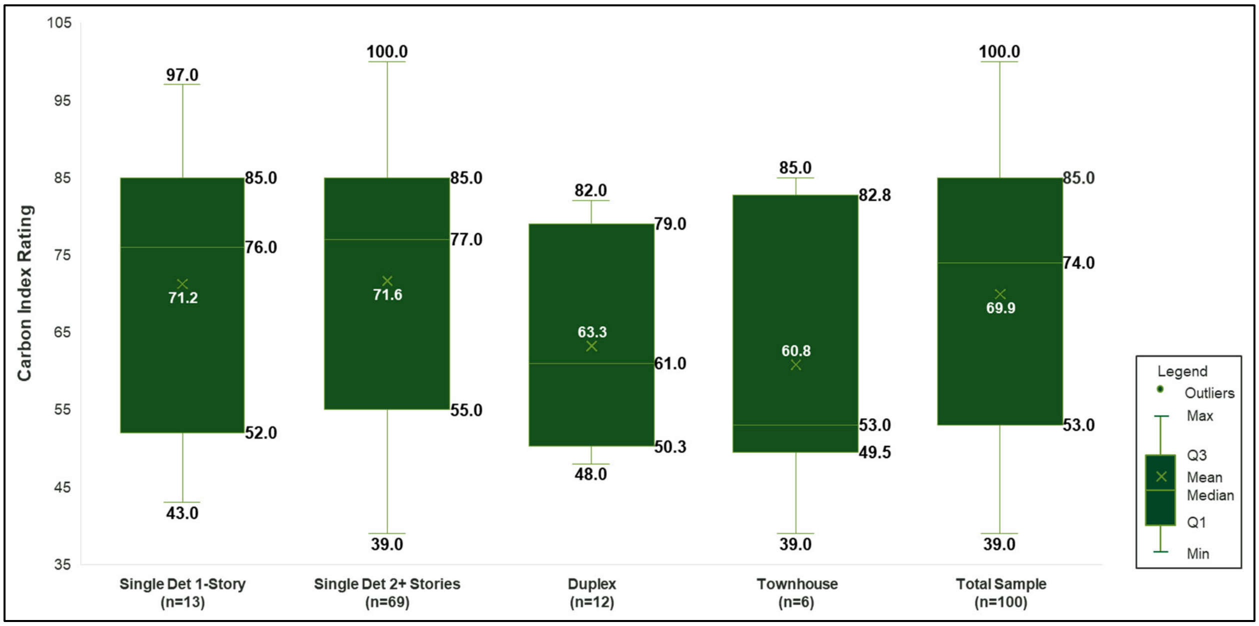


Figure 17 summarizes the overall Carbon Index scores of the sample homes by home type. Townhomes and duplexes have lower average Carbon Indexes (60.8 and 63.3) than detached single-family homes (71.2 for single-story homes, 71.6 for homes with two or more stories).

Figure 17: Carbon Index by Home Type



Total Energy Consumption

The tables in this section show annual energy consumption estimates for the homes in the sample. Energy consumption is expressed in MBtu, which normalizes the consumption from fossil fuels and electricity into a common metric. This section also provides a comparison of homes by energy use intensity (EUI), which normalizes energy use by building area (here expressed as kBtu/m^2).
Note: Emissions intensities are also normalized by area to maintain comparability.

Total Energy Consumption

Homes in the sample show some variation in overall energy usage, where detached single-family homes of more than one story use considerably more energy on average than other typologies, but energy use becomes much more similar across home types when normalizing consumption by building area using EUI.

Figure 18: Annual Energy Consumption by Home Type (Overall) (MBtu)

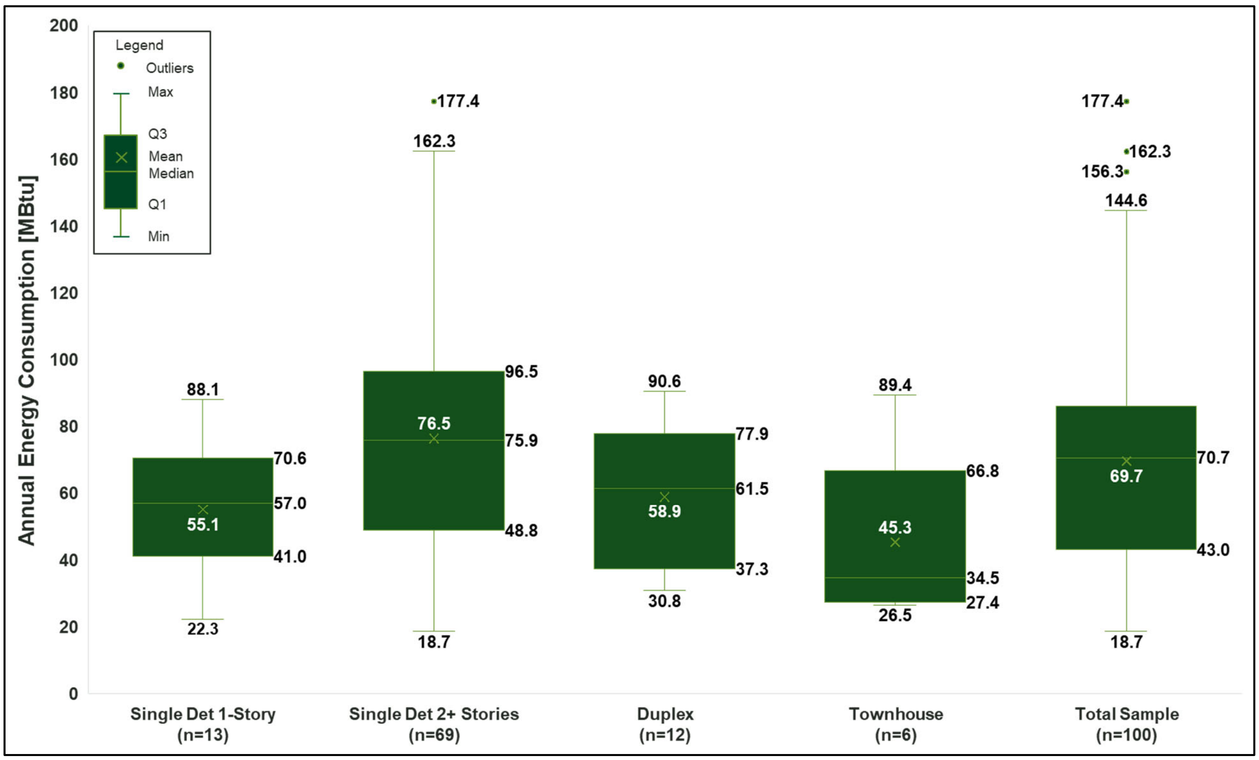
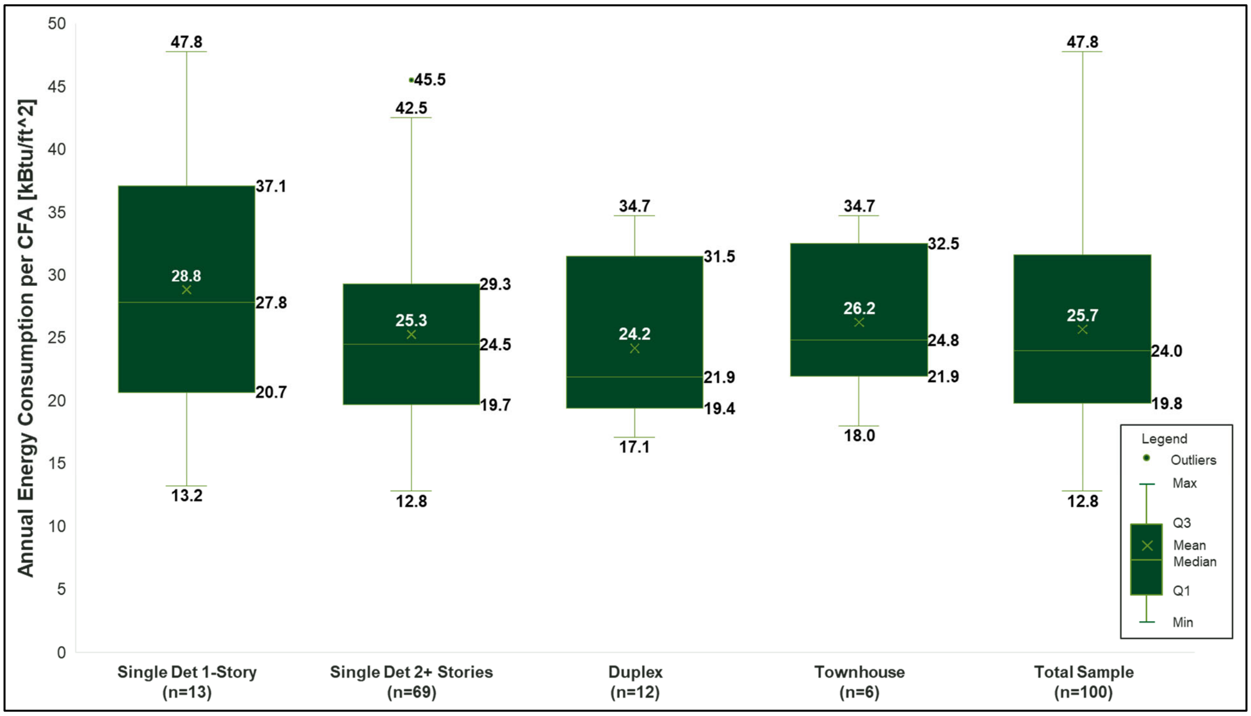


Figure 19: Annual EUI by Home Type (kBtu/m² CFA)



Operational Emissions (CO_2e)

This subsection presents estimated CO_2e emissions generated by homes in the sample during their first year of operation, assumed to be 2025.

Figure 20 and Table 2 show the average CO_2e emissions of homes, split up by end-use and further split by home type. Unsurprisingly, in a heating-dominated climate, the largest source of CO_2e emissions are heating systems, generating an average of 56.3% of all home emissions. Conversely, the smallest source of CO_2e emissions in those homes are cooling systems, a mere 1.8% of the total emissions. (Note that the cooling emissions are represented in Figure 20 but are too small to be visible.)

A similar pattern can be seen in Figure 21 and Table 3, which shows the same data normalized by conditioned floor area, expressed in square meters. Heating emissions are 55.2% and cooling emissions are 1.7% of the total home emissions by CFA. The relative cooling and heating emissions are representative of Massachusetts's cool climate, but the use of fossil fuels in primary heating systems may also influence emissions. Natural gas or propane was used by 60% of the homes in this study for their heating fuel source.

Figure 20 and Table 2 show that single-family detached homes with at least two floors have the highest average total emissions (6.09 tons per year) and townhomes have the lowest average total emissions (3.44 tons per year). However, Figure 21 and Table 3 show that this difference is largely due to differences in building size. When normalized by conditioned floor area, the differences shrink and change. The highest operational emission intensities per CFA are single-story detached homes (24.11 kg/m^2) and the lowest emissions per CFA are duplexes (19.80 kg/m^2).

Figure 20: Annual Operational Emissions by Home Type (Tons CO_2e)

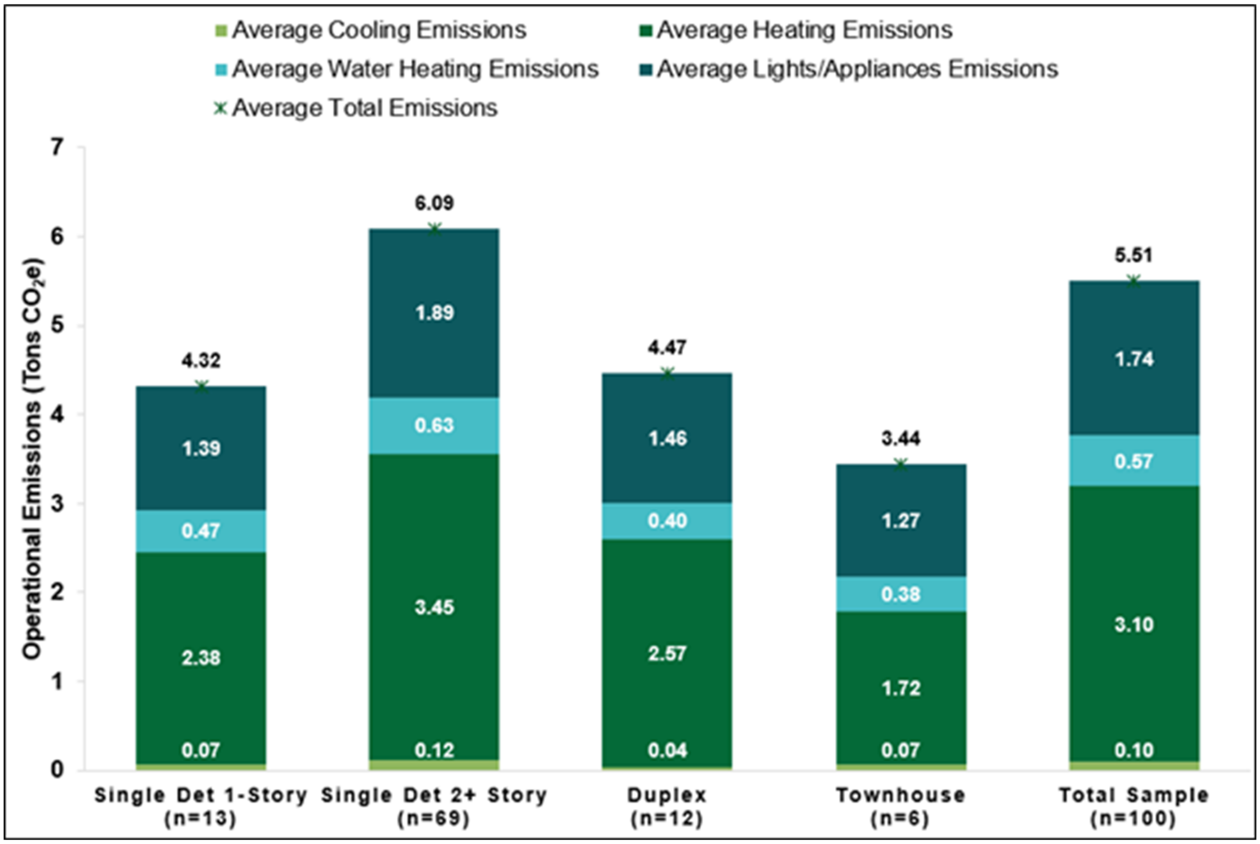


Table 2: Annual Operational Emissions by Home Type (Tons CO_2e)

(Tons)	Single Det 1-Story	Single Det 2+ Stories	Duplex	Townhouse	Total Sample
n-value	*13*	*69*	*12*	*6*	***100***
Average Total Emissions	4.32	6.09	4.47	3.44	**5.51**
Average Cooling Emissions	0.07 (1.6%)	0.12 (1.9%)	0.04 (0.9%)	0.07 (2.1%)	**0.10 (1.8%)**
Average Heating Emissions	2.38 (55.2%)	3.45 (56.6%)	2.57 (57.5%)	1.72 (49.9%)	**3.10 (56.3%)**
Average Water Heating Emissions	0.47 (10.9%)	0.63 (10.4%)	0.40 (9.0%)	0.38 (11.1%)	**0.57 (10.3%)**
Average Lights/Appliances Emissions	1.39 (32.2%)	1.89 (31.1%)	1.46 (32.6%)	1.27 (36.9%)	**1.74 (31.6%)**

Figure 21: Annual Operational End-Use Emissions by Home Type (kg CO_2e/m^2 CFA per year)

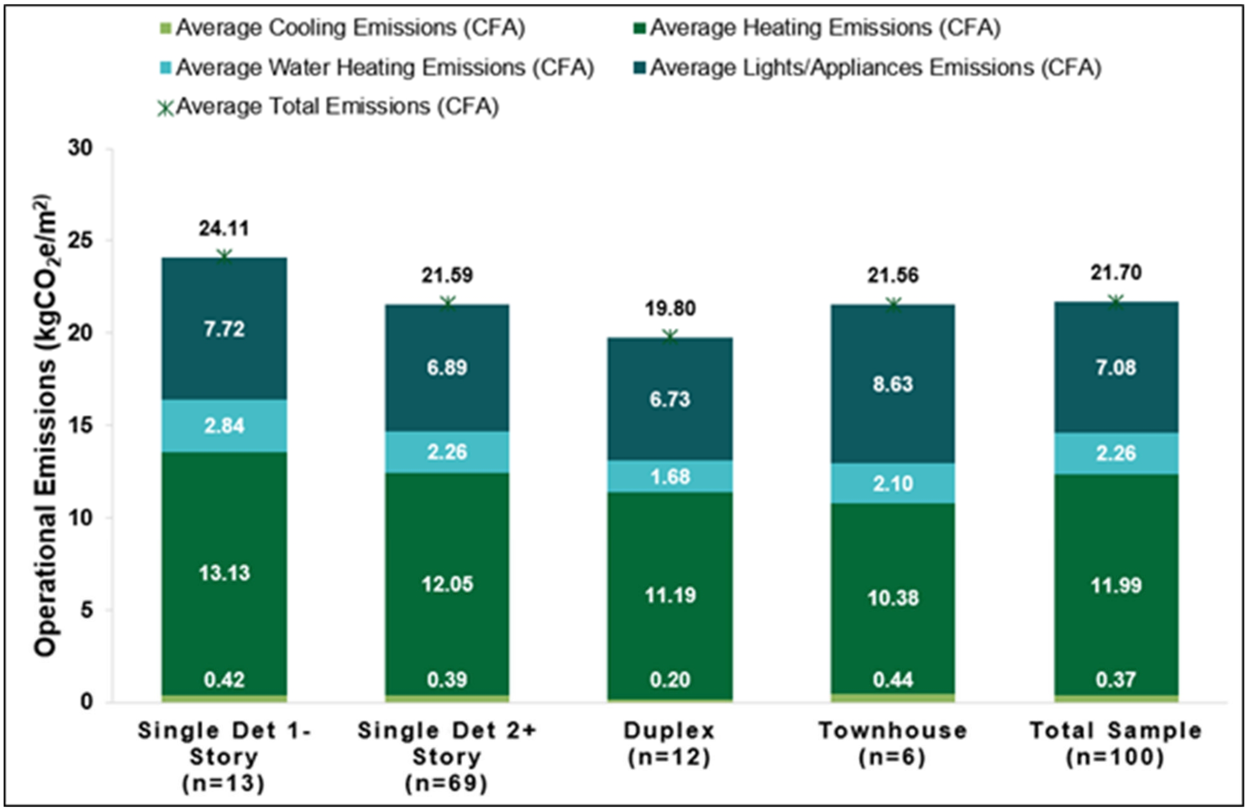


Table 3: Average Annual Operational End-Use Emissions by Home Type (CO_2e kg/m^2 CFA)

(kg/m^2/year)	Single Det 1-Story	Single Det 2+ Stories	Duplex	Townhouse	Total Sample
n-value (sample size)	*13*	*69*	*12*	*6*	***100***
Average Total Emissions per CFA	24.11	21.59	19.80	21.56	**21.70**
Average Cooling Emissions per CFA	24.11 (1.7%)	0.39 (1.8%)	0.20 (1.0%)	0.44 (2.0%)	**0.37 (1.7%)**
Average Heating Emissions per CFA	13.13 (54.4%)	12.05 (55.8%)	11.19 (56.5%)	10.38 (48.2%)	**11.99 (55.2%)**
Average Water Heating Emissions per CFA	2.84 (11.8%)	2.26 (10.5%)	1.68 (8.5%)	2.10 (9.7%)	**2.26 (10.4%)**
Average Lights/Appliances Emissions per CFA	7.72 (32.0%)	6.89 (31.9%)	6.73 (34.0%)	8.63 (40.1%)	**7.08 (32.6%)**

Cumulative Operational Carbon Emissions Forecast

The following section provides a forecast of future operational carbon emissions from the homes in the sample. Emissions associated with electricity generation are not static; they vary both by the hour of the day and the season. The state of Massachusetts has established targets to reduce emissions from electricity generation to 93% below 1990 levels. The annual emissions estimates are based on energy model outputs; the team calculated the estimates following RESNET® protocols.

To reflect projected changes in the grid emissions intensity, the study forecasted emissions from 2025 through 2050, using annual energy consumption estimates from the NREL Cambium dataset.

This forecast is based on the known emissions associated with fossil fuel use and the projected CO_2e emissions associated with electricity use in Massachusetts over the next 25 years, based on the ISO New England grid region from the 2024 Cambium dataset.

In this section, the stacked bar figures show the forecasted operational carbon emissions in five-year blocks. The amount of carbon emissions in each five-year period decreases over time, as the electrical grid is expected to improve. The corresponding whisker plots show the cumulative total of operational carbon emissions after 25 years.

On average, the findings forecast townhomes to produce the least amount of operational carbon emissions (76.2 tons) of all housing types, and single-family detached homes with at least two stories the highest (137.1 tons). Single-family detached homes with only one story (91.0 tons) are expected to produce 34% fewer operational carbon emissions than those with at least two stories (Figure 23).

Figure 22: 25-Year Forecast of Cumulative Operational Carbon Emissions by Home Type (Tons CO_2e)

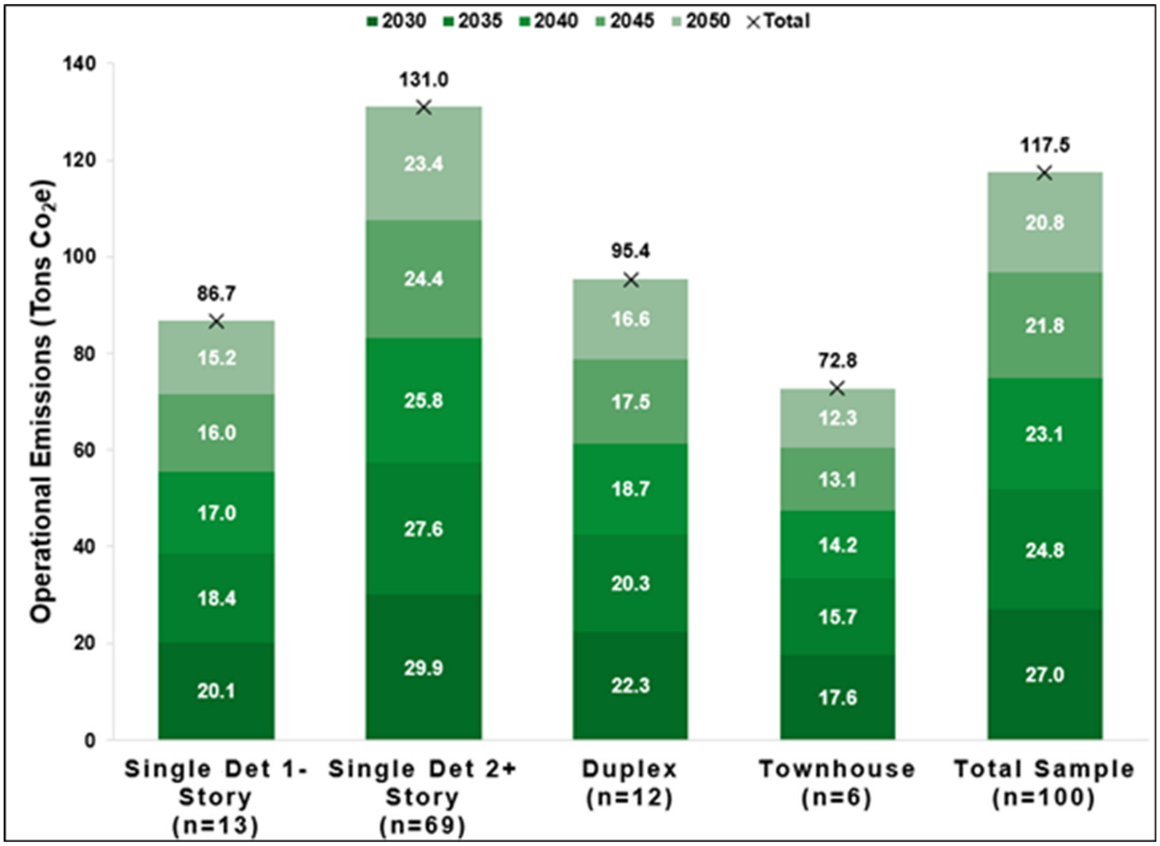
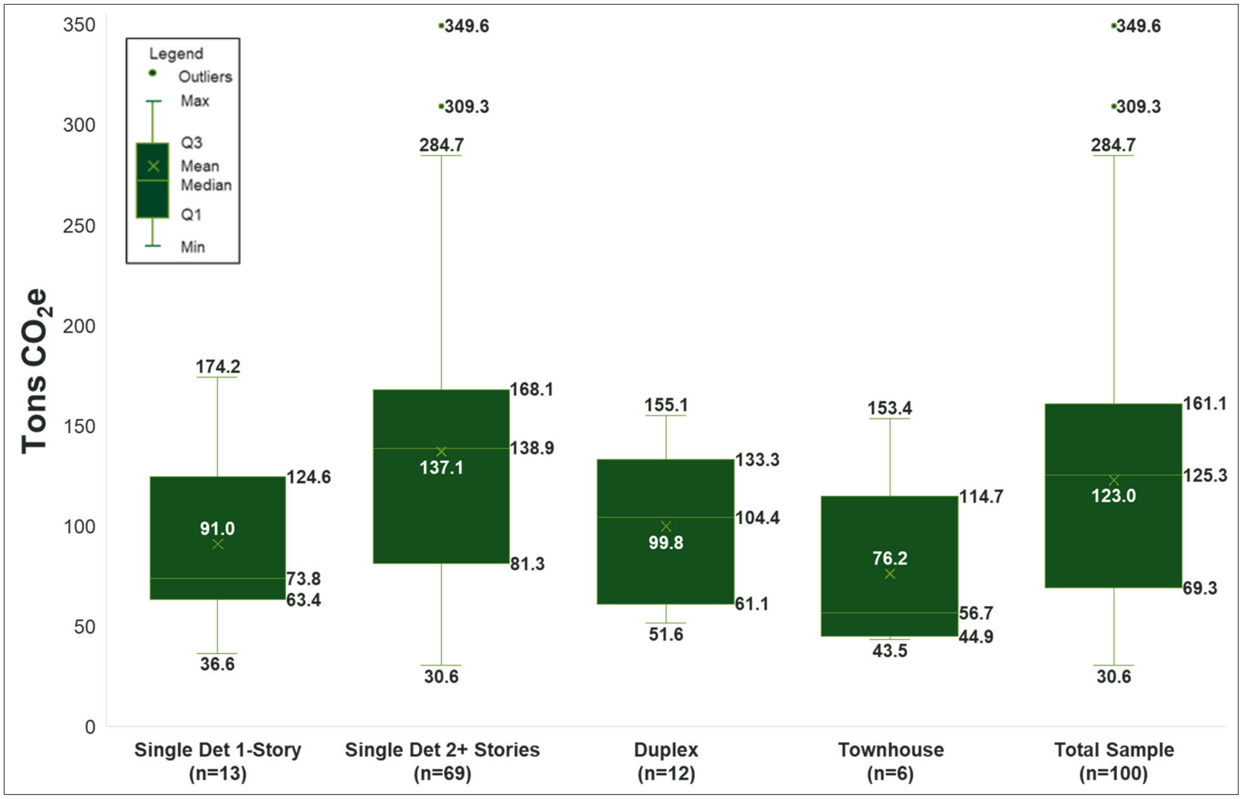


Figure 23: 25-Year Forecast of Cumulative Operational Carbon Emissions by Home Type (Tons CO_2e)



On average, all electric homes are forecasted to produce the least amount of operational carbon emissions (57.7 tons), and all fossil fuel homes the highest (180.6 tons). This difference is amplified by the expectation that the electric grid will become cleaner over time, while fossil fuel emissions will remain constant. Note: All electric homes are projected to emit an average of 14.9 tons in 2026–2030, compared to the same homes emitting 8.0 tons in 2046–2050.

Figure 24: 25-Year Forecast of Cumulative Operational Carbon Emissions by Fossil Fuel Use (Tons CO_2e)

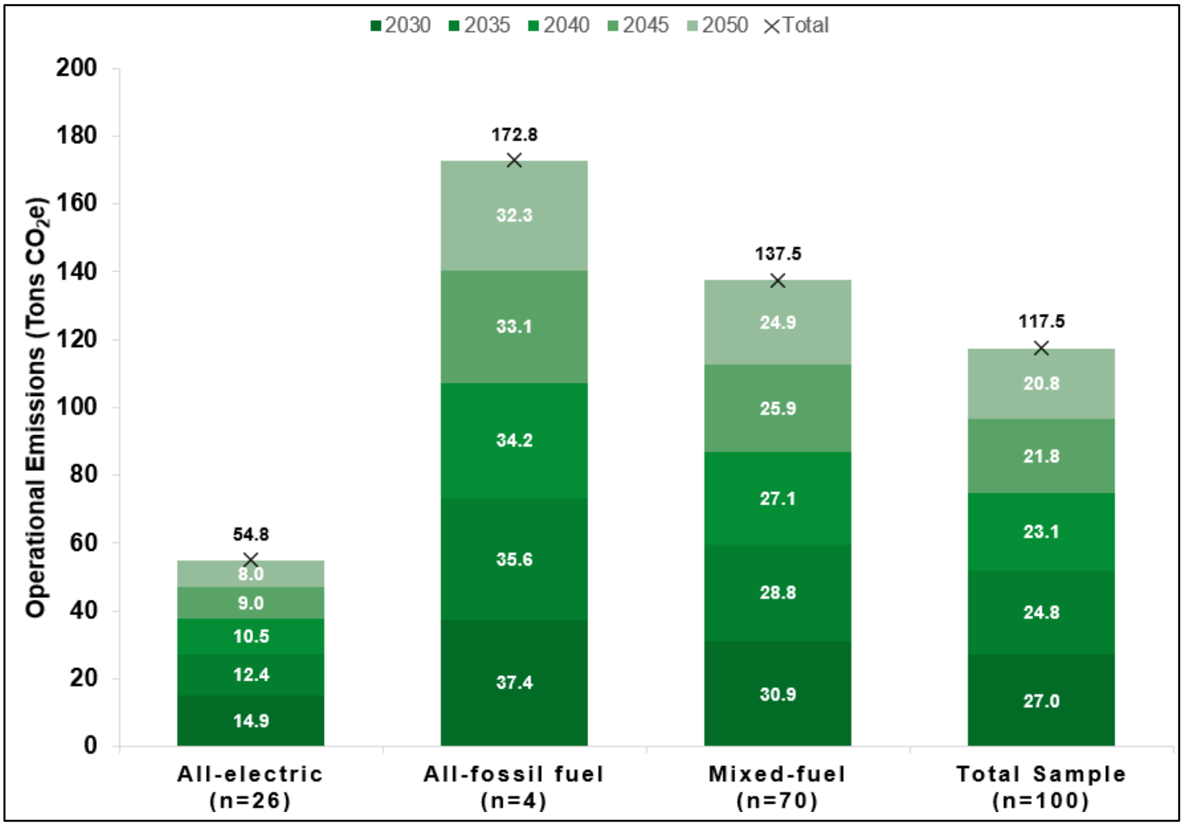
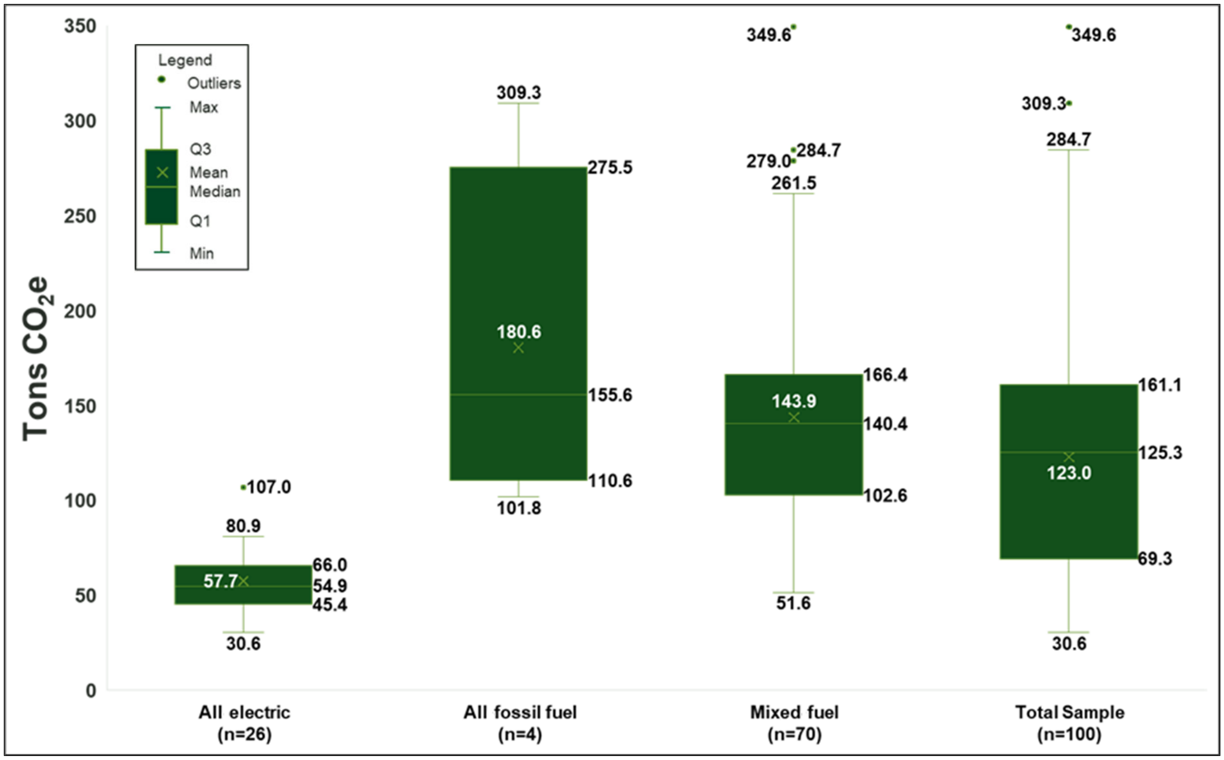


Figure 25: 25-Year Forecast of Cumulative Operational Carbon Emissions by Fossil Fuel Use (Tons CO_2e)



Cumulative Embodied Carbon and Operational Carbon Emissions

Considering upfront embodied carbon emissions offers a one-time opportunity to limit potentially significant carbon impacts from new construction. This is a priority due to the lack of awareness and action in the broader market, but operational emissions will always matter for structures that are built to operate over lifespans measured in decades. The following section presents estimates of total cumulative carbon emissions from operational and embodied carbon, including comparisons of how the two types of emissions contribute to overall emissions over time. This section also incorporates the estimates of ECE for MEP equipment installed in the sample homes. Additionally, this section forecasts operational and embodied emissions over the next 25 years to look at the long-term emissions impacts.

The total carbon emissions associated with residential new construction are analyzed as follows:

- Total carbon emissions comparing embodied carbon emissions and operational carbon emissions over a 25-year period, segmented by home type.
- Comparison of the carbon usage intensity (CUI) of homes under various scenarios of high and low emissions over a 25-year period.

Overview of Total Carbon Emissions: 25-Year Outlook

This subsection presents an overview of overall home carbon emissions. These statistics combine home ECE, including building envelope and MEP emissions[23], and OCE.

Townhomes had the lowest total carbon emissions in our sample, with 26% lower MEP-related ECE, 32% lower building enclosure ECE, and 38% lower operational carbon than the overall averages. Single-family detached homes with at least two stories produce the highest total carbon emissions, with 9% higher MEP embodied carbon, 6% higher building embodied carbon, and 11% higher operational carbon than the overall averages.

When normalized by conditioned floor area, single-story detached homes produce the highest total carbon emissions, with 7% higher MEP embodied carbon, 26% higher building embodied carbon, and 5% higher operational carbon than the overall averages. Duplexes have the lowest total carbon emissions per conditioned floor area, with 2% lower MEP embodied carbon, 7% lower building embodied carbon, and 9% lower operational carbon than the overall averages.

[23] Not including replacement materials.

Figure 26: Average 25-Year Carbon Emissions (Tons CO_2e)

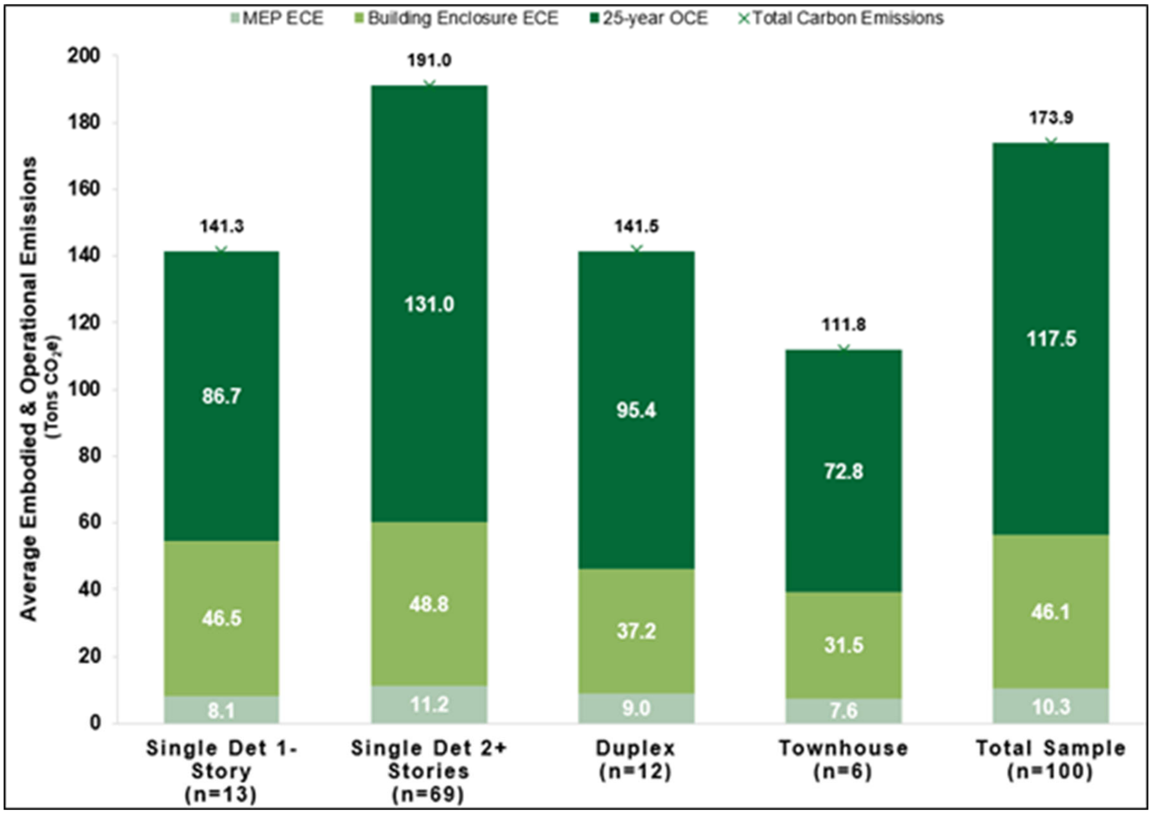
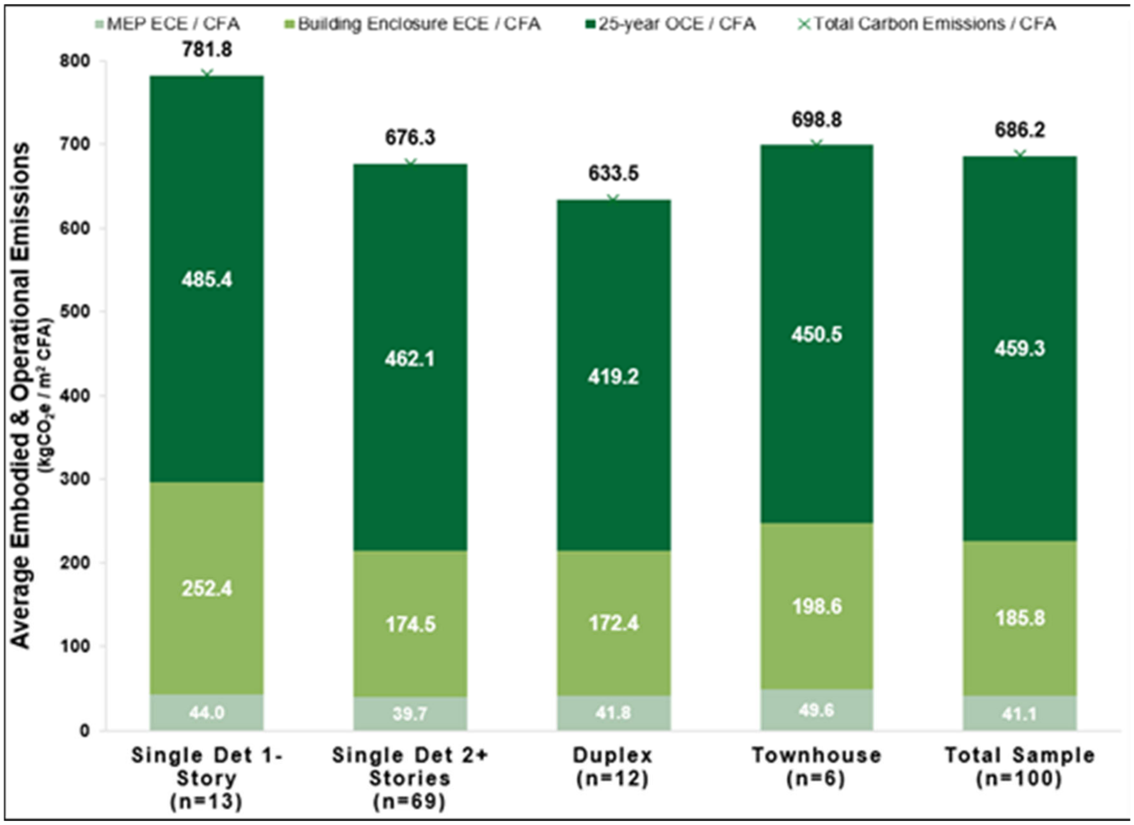


Figure 27: Average 25-Year Carbon Emissions by Building Area (kg CO_2e/m^2 CFA)

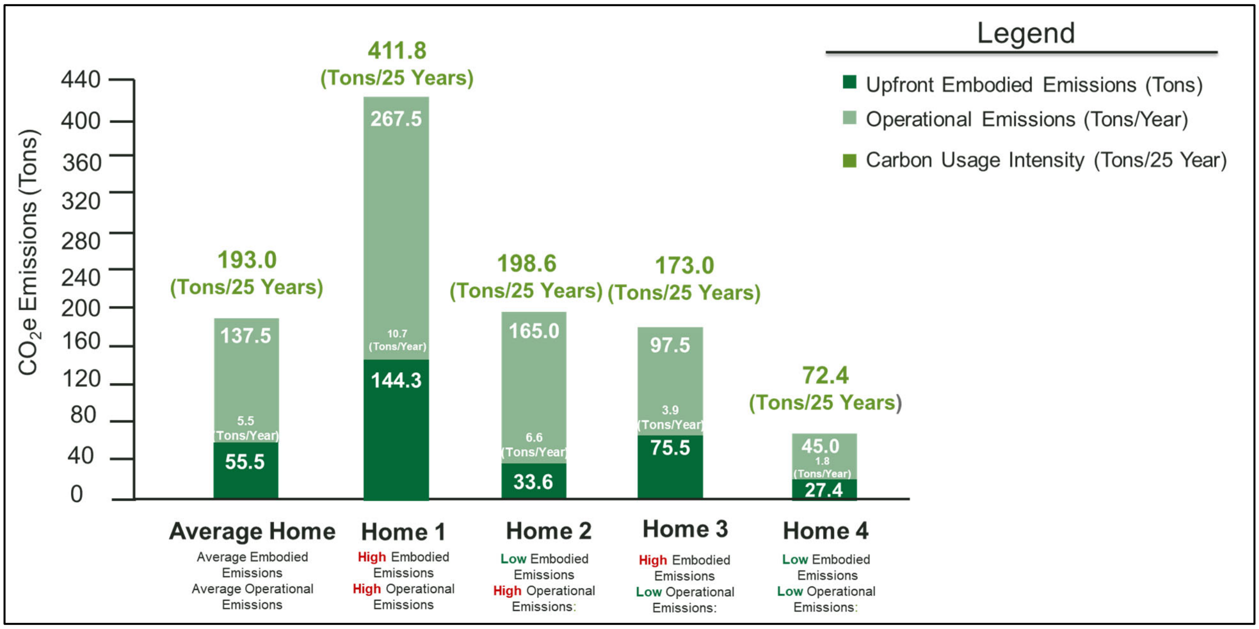


Carbon Intensity Over Time By Emissions Type

The study team's focus on upfront ECE comes with an acknowledgement that locking in lower operational emissions by ensuring structures operate efficiently over their lifespans remains vital to holistic building decarbonization. Addressing embodied carbon with low-carbon solutions during construction is crucial, but an inefficient home can still produce high emissions over the lifespan of a structure. To illustrate this, the team took four homes with different ECE and OCE profiles and forecasted their overall carbon use intensity over a 25-year period (Figure 28). The figure also includes a prototype home with the average ECE and OCE observed in the sample for comparison. A home with lower-than-average upfront ECE but higher than average operational emissions can be more carbon intensive over 25 years than a home with higher-than-average ECE and lower operational emissions. Improvements can be expected in operational efficiency in building stock over time—due to renovations to the building shell or replacement of HVAC equipment with newer, more efficient units—but these changes bring their own embodied carbon impacts. Forecasting the extent of operational efficiency improvements is challenging.

Addressing both ECE and OCE in the design phase is an essential step for creating new buildings that help Massachusetts meet its aggressive 2050 climate goals. In moving builders toward low-carbon building materials, there are opportunities to value-engineer certain trade-offs, like weighing spray foam building shell R-Values (thermal performance) against low-carbon or biogenic insulation alternatives.

Figure 28: Forecasted Carbon Usage Intensity for Example Homes



Conclusion

This study has provided deep insight into the carbon intensity of single-family new resident construction while highlighting practical, realistic recommendations to integrate embodied carbon accounting into traditional building efficiency measurement and reporting. This report summarizes a robust set of data, insights, and early recommendations, and it reflects the limitations of an effort constrained by time, resources, and the evolving nature of carbon accounting tools and standards. The study team hopes that these findings represent the beginning of a much more robust process of quantifying and mitigating embodied carbon emissions in the home-building sector. By leveraging existing industry infrastructure along with familiar tools, such as Ekotrope and BEAM, this study illustrates a scalable and practical pathway to more holistic carbon accounting that captures both operational and embodied carbon emissions. Scaling up and refining the data collection processes used in this report to benchmark embodied carbon in Massachusetts new construction will provide new opportunities for embodied carbon mitigation through policy and programmatic interventions.

The study's findings also point to a wide range of opportunities for continued research and solution generation. These include:

- Conducting deeper sensitivity analyses on material substitution
- Evaluating the incremental costs of low-carbon and biogenic material substitution
- Identifying specific market barriers to adoption
- Exploring how to accelerate uptake through policy and incentive structures.

There must be better understanding of the awareness and attitudes of key market actors like builders and developers regarding low-carbon and biogenic building materials. The success of state climate goals also requires substantial progress in decarbonizing existing buildings. The existing buildings sector offers substantial opportunity for addressing embodied carbon but also presents unique challenges compared to new construction. More research can help identify when and how to integrate low-embodied carbon considerations into renovations and additions, helping to ensure more holistic decarbonization in existing buildings.

This moment marks a critical turning point, not *if*, but *how and where* utility programs will incentivize embodied carbon tracking and integrate the processes into international building codes. The role of the HERS® Rater stands to grow along with awareness and adoption of embodied carbon assessments. This study has demonstrated how HERS® Raters, with new tools and training, can help developers, builders, and homeowners optimize both operational and embodied carbon reductions when designing and building a home, relying on common-sense substitutions within building assemblies. Coordinating workforce training, utility incentive programs, and state and local policies is essential to helping overcome market barriers around awareness, understanding, and potential cost concerns. Synergies across all platforms will build momentum toward market transformation, establishing materials embodied carbon mitigation within standard building practices.

Resources

The following links lead to additional information, resources on embodied carbon, and past studies.

- NEHERS
- Vancouver Part 9 Material Emissions Benchmark Report
- Nelson: Embodied Carbon Regulation in Canada's Building Codes
- Toronto: Embodied Carbon Pathways for Canadian Residential Equipment
- Report - NRCan Study - BUILDERS FOR CLIMATE ACTION

Appendix A Detailed Methodology

This appendix provides additional information regarding the study methodology, including details on data collection and the tools created for this study.

Embodied Carbon Assessment and RESNET® Energy Modeling Data Mapping and Tools

Given the significant overlap between data already collected by HERS® Raters for energy modeling and inputs needed for embodied carbon assessments, the team designed this study to build upon existing HERS® Rater workflows. The first phase of the study focused on identifying the additional data needed to estimate the embodied carbon of newly constructed homes from those that are already collected using RESNET® energy modeling guidelines.

To streamline data collection and identify gaps, the study team conducted a structured comparison of the input requirements for operational energy modeling and embodied carbon assessments. While the initial scope focused primarily on embodied carbon associated with the building envelope, the study later expanded to include embodied carbon from components that comprise mechanical, electrical, and plumbing (MEP) systems. To inform this expanded scope, the study team referenced RESNET's draft Standard 1550[24], which provides a default table of GWP values for MEP-related materials and equipment. The team incorporated the associated data needs into the comparison framework.

This process included:

1. Compiling a detailed list of data inputs required for RESNET-compliant HERS® ratings, using Ekotrope energy modeling software.
2. Compiling a corresponding list of inputs required for an embodied carbon assessment, using the BEAM tool's data structure.
3. Conducting an analysis to identify overlapping data fields and determining any supplemental data collection or reporting requirements.

The goal was to align the two modeling processes wherever feasible, streamline data collection, reduce redundant data entry, and minimize the additional burden on participating HERS® Raters to create an embodied carbon assessment.

[24] RESNET Standard 1550 is a draft methodology released for public comment on November 22, 2024. It establishes a consistent framework for calculating and reporting embodied carbon emissions associated with residential buildings. The standard covers both envelope and MEP components using data aligned with existing energy rating processes. https://www.resnet.us/about/standards/minhers/draft-pds-01-resnet-1550-embodied-carbon/

Ekotrope and BEAM Tool Integration

The second phase of the study focused on developing a methodology to integrate data from Ekotrope into the BEAM tool. The primary objective of the integration was to automate the transfer of relevant building design and material characteristics and quantities from energy models into an existing embodied carbon framework, streamlining the workflow, and reducing the potential for manual data entry errors. This was critical to understand how to develop and link industry tools together to support practitioners, such as HERS® Raters, to expand the purview of embodied carbon and operational emission profiles for a building.

To implement this integration, the study team developed a BETA integration worksheet, using data mapping protocol to align Ekotrope inputs and outputs with data fields required by the BEAM tool. The Ekotrope data imported into the integration worksheet captured key elements including building envelope assemblies (e.g., walls, roofs, windows) and foundation types, with their associated dimensions, and major mechanical systems. The team exported Ekotrope data into a standardized format and translated into BEAM-compatible inputs using a customized integration worksheet. Users entered additional data not captured by Ekotrope directly into the integration worksheet and subsequently transcribed into BEAM to develop an embodied carbon assessment. This includes data like interior walls and structural assemblies or garage components not directly adjacent to the thermal envelope.

To reduce user burden, the integration worksheet included pre-populated default values for common material assemblies based on industry standard practices. The user could manually override these values with project-specific details if known. Where duplicate parameters (e.g., area and perimeter) were required across multiple fields, the integration worksheet automatically populated consistent values from Ekotrope data or user inputs to avoid redundancy and improve efficiency.

The semi-automated transfer process involved exporting structured data from Ekotrope into the intermediary integration worksheet. Users then completed any missing fields before transcribing the data into the BEAM tool to complete the embodied carbon assessment. This process was applied to all building envelope components, regardless of whether the space was conditioned.

The MEP components followed a slightly different process: while Ekotrope data was similarly mapped into an MEP-specific integration worksheet, embodied carbon calculations for MEP systems were performed within that worksheet rather than in BEAM, due to BEAM not supporting MEP material emissions by default. The study used default GWP values from RESNET's draft Standard 1550.

To validate the integration process, the study team conducted spot checks, reviewed outputs from a sample of homes, and compared model results to ensure consistency. While trial participants were responsible for transcribing integration worksheet data into BEAM, the workflow was designed as a first iteration toward a more automated, software-to-software integration for future implementation. Full automation of the process may emerge out of RESNET Standard 1550 as software platforms respond to the new market. Additional funding and resources are critical to further integration.

In assessing the development of the software integration workflow in this study, the study team assumes that approximately 60%–70% of the data inputs required for the BEAM estimator tool are actively collected during the HERS® rating and energy modeling process. The precise proportion varies depending on factors, such as home design complexity, specific home features (e.g., foundation types, attached garages, and overall geometric complexity), assemblies of the home beyond the thermal envelope (e.g., interior or partition walls, attached garages, unconditioned spaces, additional structural components), and the availability of detailed material specifications.

However, even complex homes do not utilize every type of assembly available within BEAM. Note that these are estimates leveraging an integration workflow developed specifically for this study, and each embodied carbon assessment may have a different percentage of similar data collected as is required for an energy model.

Overall, these findings indicate that at least half of the necessary inputs for embodied carbon assessments can likely be integrated from Ekotrope in its current state. By aligning key data fields between the two tools, documenting procedures, and supporting user workflows, the integration improved data consistency, reduced transcription errors, and laid foundational groundwork for embedding embodied carbon assessments within standard HERS® Rater practices.

Below is an example screenshot of the Ekotrope to BEAM BETA building envelope integration worksheets developed as part of this study effort. The light grey cells include data integrated directly from Ekotrope or automatically calculated. Green cells indicate data that may require user inputs, depending on whether the home includes those features.

Figure 29: Example of Ekotrope to BEAM BETA Integration Worksheet for Foundation Wall Entries

FOUNDATION WALLS

Dimensions

	Area (ft2)	Perimeter (ft)	Thickness (in)	Instructions / Info
Encloses Conditioned Space	1068.5	114.5	10	**Rater:** Confirm wall thickness. **Ind. Avg.:** 8" thick. If Depths over 8 ft., than 10" thick - Please verify **Note:**
Encloses Conditioned Crawlspace	428	107	10	
Encloses Unconditioned Space	270	30	10	**Rater:** Make sure to include any foundation walls enclosing unconditioned space or shared with an attached structure. Exclude any window area and garage wall area.
TOTAL AREA	**1766.5**		**10**	

Foundation Walls Breakdown

	Type	Size	Area (ft2)	%	Additional Factors			Instructions / Info
Concrete	3001-4000 psi	Standard mix / NRMCA	1766.5	100%	Thickness :	10	in	
Rebar	Steel Reinforcing Bars	#5	1766.5	100%	Total Rebar Length :	1,325	ft	**Ind.Avg.:** 24" vertical Spacing / 4' horizontal spacing (Area * 0.75)
Membrane	Polyethylene sheet - 6 mil		1496.5	85%				
Framing	Steel	2", 24OC		0%	Framing Spacing:	24	in	**Rater:** If "finished unconditioned basement" - add framing, insulation, int.
Cavity Insulation	R-10 Rigid	2" Foamular NGX	396	22%	R-Value:	10		**Rater:** Confirm cavity insulation type area and R-value
Rigid Insulation	R-10 rigid	r10 rigid	1416	80%	R-Value:			**Rater:** Confirm Rigid insulation type. **Ind. Avg.:** XPS , R-10
Interior Cladding	na			0%				**Ind.Avg.:** Drywall 1/2"

The following figures provide examples of the MEP integration worksheets that the participant Raters completed to estimate the MEP-related ECE. As shown in the images, green cells were manual inputs that the Rater completed, while the light grey boxes were integrated directly from Ekotrope or automatically calculated.

Figure 30: Mechanical Integration Worksheet Example

Mechanical			Subtotal :	5768 Kg CO2e
Heating and Cooling Equipment				
Natural Gas Furnace	Equip capacity :	0	kBtu capacity	0
Ducted Heat Pump + Compressor	Equip capacity :	5	tons	3420
Mini-Split Heads + Compressor	Equip capacity :	1	tons	720
Central A/C Compressor	Equip capacity :	0	tons	0
Electric Aux Heater	Equip capacity :	0	kBtu capacity	0
Electric Baseboard	Equip capacity :	0	kBtu capacity	0
Gas boiler	Equip capacity :	0	kBtu capacity	0
Air-to-water heat pump	Equip capacity :	0	tons	0
Ground source heat pump equipment	Equip capacity :	0	tons	0
Ground source heat pump ground loop borehole	Li. feet of borehole :	0	linear foot	0
Other Equipment				
Fan coil	Equip capacity :	0	tons	0
Exhaust Fan (e.g. bath, range hood)	Number of Fan :	0	unit	0
Balanced ventilation with energy recovery	Number of units:	1	unit	350
Pump, small (e.g. circulator)	Number of small pump :	0	unit	0
Pump, large (e.g. sump, booster)	Number of large pump :	0	unit	0
Distribution				
Ductwork heating and cooling	Duct area, sq ft	380	sq ft of duct	912
Ductwork heating and cooling insulation	Duct area, sq ft	0	sq ft of duct	0
Ventilation supply distribution ductwork is shared with heating/cooling distribution		☐		
Ventilation return distribution ductwork is shared with heating/cooling distribution		☐		
Ductwork ventilation	Duct area, sq ft	152	sq ft of duct	365
Ductwork ventilation insulation	Duct area, sq ft	8	sq ft of duct	1
Hydronic radiant distribution	Sq ft radiant surface :	0	sq ft	0
Hydronic baseboard	Equip capacity :	0	kBtu	0

Participant Recruitment and Training

To execute this study, the study team utilized the NEHERS Alliance network to recruit HERS® Raters through its professional network. The intent was to leverage HERS® Raters' existing roles in the residential new construction industry—as energy modelers and energy-efficiency advisors—to conduct embodied carbon assessments. This approach allowed the study team to build on work in progress for RESNET® energy ratings and code compliance, including the development of energy models to estimate annual operational energy consumption. As a result, the study achieved greater efficiency in terms of time, cost, and practical implementation.

NEHERS conducted participant recruitment via email outreach to its Rater network. Participation requirements included:

- Completion of a three-part training series on embodied carbon assessments and the Ekotrope–BEAM integration:
  - **Session 1:** *Embodied Carbon 101*. A self-paced, recorded introduction to the embodied carbon of materials and the study framework.
  - **Session 2:** *Ekotrope–BEAM Workflow Integration*. A live 1.5-hour training on using the customized worksheet integration.
  - **Session 3:** *Developing the Final BEAM Model.* A live one-hour session focused on completing and submitting final assessments.
- Completion of a minimum of five embodied carbon assessments using homes that had recently received a RESNET®-certified HERS® rating and a corresponding energy model displaying the as-built conditions.
- Responsiveness to Quality Assurance/ Quality Control (QA/QC) inquiries from the study team throughout the study.

To compensate for the additional workload, including training and modeling tasks, participant HERS® Raters received $500 per completed assessment. A total of 15 HERS® Raters participated in this study.

Energy Modeling—Ekotrope

Modeling Tools

Ekotrope Energy modeling software is a cloud-based, RESNET®-approved software platform used to model home energy performance and provide official HERS® ratings.[25] HERS® Raters in Massachusetts use Ekotrope often; it provides support for assessing energy code compliance for homes built in stretch-code communities. It estimates annual energy consumption based on detailed home characteristics using hourly simulations that incorporate local climate data. Ekotrope also provides operational GHG emissions estimates based on energy consumption by fuel type. These calculations follow RESNET® protocols and incorporate carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) emission factors, using grid-based emissions data from National Renewable Energy Laboratory (NREL) 2021 Cambium database.[26,27,28] These results are reported as the RESNET® Carbon Index score, which is a rating scale like the HERS® score.

Study participant HERS® Raters primarily used previously developed, conventional, RESNET®-registered energy models for each of the 100 homes in the study using Ekotrope software and standard RESNET® protocols. The models align with those commonly produced for energy code compliance, energy-efficiency program participation, and baseline studies. To ensure consistency across Raters, the modeling used as-built conditions and documentation to input building-specific details and determined equipment efficiencies and followed standardized RESNET® assumptions for modeling aspects such as default occupancy levels, thermostat setpoints, and ventilation rates. The homes had been RESNET® Registered, meaning they were subject to the HERS® Rating Quality Assurance process and requirements.[29,30] The team used Ekotrope Version 4.2.3, which complies with ANSI-301-2019.[31] The modeling did not involve custom overrides or non-standard software configurations beyond what is permitted under standard HERS® rating procedures.

Because the projects were certified by RESNET® and under the QA/QC protocols of HERS® 301, all of the QA/QC efforts in this study were focused on the embodied carbon assessments and related data inputs. Energy model inputs were reviewed by the QA team for completeness and consistency but were not subject to full independent validation by the study team.

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25 https://www.ekotrope.com/

26 https://www.ekotrope.com/blog/ekotrope-rater-now-supports-resnets-carbon-rating-index

27 https://view.officeapps.live.com/op/view.aspx?src=https%3A%2F%2Fwww.resnet.us%2Fwp-content%2Fuploads%2FFS_301-2019AdndmD_webpost.docx&wdOrigin=BROWSELINK

28 Gagnon, Pieter, Elaine Hale, and Wesley Cole. 2022. "Long-Run Marginal Emission Rates for Electricity - Workbooks for 2021 Cambium Data." NREL Data Catalog. Golden, CO: National Renewable Energy Laboratory. Last updated: January 21, 2025. DOI: 10.7799/1838370.

29 https://standards.resnet.us/docs/904-responsibilities-and-requirements-for-rating-quality-assurance-providers

30 https://standards.resnet.us/docs/102-accreditation-criteria-for-rating-quality-assurance-providers

31 https://www.resnet.us/wp-content/uploads/archive/resblog/2019/01/ANSIRESNETICC301-2019_vf1.23.19.pdf

Embodied Carbon Emissions Assessments

BEAM Estimator Tool

Builders Emissions Accounting for Materials (BEAM) estimator tool is a free, publicly available tool developed by Builders for Climate Action. The BEAM tool estimates embodied carbon emissions for low- and mid-rise residential buildings. [32] BEAM leverages a large material library and focuses on area-based inputs to estimate embodied carbon from materials, largely aligning with a typical HERS® Rater experience. BEAM has been used to conduct other studies exploring embodied carbon emissions in residential new construction. It supports analysis of material and assembly choices by applying GWP factors from EPDs to user-entered material quantities and is often used to create a whole-building ECE estimate. BEAM focuses on the building structure, enclosure, and interior partitions, and includes biogenic carbon accounting for qualifying materials. The tool does not include emissions for fixtures, appliances, surface finishes, or site work, and does not natively estimate mechanical, electrical, and plumbing (MEP) material emissions. As discussed above, MEP-related embodied carbon estimates were developed using the RESNET® draft Standard 1550 default GWP values. This was a distinct effort by Builders for Climate Action for this study, separate from the existing BEAM estimator tool. The study team incorporated this as a part of the integration process, developing a specific integration worksheet for this study.

The BEAM Estimator tool contains an extensive materials library with associated GWP data.[33] The tool calculates estimates of ECE of a product or assembly by applying the GWP for each material and scales that to the quantity of material used. GWP values are primarily sourced from product-specific and industry-average EPDs.[34] When EPDs are unavailable, BEAM defaults to average GWP values derived from peer-reviewed lifecycle assessments for the broader material class.

Users input dimensions for major building assemblies and then select the product type and any adjustments to the default quantity calculations. In cases where the specific product was known, and that product had an EPD in BEAM, those specific GWP values were used—in absence of this criteria industry-average, GWP for a given EPD product class were used.

GGGGGGGGGG EEEEEE (kkkk EECC2ee) = MMMMMMeeGGMMMMMM QQQQMMQQMMMMMMQQ x MMMMMMeeGGMMMMMM GGGGGG

In addition to gross ECE, BEAM estimates carbon storage in biogenic materials—materials derived from agricultural or forestry residues or other biomass waste streams. When available, BEAM uses EPD data for biogenic carbon flows or estimates the mass of biogenic carbon based on chemical composition data from the Phyllis database.[35] These results are expressed in kg CO_2. The tool also calculates net carbon emissions for these materials, subtracting biogenic storage from the gross emissions. In some cases, net ECE can be negative, indicating that more carbon is stored than emitted. These materials are referred to as *carbon-storing*.

NNeeMM EEEEEE (kkkk EECC2ee) = EEEEMMGGGGMMGGQQGG – BBMMGGkkeeQQMMBB SSMMGGGGMMkkee

[32] https://www.buildersforclimateaction.org/beam-estimator.html

[33] https://www.buildersforclimateaction.org/beam-estimator.html

[34] EPDs are third-party certified reports prepared according to ISO 14025 in addition to either EN 15804 or ISO 21930: 2017. https://www.iso.org/standard/66123.html

[35] Phyllis Database for biomass and waste is managed by the Netherlands Energy Research Center (ECN): https://knowledge4policy.ec.europa.eu/dataset/beo-ecnphyllis_en

It is important to note that BEAM does not automatically assign carbon storage values to virgin timber products, such as framing lumber, plywood, Oriented Strand Board (OSB), trusses, or engineered wood I-joists. While ISO 21930 provides guidance for biogenic carbon accounting, current concerns about emissions from logging operations, soil disturbance, and lost forest carbon potential have led BEAM to exclude storage credits for these materials. [36] In addition, the methodology for the RESNET® draft Standard 1550 excludes carbon storage from virgin wood products.

Embodied carbon estimates for MEPs were calculated separately from the building enclosure in this study; when combined, these estimates show cumulative ECE.

Participant Rater ECE Modeling Workflow

Each of the 100 homes included in the study had already received a HERS® rating. Participating HERS® Raters received training in embodied carbon concepts, the BEAM tool, and the integration process between Ekotrope and BEAM. Raters completed BEAM models for each of their projects and underwent a structured QA/QC process conducted by the study team. Key elements of the QA/QC process included:

- **Initial training QA/QC:** As part of the training, each Rater was required to complete an initial project all the way through transcription from the integration worksheet to the BEAM tool. This covered energy modeling, data integration, and additional material inputs. The study team reviewed and approved the initial submission before allowing Raters to proceed with additional projects.
- **Project organization:** Each Rater was assigned a dedicated project folder shared with the study team. These folders included a master tracker that listed all required project components. This included architectural drawings, SketchUp models, the integration worksheet, BEAM model, and a link to the Ekotrope energy model. Status updates were logged by the QA team for each project, including QA progress and any required revisions.
- **Project-specific QA worksheets:** The study team developed a customized QA checklist for each project to ensure consistency and completeness. These worksheets identified key home features and flagged corresponding elements for targeted review.
- **Sequential QA process:** The study team reviewed the integration worksheets first, followed by the MEP data, and then the final BEAM model to confirm consistency across data sources. Only projects that passed QA in all three areas were then included in the final results.
- **Final database compilation:** Once a project passed QA, the final BEAM and MEP results were saved in the consolidated project database used for analysis.

Overall, 163 QA/QC checks were completed, with 133 related to the building envelope and 30 related to MEPs.

[36] https://www.iso.org/standard/61694.html

Selected Homes

The study targeted a sample of 100 newly constructed single-family homes in Massachusetts, including both detached and attached homes. Attached home types consist of duplexes and townhomes. This study relied on voluntary participation from HERS® Raters and the availability of completed, as-built projects. Consequently, the sample was shaped by the Raters' ability to provide projects that met specific criteria: homes permitted after January 1, 2023, and before July 1, 2024, with completed HERS® energy models, and sufficient project documentation to support BEAM modeling, such as architectural plans, assembly details, SketchUp models, and material specifications.[37] The overall pool of projects available from participant Raters totaled 170 dwelling units. Projects that lacked adequate documentation were discarded to maintain the targeted 100-home sample size.

To approximate the diversity of the Massachusetts new construction market, the study team drew on professional expertise and aggregated data from Ekotrope models of recently constructed homes across the state. The team set out to capture a representative cross-section of home types, mechanical system configurations, HERS® scores, floor areas, and fuel types—particularly with an emphasis on including all electric homes. These factors were then prioritized to better understand how equipment and fuel choices influence embodied emissions from both the building envelope and mechanical systems, and their broader impact on total home-related carbon emissions.

The sample design also aimed to ensure diversity in physical and energy-efficiency characteristics. Sample goals and outcomes achieved included:

- A balanced distribution of home energy performance, with approximately 50% of homes having HERS® scores greater than or equal to 51, and 50% were less than or equal to 50—with no homes having HERS® scores below 39.
- A maximum of 20 attached homes (duplexes or townhomes).
- A minimum of ten homes with an attached garage.
- Variation in heating equipment types and fuel sources.
- Representation of different foundation types.

Tables 4-6 summarize the general characteristics of the homes within the sample, detailed by home type, a data segmentation commonly used throughout this report. The average home in the sample had a HERS® score of 49.6, with nearly 2,900 square feet of conditioned floor area (CFA) and included three bedrooms and two stories. These characteristics are broadly consistent with findings from the recent *MA23R60 Baseline study*, which analyzed thousands of recently constructed homes in Massachusetts and reflects prevailing trends in the residential new construction market.[38] The general characteristics, equipment saturations, and efficiency details are provided in detail by home type and by home fuel type in Table 4.

[37] Homes permitted in this time frame will fall within the 2023 Stretch Code update. https://www.mass.gov/info-details/building-energy-code

[38] Single-Family and Low-Rise Multifamily New Construction Baseline Study (MA23R60), NMR Group Inc. on behalf of the Massachusetts Program Administrators. September 30, 2024. https://ma-eeac.org/wp-content/uploads/MA23R60_RNC-Baseline-Report_2024.09.30.pdf

Table 4: Sample Characteristics

	Single Det 1-Story	Single Det 2+ Stories	Duplex	Townhouse	Total Sample
n-value (sample size)	*13*	*69*	*12*	*6*	***100***
Average CFA	2,133	3,220	2,448	1,668	**2,893**
Average number of bedrooms	2.3	3.6	2.4	3.2	**3.2**
Average HERS® score	50.2	49.6	48.8	51.0	**49.6**
Average Carbon Index	71.2	71.6	63.3	60.8	**69.9**
Homes with attached garages	69%	64%	75%	50%	**65%**
Homes that are all electric	39%	19%	33%	67%	**26%**
Homes that are all-fossil fuel	8%	3%	0%	17%	**4%**
Homes that are mixed fuel	54%	78%	67%	17%	**70%**

One notable deviation between this study's sample and the *MA23R60 Baseline study* is the significantly higher prevalence of all electric homes. In this study, 26% of homes were fully electric compared to just 4% in the *MA23R60* sample. Similarly, 40% of homes in this study used electricity as the primary heating source, compared to only 9% in the *MA23R60 Baseline study*. In the *MA23R60* study, most single-family homes (85%) used gas or propane furnaces, while just over half (53%) of homes in this study's sample used furnaces.

Table 5: Primary Heating Fuel Type

	Single Det 1-Story	Single Det 2+ Stories	Duplex	Townhouse	Total Sample
n-value (sample size)	*13*	*69*	*12*	*6*	***100***
Electric	6%	24%	6%	4%	**40%**
Natural Gas	5%	23%	6%	2%	**36%**
Propane	2%	22%	0%	0%	**24%**

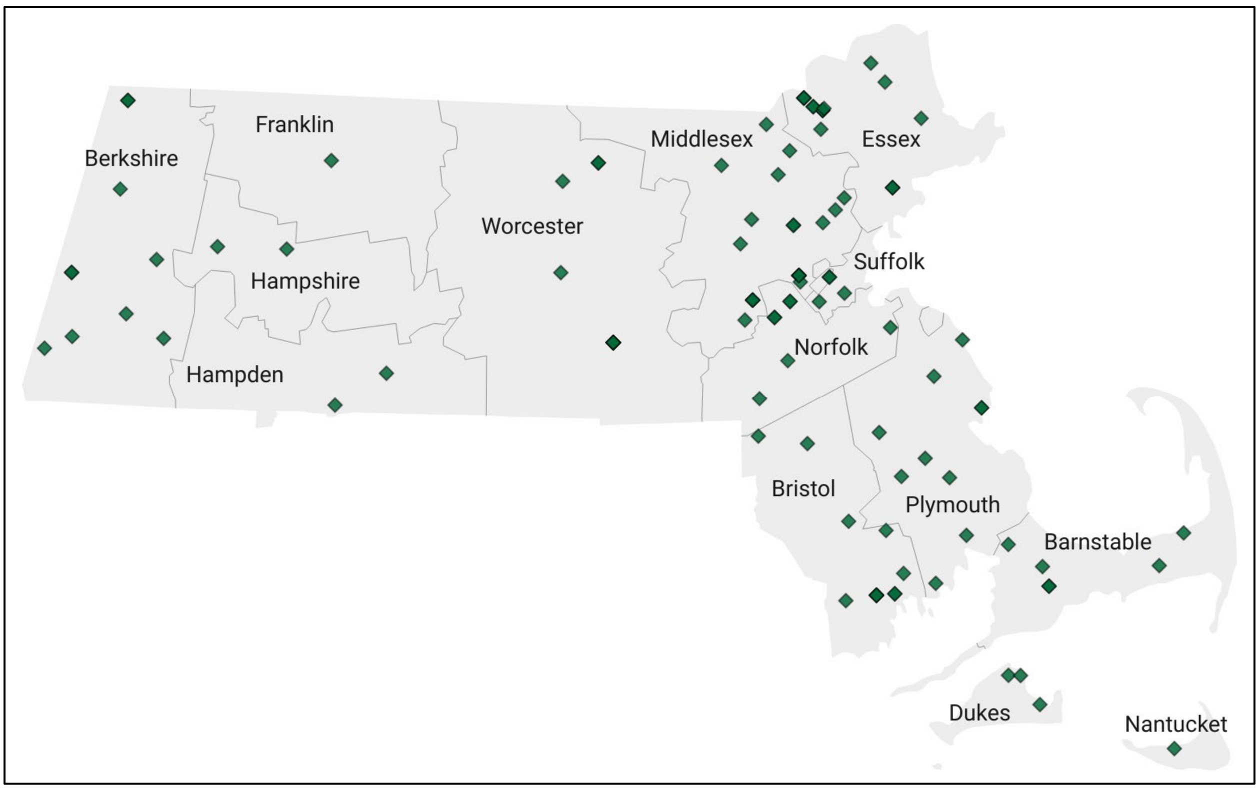
Over half of the sample had either a conditioned or unconditioned basement, while nearly two-fifths of homes had multiple foundation types. Only 15 homes were built on a slab, with a few homes in the sample built over crawlspaces and garages. Comparisons to the MA23R60 study were unavailable for foundation type.

Table 6: Sample Foundation Type Characteristics

	Single Det 1-Story	Single Det 2+ Stories	Duplex	Townhouse	Total Sample
n-value (sample size)	*13*	*69*	*12*	*6*	***100***
Conditioned basement	6%	20%	4%	1%	**31%**
Unconditioned basement	3%	21%	0%	1%	**25%**
More than one type	1%	19%	1%	0%	**21%**
Slab	1%	3%	7%	4%	**15%**
Open crawl space/raised floor	0%	4%	0%	0%	**4%**
Over Garage	2%	1%	0%	0%	**3%**
Enclosed crawl space	0%	1%	0%	0%	**1%**

Figure 31 shows the location of the sampled homes. Most of the sampled homes are in eastern Massachusetts, but western and central Massachusetts are also represented in the sample. The only geographic target included in the study parameter is that homes were built in Massachusetts.

Figure 31: Sampled Home Locations in Massachusetts



Analysis and Reporting

The analyses presented throughout the main report are categorized by home type. As previously described, the study was limited to single-family detached and attached homes. Within this group, homes are further segmented based on structural configuration: detached homes with a single story above grade; detached homes with two or more stories above grade; duplexes; and townhomes. Additional data segmentations include:

- Home fuel usage: segment results based on fuel type, determined by the primary energy sources for heating, domestic hot water, cooking, and laundry.
- Homes are grouped into three categories: all electric homes, all fossil fuel-based homes, and mixed fuel homes.
- Primary heating type: segments results based on the primary heating equipment and fuel used in the home (e.g., air-source heat pumps, gas furnace, propane furnace).
- Foundation type: segments results based on the foundation type of the home (e.g., conditioned basements, unconditioned basements, on-grade slabs)

All results presented in this report are unweighted and reflect the raw distributions of the sample.

Analysis of Embodied Carbon Emissions Data

The study team used the BEAM estimator model outputs to estimate the gross and net ECE associated with the construction of the 100 homes included in this study.

In addition to BEAM outputs, emissions estimates associated with MEP systems were accounted for using methodologies consistent with RESNET® draft Standard 1550. These values were integrated into the overall material emissions profile for each home.

To enable comparison and contextualize the results, the embodied carbon data are presented in metric tons of CO_2e, and when normalized are presented in kg CO_2e per square meter of conditioned floor area (CFA). This aligns with similar reporting of emission metrics associated with embodied carbon in other reports. To make the data more accessible to readers who may be less familiar with metrics normalized by square meters, we also show the percentage of emissions that are associated with various components of the home.

Analysis of Operational Carbon Emissions and Annual Energy Consumption

The study team used Ekotrope energy model outputs to estimate both the operational carbon emissions and annual energy consumption for the 100 homes included in this study. These outputs reflect the as-built conditions of each home using RESNET-compliant modeling procedures. Key outputs from the models include total and fuel-specific annual energy consumption, estimated annual GHG emissions, mechanical system types and specifications, building envelope insulation values, HERS® Index scores, and CO_2 Index scores.

Cumulative Operational Carbon Emissions Forecast: 2025–2050

As part of this study, the team developed operational emissions forecasts to estimate CO_2e impacts for the period from 2025 through 2050. Annual energy consumption estimates were used as the basis for projecting operational emissions over this period of time. To reflect evolving emissions factors associated with electricity generation, the NREL 2024 Cambium dataset was utilized to construct a time series of grid emission factors specific to the New England ISO.[39] The study team attempted to align these factors with the methodologies used by RESNET® for calculating carbon emissions in energy modeling tools such as Ekotrope. The goal was to create a consistency between operational energy modeling and emissions estimation.[40] However, it should be noted that this study was not able to apply hourly emissions estimates, rather the annualized long-run marginal emissions rate were applied to the annual energy consumption data.

Electric end-use consumption was converted to CO_2e emissions using the projected long-run marginal grid emissions factors for each year from 2026 through 2050, while emissions for 2025 were assumed to match modeled outputs directly. For fossil fuels, emissions were estimated using static emissions factors—the same factors as RESNET® applies for the Carbon Index—throughout the forecast period, as the study assumed no significant changes in fuel-specific emissions factors over time.[41] It is important to note that the fossil fuel emission factors reflect on-site consumption only and exclude upstream impacts such as methane leakage in gas distribution systems, which would contribute additional GHGs.

The study team couldn't identify Massachusetts-specific projections of electric grid emissions factors extending to 2050 that were suitable for integration with this study's modeling outputs. While state policy targets exist—such as the 93% reduction in electric grid emissions relative to 1990 levels, the study team found no publicly available data source providing consistent, annual, state-level emission factors through 2050 that could be applied to this analysis.

Cumulative Embodied and Operational Carbon Emissions

The cumulative carbon emissions estimates presented in this report are a result of compiling the embodied carbon and operational carbon emission results together. The emissions values are expressed in metric tons of CO_2e when looking at annual emissions and kg CO_2e when looking at carbon intensities. Additionally, the study provides projections of cumulative emissions estimated from operations between 2025 and 2050.

[39] https://data.nrel.gov/submissions/289

[40] https://www.resnet.us/about/standards/resnet-ansi/draft-pds-02-bsr-resnet-icc-301-2022-addendum-b-co2e-index/

[41] Developed from the U.S. EPA AP 42, Fifth Edition Compilation of Air Pollutant Emissions Factors, Volume 1, Chapter 1: External Combustion Sources. https://www.epa.gov/air-emissions-factors-and-quantification/ap-42-fifth-edition-volume-i-chapter-1-external-0

Limitations and Sources of Uncertainty

Self-selection bias and Rater participation. Due to the nature of this study, several inherent limitations arose. Participation relied on recruiting HERS® Raters already active in the market, who then provided samples of recently completed projects with available energy models and sufficient documentation for embodied carbon assessments. This necessity constrained the pool of projects the study team could select and limited the ability to generate a fully blind or randomized sample of homes. Nonetheless, the selected homes and their characteristics were carefully reviewed to align with the study's objectives. Additionally, since participating Raters underwent training on embodied carbon assessment, it is unlikely that the self-selection of projects significantly biased results compared to other newly constructed homes from the same period.

Energy Modeling. Operational energy consumption and associated emission results are based on modeled results and not metered data. In addition, material selection in energy modeling software typically does not provide a robust number of options and limits the ability to have material-specific data extracted from these models.

Embodied Carbon Emission Estimates. Limitations and uncertainties associated with embodied carbon estimates in this study include:

- Lack of, or limited, product specification in project documentation. In addition, due to the embodied carbon assessments occurring after the HERS® rating was completed, on-site verification for the specific products used was not feasible. This resulted in materials without specifications leveraging industry-average values for the product class. It should be noted that in a real-world scenario the embodied carbon assessment would likely occur at the same time as the HERS® rating or energy modeling.
- Not all components of the home are represented in the BEAM estimator tool, such as emissions for fixtures, appliances, surface finishes, or site work. While these exclusions are noted above, and are not driving the bulk of embodied carbon emissions in residential new construction, it does result in an underestimation of emissions.
- It's possible that certain details were missed due to the variation in the completeness of project documentation and Rater inexperience. This challenge may have also resulted in the inadvertent exclusion of certain materials, such as interior partition wall insulation.

Mechanical, Electrical, and Plumbing (MEP) estimates. MEP emission estimates were developed using the RESNET® 1550 standard, which were still in draft form at the time of this study.[42] Additionally:

- Manufacturer-specific EPDs for HVAC and water heating systems were not widely available for this study. The study relied on default values from the RESNET® draft Standard 1550.
- Emissions associated with the GWP of refrigerants for heat pumps, and the associated potential refrigerant leakage, were excluded from this analysis. This omission aligns with the methodology laid out in the RESNET® draft Standard 1550. However, it is important to note that emissions from refrigerant leakage do have significant global warming potential implications.

[42] However, it should be noted that none of the specific GWP factors changed as a result of public comments, so while in draft form, this study should align with the final standard.

Operational Emissions Forecasts. Operational carbon forecasts in this study are based on the 2024 NREL Cambium Data for the ISO New England Grid Region. Limitations include:

- The data may not fully represent the Massachusetts-specific grid emission factors.
- Forecasts are inherently uncertain projections of future grid emissions and fuel mixes.
- Projections use annual average levelized marginal emissions rates rather than hourly (8,760-hour) profiles. This simplification could over- or understate emissions depending on the timing of electricity demand relative to grid carbon intensity.

Fossil fuel emission estimates are based solely on site-level consumption and do not account for upstream methane leakage from natural gas distribution pipelines, leakage that may occur within the home, or losses from propane storage and distribution, which contribute additional GHG emissions.

Appendix B Participant HERS® Rater Feedback

This section contains the participant Rater's responses from the HERS® Rater Feedback survey. A total of 12 HERS® Raters of the 15 that participated in this study responded to the survey. The survey aimed to assess the Rater's experience with the BEAM-Ekotrope BETA integration worksheet and build an understanding of the following:

- Workflow implications for assessing ECE
- Challenges and barriers to incorporating ECE assessments into typical workflows
- Potential pathways for program and policy interventions to encourage adoption of low-embodied carbon building practices

At its core, the study tested the proof-of-concept that HERS® Raters, who already collect and model data related to home energy use, could reasonably integrate embodied carbon assessments into their existing processes. The team aimed to assess the practicality of this integration, identify barriers and opportunities, and generate early, actionable insights for shifting from an energy-centric to a carbon-centric perspective in residential construction. By focusing on Carbon Use Intensity versus gross emissions for a specific material, it becomes possible to reduce emissions from a combination of components within a given assembly based on the needs of a specific project.

Key outcomes of the study include:

- The first practical test of scaling embodied carbon assessments within the HERS® rating workflow.
- A refined data collection and analysis workflow tailored for HERS® Raters.
- Development and beta testing of an automated workflow between Ekotrope (RESNET-accredited energy modeling software) and BEAM (embodied carbon estimation software for residential construction), developed by Builders for Climate Action.
- Creation of a dedicated HERS® Rater training curriculum to support education.
- Design and implementation of a quality assurance (QA) framework to enable repeatability and scalability.
- Initial development of a Massachusetts-specific embodied carbon baseline for newly constructed homes.

These outcomes were developed specifically to evaluate feasibility within this study's structure, leveraging new homes that already had completed HERS® ratings and energy models. This aim was to demonstrate the potential to incorporate embodied carbon assessments into the HERS® Rater workflow and represent a foundation to build further learnings, tools, and industry awareness. In practical implementation, embodied carbon assessments would occur concurrently with the HERS® rating, not retroactively. Further discussions of potential future applications are presented in the conclusion of this report.

Key Findings and Considerations from the Participant HERS® Raters.

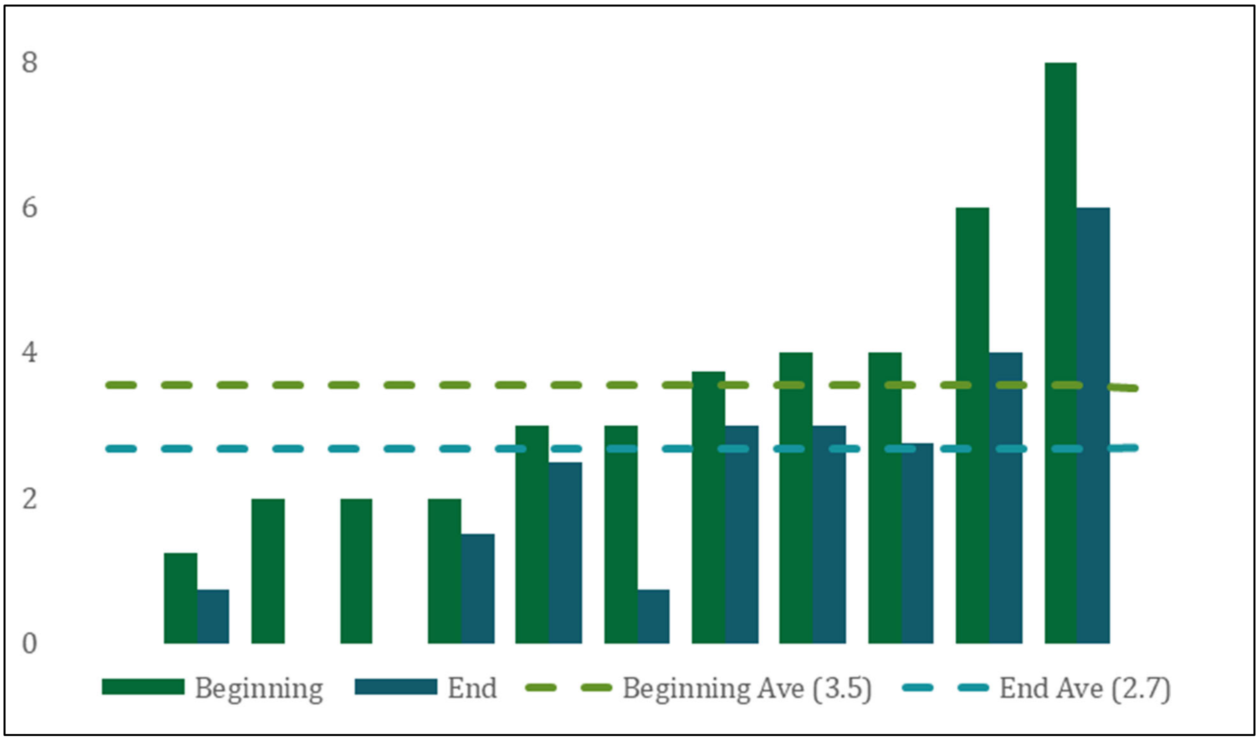
Based on feedback gathered during the study, HERS® Raters offered several recommendations and considerations to advance the integration of embodied carbon assessments into residential new construction practices:

- **Develop practical guides for builders.** Create clear, builder-focused guides that identify alternative materials with low-ECE or carbon-storing properties. These guides should focus on materials readily available through industry-standard supply chains, while also highlighting lesser-known biogenic materials that could offer additional carbon benefits.
- **Implement incentive programs.** Establish new incentive programs —or redesign existing ones—to provide financial or policy incentives that encourage the use of low-ECE building practices, low-ECE materials, and carbon-storing materials in residential new construction projects.
- **Broaden industry education efforts.** Expand educational outreach to industry stakeholders and market actors. Educational resources should aim to simplify decision-making by clearly identifying low carbon material options and helping practitioners understand how to assess alternatives, inform design decisions, and implement practical building solutions.
- **Provide targeted technical training.** Develop and deliver training programs for HERS® Raters and other professionals involved in design, specification, and material selection. Priority topics include:
  - Structural assemblies and their carbon implications.
  - Industry standard materials and practices compared to lower carbon alternatives.
  - Techniques for reading and interpreting building plans and specifications.
  - Methods for identifying specific products both in documentation and in the field.
- **Enhance software integration.** Continue to refine the integration between Ekotrope and BEAM modeling tools to simplify workflows and encourage broader industry engagement and adoption in evaluating both operational and material emissions. Deeper integration could reduce manual effort, improve consistency, and help make embodied carbon assessments a routine component of energy modeling and building analysis.

Workflow Implications

As Raters made use of the BEAM-Ekotrope Beta Integration Worksheet, they became more comfortable using it and data collection proficiency improved. All but one respondent experienced improvement over time with their productivity when asked about their ability to calculate the ECE per project. The average respondent reduced completion time from 3.5 to 2.7 hours, or a 23% reduction in time after completing between five and ten projects (Figure 32). Three respondents indicated they completed the integration worksheet and BEAM model transcription in less than two hours by the end of the study. Though participants reported that time spent increased when assessing more complicated or larger homes.

Figure 32: Reduction in Respondent Time to Complete Embodied Carbon Assessment

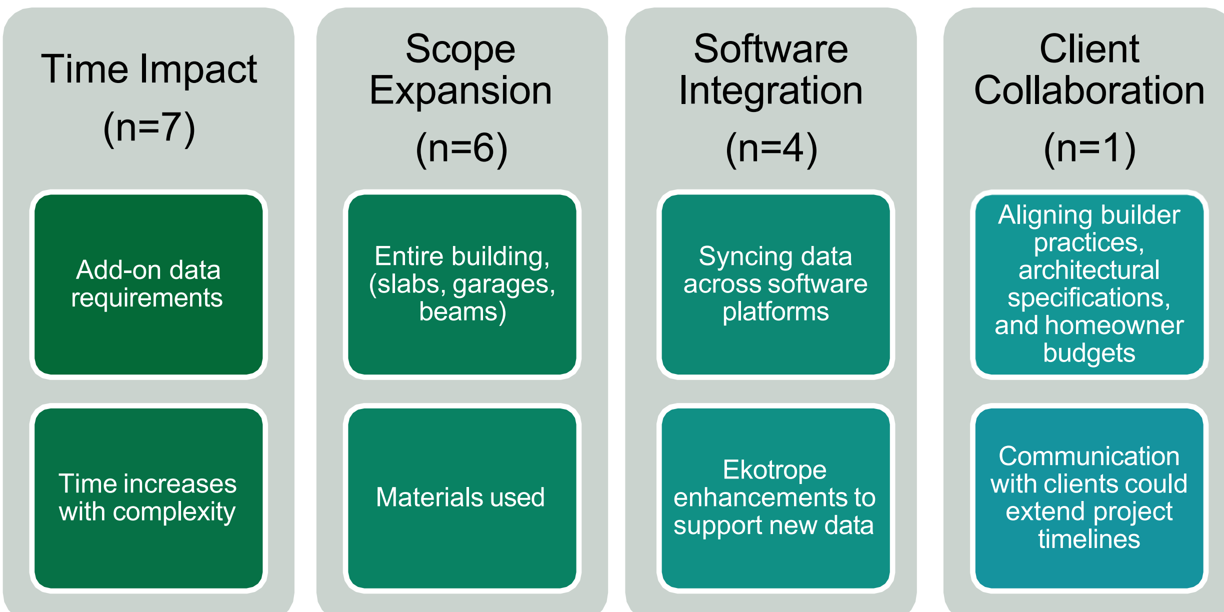


Most respondents estimate that it takes between two and four hours for a typical project with the full ECE workflow executed in this study. This was possible because of the availability of the Ekotrope to BEAM beta integration worksheet in this study, which reduced redundant data entry that had been already entered for energy modeling purposes. Outliers suggest much longer durations could occur for future embodied carbon assessments depending on whether they are tasked with accounting for every product or in a unique, complex project. The variability reflects dependencies on project type (e.g., single-family vs. multifamily), scope of the embodied carbon assessment (e.g., full accounting for every product included, such as fasteners, hardware, and paint), and available data (e.g., HERS® rating).

“I found it depends on the size of the house and how much variation it had. The range could be either from 2 hours on the quickest to 6+ on the biggest and most varied.”

Time, scope expansion, and software integration were identified as key considerations by Raters when questioned about the potential impact of incorporating ECE analysis into their workflow, as illustrated in Figure 33. Factors contributing to increased time include the need for additional data points and the complexity associated with unique homes. The requirement for more data points also necessitates an expanded scope, compelling Raters to focus on the entirety of the building, including areas outside the conditioned space and envelope assembly. This expanded scope also encompasses the detailed examination of materials used. Software integration and enhancements are essential to support ECE assessments and overall embodied carbon estimates and ensure synchronization between various platforms. Furthermore, one response highlighted the necessity of adjusting client collaboration to align builder practices, architectural specifications, and homeowner budgets.

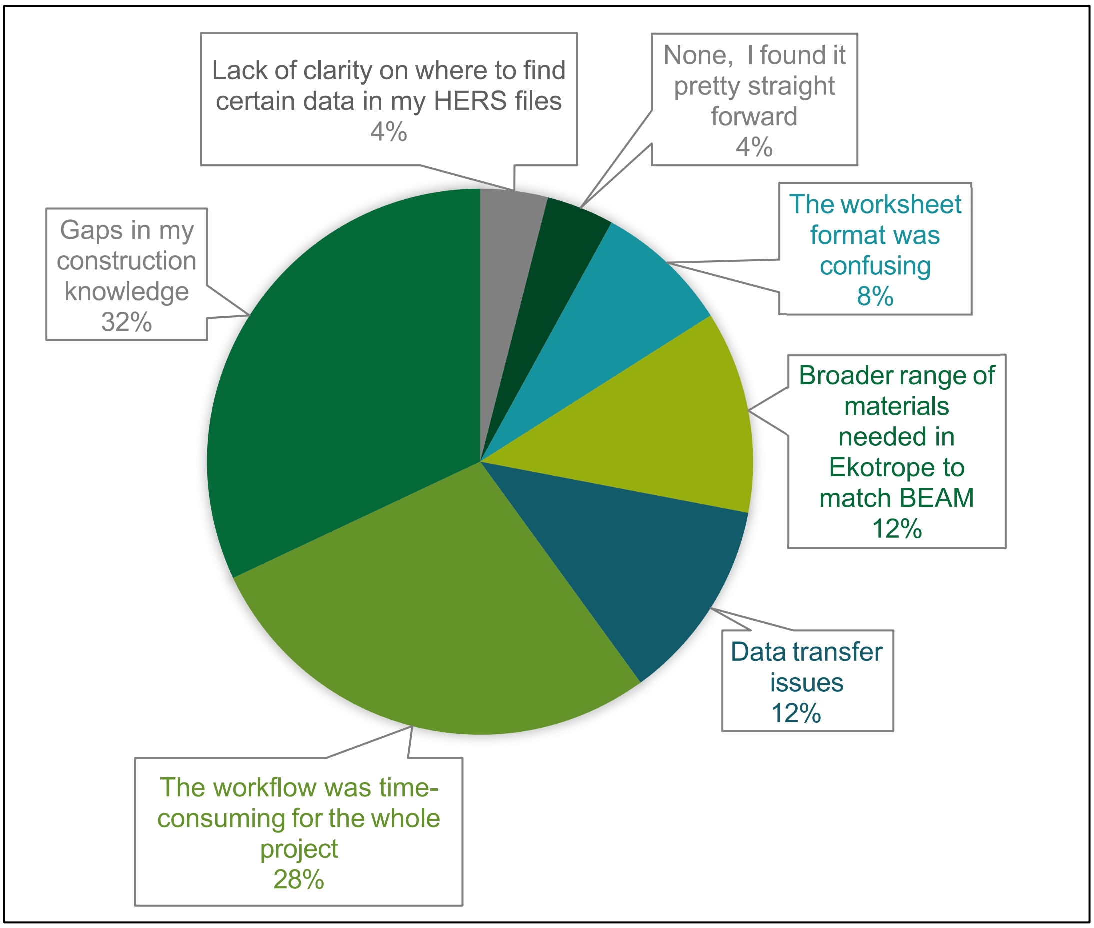
Figure 33: Change in Workflow for Embodied Carbon Assessments and Analysis (n=12)



Challenges and Barriers to ECE Assessments

The primary obstacles respondents reported during these assessments included gaps in their construction knowledge (32%), meaning their ability to read building plans, assembly details, and to identify specific materials and quantities effectively and efficiently beyond what is typically required for energy modeling. Additional data entry was also a challenge, which affected their overall workflow, and proved time-consuming for the entire project (28%). Figure 34 presents a detailed breakdown of participants' responses when asked to identify any challenges encountered while using the Ekotrope-BEAM Beta Integration Worksheet.

Figure 34: Challenges Raters Faced with Ekotrope to BEAM

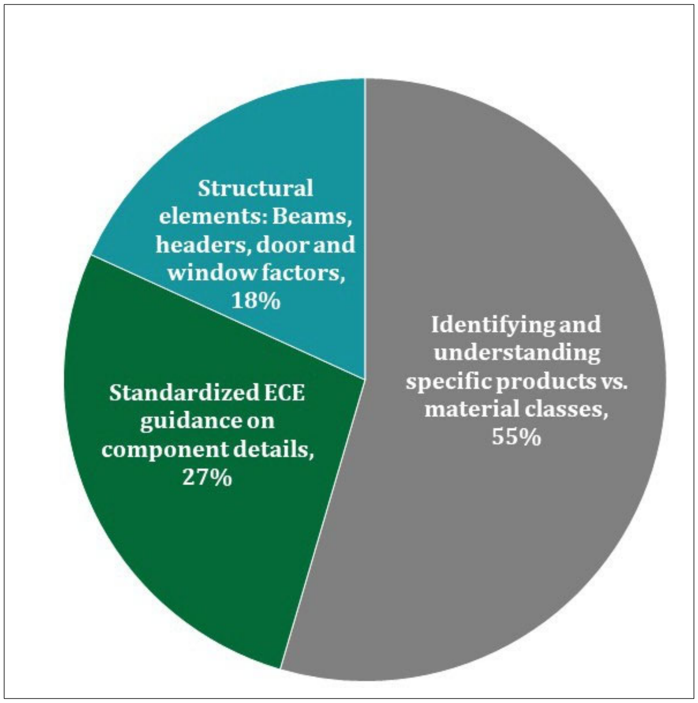


To help future HERS® Raters with the integration worksheet and their understanding of embodied carbon principles and ECE assessments, respondents suggested additional training on materials, components, and structural elements—and how to interpret those in building plans. Half of the respondents struggled to identify the specific product used for materials from plans or even during in-person site walkthroughs. Questions arose about general embodied carbon principles (e.g., extraction, transportation to construction sites, HVAC equipment and MEPs) and structural elements, (e.g., methods to assess framing for headers on doors and windows). This indicates a need for standardized guidance on the level of detail that is necessary to complete an acceptable ECE assessment.

"The concepts make sense. The most difficult part is really knowing what specific materials were used. It could have just been the plans I was working from, but I found it challenging to figure out how much concrete was in foundation walls/footings/slabs."

"Always good to have action items or takeaways to tell builders or simple material switches. So, if this were to be done again, the team could provide a where do we go from here & what takeaways do you want to have for HERS® ratings."

Figure 35: Gaps in Understanding Embodied Carbon

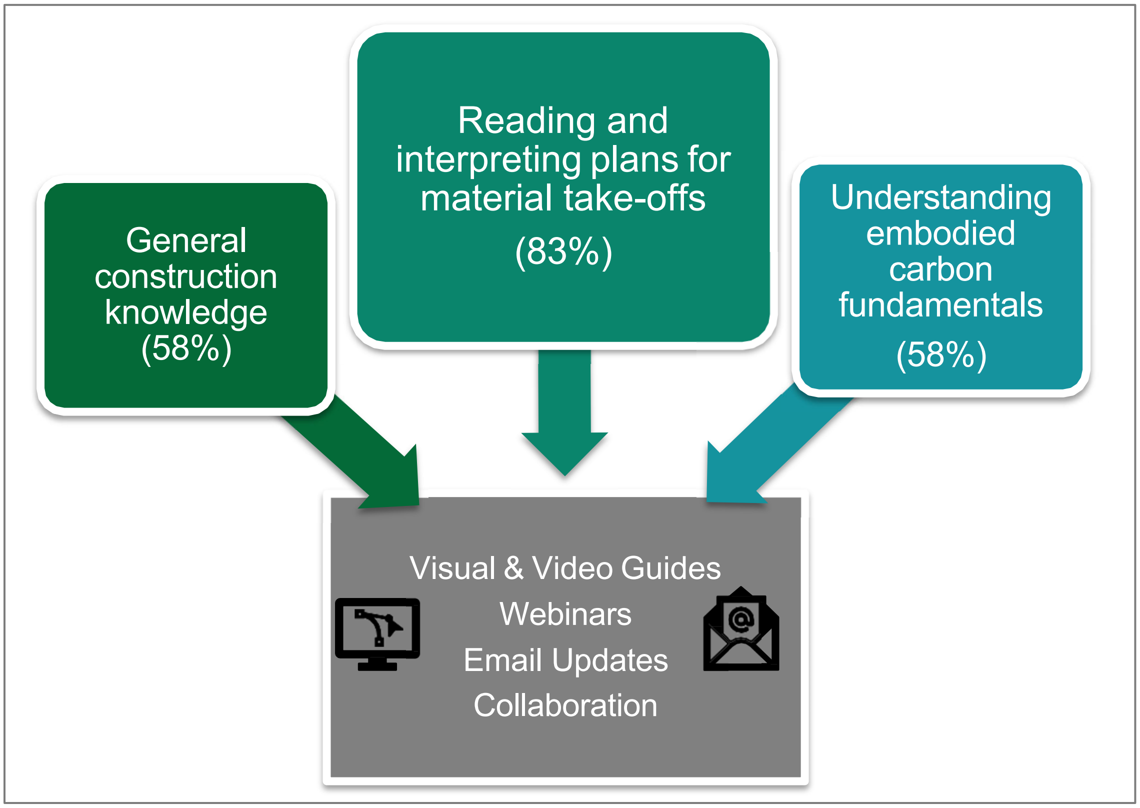


Most respondents (10 of 12) requested more training around reading and interpreting building plans for material take-offs to help HERS® Raters estimate ECE using BEAM or other tools. They also suggested training on general construction knowledge and understanding embodied carbon fundamentals as useful introductory topics. Video and visual guides were preferred for training materials, while webinars, email updates with links, and collaboration were other recommended methods for receiving new information (Figure 36).

"Both the webinar instruction and the slides used were helpful. Maybe also where to look in the plans for specific materials."

"Visual guides and example models."

Figure 36: Recommended Embodied Carbon Assessment Trainings and Delivery[43]



Program Awareness and Opportunities

Over half of the participants were unaware of the Massachusetts Department of Energy Resources (DOER) embodied carbon credit (Figure 37).[44] The likeliness that respondents and/or their teams were to recommend low carbon assemblies to builders and homeowners to achieve that credit was mixed; Raters provided a range from very likely to unlikely (Figure 38). Some Raters noted that advocacy for low-embodied carbon projects will likely fall to the builder and Rater, who must value-engineer the greatest combined reduction of emissions for the lowest cost.

"Most of the builders I work with just want to get past the HERS® hurdle. If I have a builder that cares about climate I will ask."

"Not likely, as low EC mindful clients are typically already well below code. Concrete credit could be viable, with qualifying material options on market for [a] low [cost] premium over standard [concrete]."

[43] Totals greater than 100% occur as respondents could indicate multiple applicable choices.

[44] The embodied carbon credit provides a three-point reduction in the HERS® score of a home for using low GWP concrete or low-GWP insulation materials. MA 2025 Residential Stretch code and Specialized Opt-in code (IECC 2021 with MA amendments) DOER Final Draft 12-17-24, section R406.5.2

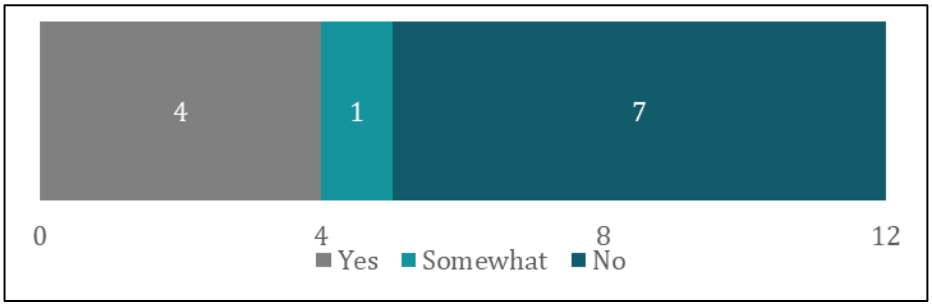


Figure 37: DOER Embodied Carbon Credit Code Provision Awareness

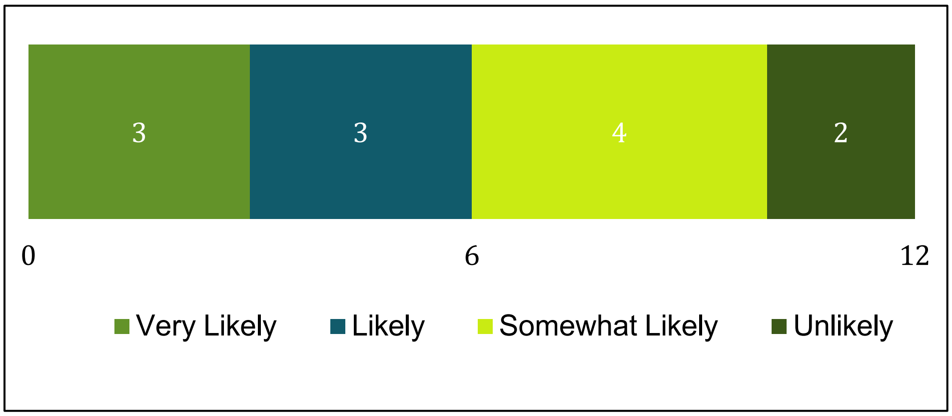


Figure 38: Likeliness to Recommend Low Carbon Assemblies

Incentives were identified as key measures to encourage low-carbon material choices. Respondents highlighted the importance of financial incentives, rebates, and HERS® score credits. Education also plays a crucial role—it should simplify decision-making and make low-carbon options easy to understand and adopt. Training and guidance can build confidence in using alternative materials. Transparency about costs is essential, as builders often perceive new materials and new construction methods to be more expensive. Assessing cost comparisons between commonly used, low-embodied carbon and biogenic materials can alleviate these concerns (Table 7).

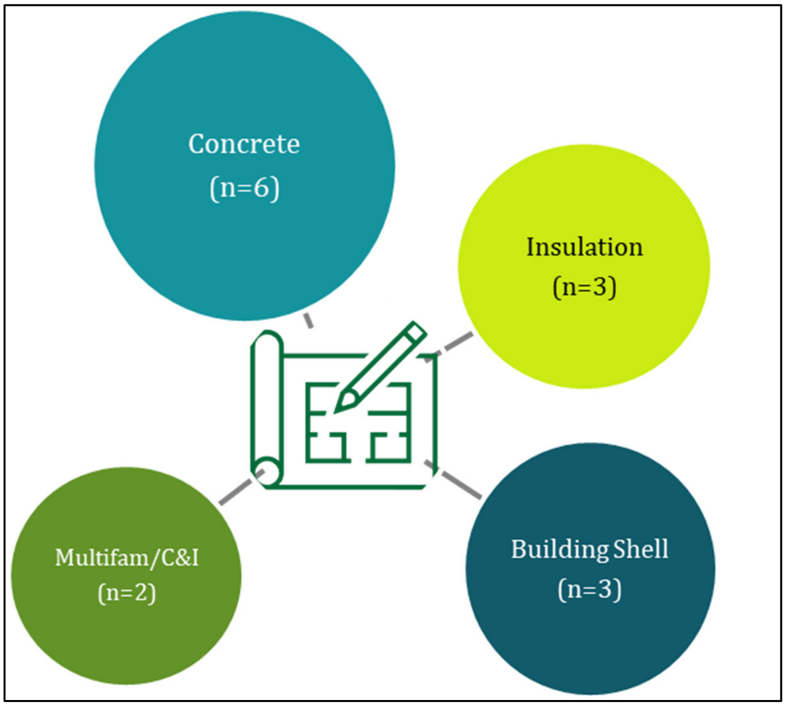
"Monetary incentives. Cut sheets of [material] cost comparisons. Make it as simple and accessible as possible. Take away as much thinking as possible for people to decide to make a choice different from their historical patterns."

Table 7: Drivers to Increase Low-ECE Projects

Responses	Counts (n=12)
Incentives	6
Education	5
Address Cost Concerns	3
Nothing	1

Half of the participants identified concrete as one of the most significant contributors to ECE and possibly the best opportunity for reducing overall embodied carbon (Figure 39). The ongoing practices and material usage that respondents believe would be most effective in achieving substantial reductions in ECE are related to the structural and insulation materials. There is also a need for greater clarity and support regarding which materials qualify as carbon sinks. Designers and builders often default to foam insulation due to its thermal efficiency properties on a per-inch basis but may have a lack of awareness of the ECE implications; therefore, improved guidance and education are essential.

Figure 39: Materials to Reduce Embodied Carbon



Many respondents anticipate that, in the future, projects already designed for high performance construction and those that are typically driven by incentives will require an embodied carbon or ECE assessment. Additionally, respondents believe that new construction projects and larger buildings with high energy usage would benefit from such a rating.

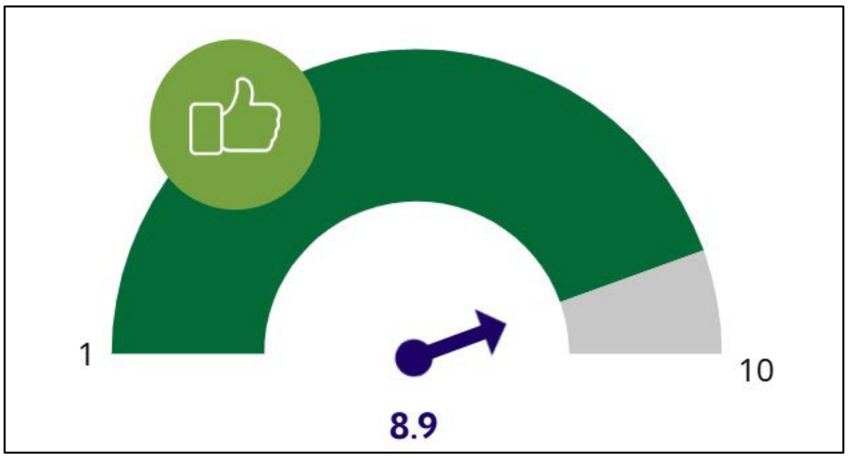
“Projects seeking funding that need to conduct feasibility studies to show a certain efficiency or reduction in energy use.”

“Larger projects where the assemblies are more generic and there is a large volume, and the budget can absorb the cost. We hear there are more professionals involved in commercial projects. Perhaps tract homes where the same model house is built numerous times.”

Figure 40: Future Drivers of Embodied Carbon Assessments

In rating the overall quality of the training on a scale of 1 to 10, the participants, on average, rated the experience as 8.9.

Figure 41: Average Rating on the Quality of Training



Five of the twelve participant respondents referred to the thorough and detailed nature of the training as a positive quality (Figure 42), and noted that the timeline and organization of the trainings factor needed the most improvement (Figure 43). The consensus of positive attributes of the training includes the instructor's patience and overall knowledge, constructive feedback, strong answers to questions and useful resources. Respondents also found the instructors were communicative, helpful, and available for questions. The rest of the attributes of the training, believed to need improvement, were additional guidance using the integration worksheet, software guidance, and the QA/QC processes.

"They were very thorough and available to give helpful answers to questions." – A Rater's positive experience

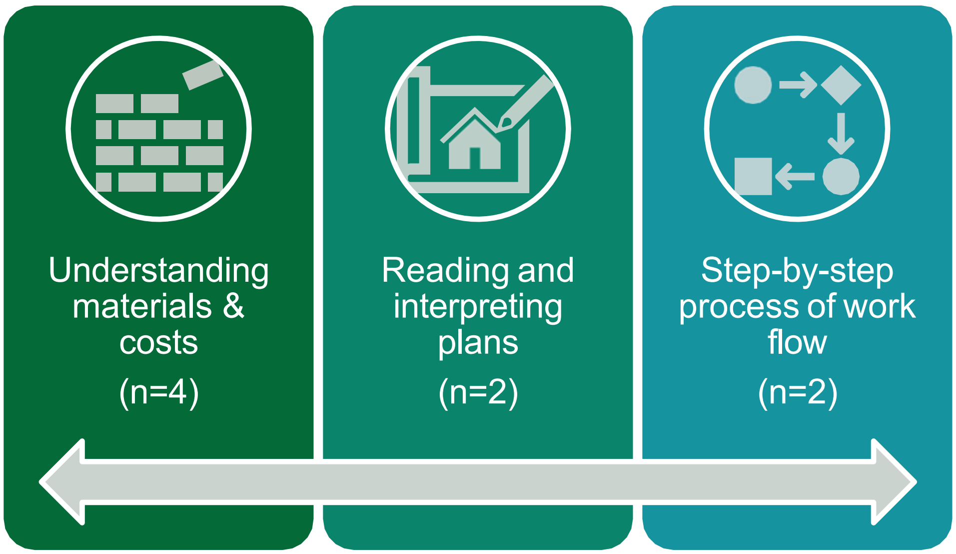
"Having a clearer idea of what the goal was at the beginning of the project to better choose what info would be needed." – A Rater's suggestion for improvement

Figure 42: Successful Training Qualities

Figure 43: Suggestions to Improve Future Trainings

The importance of understanding materials and their true costs —meaning financial, ECE impacts, and energy impacts—was a recurring theme among respondents. They emphasized how essential this knowledge is in advancing projects that achieve low-embodied carbon, benefiting not only the rater community, but all stakeholders involved. This topic was highlighted by Raters not only when asked about future training subjects (four of eight) but also in other responses throughout the survey. Additionally, reading and interpreting building plans, along with a step-by-step process of workflow, were identified as valuable topics for future training sessions.

Figure 44: Suggested Future Training (n=8)



Appendix C Selected Homes' General Characteristics and Efficiency Data

This appendix provides details on the general characteristics of the home along with general efficiency characteristics of key components of the home. This is provided for interested readers who want to further explore the make of the selected homes in this study. These data are only presented by home type and fuel use.

General Characteristics by Home Type

Table 8: Conditioned Floor Area by Home Type [ft^2]

	Single Det 1-Story	Single Det 2+ Stories	Duplex	Townhouse	Total Sample
n-value	*13*	*69*	*12*	*6*	***100***
Mean	2133.15	3219.83	2448.25	1667.83	**2892.85**
Median	2011.00	2723.00	2124.00	1591.50	**2530.00**
Min	900	682	1649	1116	**682**
Max	4098	7427	3847	2812	**7427**
Std. Deviation	1051.64	1610.88	852.61	627.69	**1510.74**

Table 9: Number of Bedrooms by Home Type

	Single Det 1-Story	Single Det 2+ Stories	Duplex	Townhouse	Total Sample
n-value	*13*	*69*	*12*	*6*	***100***
Mean	2.31	3.55	2.42	3.17	**3.23**
Median	3.00	4.00	2.00	3.00	**3.00**
Min	1	1	1	2	**1**
Max	3	6	4	5	**6**
Std. Deviation	0.85	1.21	0.79	0.98	**1.21**

Table 10: Number of Stories Above Grade by Home Type

	Single Det 1-Story	Single Det 2+ Stories	Duplex	Townhouse	Total Sample
n-value	*13*	*69*	*12*	*6*	***100***
Mean	1.00	2.12	2.00	1.83	**1.94**
Median	1.00	2.00	2.00	2.00	**2.00**
Min	1	2	2	1	**1**
Max	1	3	2	2	**3**
Std. Deviation	0.00	0.32	0.00	0.41	**0.47**

Table 11: Effective Wall R-Value by Home Type

	Single Det 1-Story	Single Det 2+ Stories	Duplex	Townhouse	Total Sample
n-value	*13*	*69*	*12*	*6*	***100***
Mean	20.45	19.47	18.22	19.79	**19.46**
Median	18.50	17.70	18.45	17.40	**17.70**
Min	16.78	14.84	16.86	15.32	**14.84**
Max	40.65	44.27	19.19	35.58	**44.27**
Std. Deviation	6.312	4.886	1.045	7.813	**4.975**

Table 12: Ceiling R-Value by Home Type

	Single Det 1-Story	Single Det 2+ Stories	Duplex	Townhouse	Total Sample
n-value	*13*	*69*	*12*	*6*	***100***
Mean	45.22	44.11	45.40	46.23	**44.54**
Median	42.04	43.68	48.70	44.97	**43.68**
Min	30.35	20.86	33.62	33.17	**20.86**
Max	78.48	63.49	49.18	60.33	**78.48**
Std. Deviation	12.73	9.43	5.74	13.03	**9.66**

Table 13: Framed Floor R-Value by Home Type

	Single Det 1-Story	Single Det 2+ Stories	Duplex	Townhouse	Total Sample
n-value	*13*	*69*	*12*	*6*	***100***
Mean	28.36	29.04	29.84	28.27	**28.99**
Median	27.60	27.68	29.65	28.51	**27.68**
Min	26.66	19.91	29.65	26.66	**19.91**
Max	33.1	45.97	30.41	29.65	**45.97**
Std. Deviation	2.40	4.12	0.38	1.51	**3.79**

Table 14: Framed Floor Over Unconditioned Basement R-Value by Home Type
(filter: only homes with an unconditioned basement)

	Single Det 1-Story	Single Det 2+ Stories	Duplex	Townhouse	Total Sample
n-value	*3*	*21*	*0*	*1*	***25***
Mean	27.35	27.56	N/A	26.66	**27.50**
Median	27.52	27.52	N/A	26.66	**27.52**
Min	26.85	23.56	N/A	26.66	**23.56**
Max	27.68	33.32	N/A	26.66	**33.32**
Std. Deviation	0.44	1.83	N/A	N/A	**1.69**

Table 15: Framed Floor Over Crawlspace R-Value by Home Type (filter: only homes with a crawlspace)

	Single Det 1-Story	Single Det 2+ Stories	Duplex	Townhouse	Total Sample
n-value	*0*	*5*	*0*	*0*	***5***
Mean	N/A	33.07	N/A	N/A	**33.07**
Median	N/A	33.05	N/A	N/A	**33.05**
Min	N/A	26.15	N/A	N/A	**26.15**
Max	N/A	45.97	N/A	N/A	**45.97**
Std. Deviation	N/A	7.95	N/A	N/A	**7.95**

Table 16: Framed Floor Over Garage R-Value by Home Type (filter: only homes above a garage)

	Single Det 1-Story	Single Det 2+ Stories	Duplex	Townhouse	Total Sample
n-value	*2*	*1*	*0*	*0*	***3***
Mean	29.88	27.52	N/A	N/A	**29.09**
Median	29.88	27.52	N/A	N/A	**27.52**
Min	26.66	27.52	N/A	N/A	**26.66**
Max	33.1	27.52	N/A	N/A	**33.1**
Std. Deviation	4.55	N/A	N/A	N/A	**3.50**

Table 17: Foundation Wall Cavity R-Value by Home Type (filter: only homes with foundation wall cavity insulation)

	Single Det 1-Story	Single Det 2+ Stories	Duplex	Townhouse	Total Sample
n-value	*3*	*14*	*1*	*0*	***18***
Mean	15.58	16.69	14.00	N/A	**16.35**
Median	16.25	15.83	14	N/A	**15.63**
Min	13	12.95	14	N/A	**12.95**
Max	17.5	22	14	N/A	**22**
Std. Deviation	2.32	3.77	N/A	N/A	**3.47**

Table 18: Foundation Wall Continuous R-Value by Home Type (filter: only homes with continuous foundation wall insulation)

	Single Det 1-Story	Single Det 2+ Stories	Duplex	Townhouse	Total Sample
n-value	*4*	*30*	*5*	*1*	***40***
Mean	14.15	14.48	13.85	15.00	**14.38**
Median	14.00	15.00	13.00	15.00	**15.00**
Min	7	3.7	7	15	**3.7**
Max	21.6	30	20	15	**30**
Std. Deviation	6.02	6.25	4.79	N/A	**5.85**

Table 19: Window U-Factor by Home Type

	Single Det 1-Story	Single Det 2+ Stories	Duplex	Townhouse	Total Sample
n-value	*13*	*69*	*12*	*6*	***100***
Mean	0.262	0.280	0.274	0.250	**0.275**
Median	0.28	0.28	0.29	0.28	**0.28**
Min	0.15	0.13	0.24	0.14	**0.13**
Max	0.3	0.32	0.29	0.28	**0.32**
Std. Deviation	0.0479	0.0302	0.0215	0.0562	**0.0346**

Table 20: Window SHGC by Home Type

	Single Det 1-Story	Single Det 2+ Stories	Duplex	Townhouse	Total Sample
n-value	*13*	*69*	*12*	*6*	***100***
Mean	0.308	0.307	0.288	0.307	**0.305**
Median	0.31	0.28	0.28	0.31	**0.28**
Min	0.16	0.17	0.27	0.27	**0.16**
Max	0.51	0.51	0.41	0.35	**0.51**
Std. Deviation	0.0914	0.0787	0.0386	0.0344	**0.0743**

Table 21: Door U-Value by Home Type

	Single Det 1-Story	Single Det 2+ Stories	Duplex	Townhouse	Total Sample
n-value	*13*	*69*	*12*	*6*	***100***
Mean	0.181	0.238	0.177	0.185	**0.220**
Median	0.200	0.200	0.170	0.200	**0.200**
Min	0.133	0.133	0.14	0.143	**0.133**
Max	0.22	0.752	0.2	0.2	**0.752**
Std. Deviation	0.0288	0.1136	0.0193	0.0243	**0.0985**

Table 22: Primary Heating Efficiencies by Home Type

	Single Det 1-Story	Single Det 2+ Stories	Duplex	Townhouse	Total Sample
Air Source Heat Pumps					
n-value	*6*	*24*	*6*	*4*	***40***
Avg COP	-	-	-	4.0	**4.0**
Avg HSPF	9.2	10.5	10.0	10.0	**10.1**
Avg HSPF2	8.9	9.5	7.9	7.5	**9.1**
Furnaces					
n-value	*4*	*41*	*6*	*2*	***53***
Avg AFUE	96.4	95.9	96.0	96.0	**96.0**
Boilers					
n-value	*3*	*4*	*0*	*0*	***7***
Avg AFUE	95.4	95.0	N/A	N/A	**95.2**

Table 23: Primary Cooling Efficiencies by Home Type

	Single Det 1-Story	Single Det 2+ Stories	Duplex	Townhouse	Total Sample
Air Conditioners					
n-value	*7*	*42*	*6*	*2*	***57***
Avg SEER	14.7	14.0	13.0	13.5	**13.9**
Avg SEER2	14.3	14.3	-	-	**14.3**
Air Source Heat Pumps					
n-value	*6*	*27*	*6*	*4*	***43***
Avg SEER	17.0	19.2	20.0	15.3	**18.5**
Avg SEER2	18.3	17.9	16.5	16.1	**17.5**

Table 24: Water Heating Efficiencies by Home Type

	Single Det 1-Story	Single Det 2+ Stories	Duplex	Townhouse	Total Sample
Heat Pump Water Heater					
n-value	*5*	*24*	*5*	*4*	***38***
Avg EF	3.81	4.01	4.09	3.77	**3.98**
Avg UEF	3.76	3.72	3.80	3.80	**3.73**
Storage Tanks					
n-value	*3*	*16*	*0*	*1*	***20***
Avg EF	0.70	0.91	-	-	**0.89**
Avg UEF	0.89	0.81	-	0.69	**0.81**
Instantaneous DWH					
n-value	*5*	*29*	*7*	*1*	***42***
Avg EF	0.96	0.94	0.96	0.96	**0.95**
Avg UEF	0.95	0.95	0.95	-	**0.95**

Table 25: Cooking Fuel by Home Type

	Single Det 1-Story	Single Det 2+ Stories	Duplex	Townhouse	Total Sample
n-value	*13*	*69*	*12*	*6*	***100***
Electric	7%	22%	10%	4%	**43**
Natural Gas	4%	25%	1%	2%	**32**
Propane	2%	22%	1%	0%	**25**

Table 26: Dryer Fuel by Home Type

	Single Det 1-Story	Single Det 2+ Stories	Duplex	Townhouse	Total Sample
n-value	*13*	*69*	*12*	*6*	***100***
Electric	12%	66%	12%	5%	**95%**
Natural Gas	0%	0%	0%	1%	**1%**
Propane	1%	3%	0%	0%	**4%**

Table 27: Foundation Types by Home Type

	Single Det 1-Story	Single Det 2+ Stories	Duplex	Townhouse	Total Sample
n-value	*13*	*69*	*12*	*6*	***100***
Conditioned Basement	6%	20%	4%	1%	**31%**
Unconditioned Basement	3%	21%	0%	1%	**25%**
More than one type	1%	19%	1%	0%	**21%**
Slab	1%	3%	7%	4%	**15%**
Open Crawl Space/Raised Floor	0%	4%	0%	0%	**4%**
Over Garage	2%	1%	0%	0%	**3%**
Enclosed Crawl Space	0%	1%	0%	0%	**1%**

General Characteristics by Home Fuel Type

Table 28: Conditioned Floor Area by Fuel Type [ft^2]

	All Electric	All Fossil Fuel	Mixed Fuels	Total Sample
n-value	*26*	*4*	*70*	***100***
Mean	1828.65	3594.25	3248.05	**2892.85**
Median	1780.00	2955.00	2793.50	**2530.00**
Min	682	1709	900	**682**
Max	3306	6758	7427	**7427**
Std. Deviation	739.33	2380.03	1499.02	**1510.74**

Table 29: Number of Bedrooms by Fuel Type

	All Electric	All Fossil Fuel	Mixed Fuels	Total Sample
n-value	*26*	*4*	*70*	***100***
Mean	2.62	3.00	3.47	**3.23**
Median	3.00	2.50	3.00	**3**
Min	1	2	1	**1**
Max	4	5	6	**6**
Std. Deviation	0.94	1.41	1.22	**1.21**

Table 30: Number of Stories Above Grade by Fuel Type

	All Electric	All Fossil Fuel	Mixed Fuels	Total Sample
n-value	*26*	*4*	*70*	***100***
Mean	1.85	1.75	1.99	**1.94**
Median	2.00	1.50	2.00	**2**
Min	1	1	1	**1**
Max	3	3	3	**3**
Std. Deviation	0.46	0.96	0.43	**0.47**

Table 31: Effective Wall R-Value by Fuel Type

	All Electric	All Fossil Fuel	Mixed Fuels	Total Sample
n-value	*26*	*4*	*70*	***100***
Mean	22.16	17.39	18.58	**19.46**
Median	17.81	17.40	17.77	**17.70**
Min	15.32	17.06	14.84	**14.84**
Max	44.27	17.7	25.67	**44.27**
Std. Deviation	8.763	0.342	1.978	**4.975**

Table 32: Ceiling R-Value by Fuel Type

	All Electric	All Fossil Fuel	Mixed Fuels	Total Sample
n-value	*26*	*4*	*70*	***100***
Mean	46.50	43.14	43.89	**44.54**
Median	46.80	40.94	43.68	**43.68**
Min	26.73	37.29	20.86	**20.86**
Max	78.48	53.39	63.49	**78.48**
Std. Deviation	12.62	7.08	8.49	**9.66**

Table 33: Framed Floor R-Value by Fuel Type

	All Electric	All Fossil Fuel	Mixed Fuels	Total Sample
n-value	*26*	*4*	*70*	***100***
Mean	29.33	27.34	29.03	**28.99**
Median	29.65	27.50	27.68	**27.68**
Min	19.91	23.39	23.39	**19.91**
Max	35.17	30.99	45.97	**45.97**
Std. Deviation	3.86	3.18	3.85	**3.79**

Table 34: Framed Floor Over Unconditioned Basement R-Value by Fuel Type (filter: only homes with an unconditioned basement)

	All Electric	All Fossil Fuel	Mixed Fuels	Total Sample
n-value	*4*	*1*	*20*	***25***
Mean	29.51	26.66	27.14	**27.50**
Median	29.02	26.66	27.52	**27.52**
Min	26.66	26.66	23.56	**23.56**
Max	33.32	26.66	27.68	**33.32**
Std. Deviation	3.29	N/A	0.93	**1.69**

Table 35: Framed Floor Over Crawlspace R-Value by Fuel Type (filter: only homes with a crawlspace)

	All Electric	All Fossil Fuel	Mixed Fuels	Total Sample
n-value	*1*	*0*	*4*	***5***
Mean	33.32	N/A	33.01	**33.07**
Median	33.32	N/A	29.95	**33.05**
Min	33.32	N/A	26.15	**26.15**
Max	33.32	N/A	45.97	**45.97**
Std. Deviation	N/A	N/A	9.18	**7.95**

Table 36: Framed Floor Over Garage R-Value by Fuel Type (filter: only homes over a garage)

	All Electric	All Fossil Fuel	Mixed Fuels	Total Sample
n-value	*1*	*0*	*2*	***3***
Mean	26.66	N/A	30.31	**29.09**
Median	26.66	N/A	30.31	**27.52**
Min	26.66	N/A	27.52	**26.66**
Max	26.66	N/A	33.1	**33.1**
Std. Deviation	N/A	N/A	3.95	**3.50**

Table 37: Foundation Wall Cavity R-Value by Fuel Type (filter: only homes with foundation wall cavity insulation)

	All Electric	All Fossil Fuel	Mixed Fuels	Total Sample
n-value	*4*	*1*	*13*	***18***
Mean	13.24	21.00	16.95	**16.35**
Median	13.00	21.00	16.65	**15.63**
Min	12.95	21	13	**12.95**
Max	14	21	22	**22**
Std. Deviation	0.51	N/A	3.40	**3.47**

Table 38: Foundation Wall Continuous R-Value by Fuel Type
(filter: only homes with continuous foundation wall insulation)

	All Electric	All Fossil Fuel	Mixed Fuels	Total Sample
n-value	*10*	*1*	*29*	***40***
Mean	15.76	15.00	13.88	**14.38**
Median	14.00	15.00	15.00	**15.00**
Min	7	15	3.7	**3.7**
Max	30	15	21	**30**
Std. Deviation	7.69	N/A	5.27	**5.85**

Table 39: Window U-Factor by Fuel Type

	All Electric	All Fossil Fuel	Mixed Fuels	Total Sample
n-value	*26*	*4*	*70*	***100***
Mean	0.253	0.295	0.283	**0.275**
Median	0.28	0.30	0.28	**0.28**
Min	0.13	0.28	0.18	**0.13**
Max	0.31	0.31	0.32	**0.32**
Std. Deviation	0.0521	0.0129	0.0216	**0.0346**

Table 40: Window SHGC by Fuel Type

	All Electric	All Fossil Fuel	Mixed Fuels	Total Sample
n-value	*26*	*4*	*70*	***100***
Mean	0.297	0.265	0.311	**0.305**
Median	0.28	0.29	0.28	**0.28**
Min	0.19	0.17	0.16	**0.16**
Max	0.51	0.31	0.51	**0.51**
Std. Deviation	0.0648	0.0640	0.0780	**0.0743**

Table 41: Door U-Value by Fuel Type

	All Electric	All Fossil Fuel	Mixed Fuels	Total Sample
n-value	*26*	*4*	*70*	***100***
Mean	0.238	0.182	0.215	**0.220**
Median	0.14	0.16	0.133	**0.133**
Min	0.752	0.2	0.54	**0.752**
Max	0.1260	0.0210	0.0887	**0.0985**
Std. Deviation	0.200	0.184	0.200	**0.200**

Table 42: Primary Heating Efficiencies by Fuel Type

	All Electric	All Fossil Fuel	Mixed Fuels	Total Sample
Air Source Heat Pumps				
n-value	*26*	*0*	*14*	***40***
Avg COP	4.0	-	-	**4.0**
Avg HSPF	10.4	-	9.2	**10.1**
Avg HSPF2	8.7	-	9.6	**9.1**
Furnaces				
n-value	*0*	*1*	*52*	***53***
Avg AFUE	-	96.0	96.0	**96.0**
Boilers				
n-value	*0*	*3*	*4*	***7***
Avg AFUE	-	95.0	95.3	**95.2**

Table 43: Primary Cooling Efficiencies by Fuel Type

	All Electric	All Fossil Fuel	Mixed Fuels	Total Sample
Air Conditioners				
n-value	*0*	*3*	*54*	***57***
Avg SEER	-	13.5		
Avg SEER2	-	16.0		
Air Source Heat Pumps				
n-value	*26*	*1*	*16*	***43***
Avg SEER	18.9	19.2	17.0	**18.5**
Avg SEER2	17.0	-	18.3	**17.5**

Table 44: Water Heating Efficiencies by Fuel Type

	All Electric	All Fossil Fuel	Mixed Fuels	Total Sample
Heat Pump Water Heater				
n-value	*21*	*0*	*17*	***38***
Avg EF	3.94	-	4.17	**3.98**
Avg UEF	3.71	-	3.75	**3.73**
Storage Tanks				
n-value	*5*	*2*	*13*	***20***
Avg EF	0.94	0.88	0.86	**0.89**
Avg UEF	0.91	-	0.79	**0.81**
Instantaneous Water Heater				
n-value	*0*	*2*	*40*	***42***
Avg EF	-	0.96	0.95	**0.95**
Avg UEF	-	0.95	0.95	**0.95**

Appendix D Results by Home Fuel Usage

This appendix provides additional information on embodied carbon emissions, operational energy consumption, and operational energy emissions based on the fuel use in the home. The data is segmented into:

- **All electric:** Homes that use electricity for heating, water heating, cooking, and laundry end-uses
- **All fossil fuel:** Homes that only use fossil fuels for fuel-specific end-uses
- **Mixed fuels:** Homes that have a combination of electric and fossil fuel equipment

The appendix provides additional data for interested readers. Some results may need additional analyses and assessments to fully contextualize the results. However, due to time and resource constraints, these data segmentations were not further explored in this study. It is recommended that deeper, specific analysis is conducted to supplement the findings presented in the main body of the report with these additional segmentations to provide alternative perspectives on embodied carbon and operational carbon emission impacts.

Some general observations for the combined cumulative operational emissions and embodied carbon emissions by home fuel use:

- All electric homes have substantially lower total carbon emissions than homes that rely on fossil fuels. The average MEP-related embodied carbon of all electric homes is 30% less than fossil fuel homes and 33% less than mixed fuel homes. The building enclosure ECE of electric homes are42% less than fossil fuel homes and 53% less than mixed fuel homes. The operational carbon emissions of electric homes are 68% less than fossil fuel homes and 60% less than mixed fuel homes. This is a forecast for the total operational carbon emissions over the next 25 years, so all electric homes will receive the anticipated benefits of future improvements to the electrical grid at a greater rate than those with fossil fuels.
- When normalized by conditioned floor area, the average MEP embodied carbon of all electric homes is 38% higher than fossil fuel homes and 24% higher than mixed fuel homes. The building enclosure embodied carbon of electric homes are 3% less than fossil fuel homes and 14% higher than mixed fuel homes. However, the operational carbon emissions of electric homes are 40% less than fossil fuel homes and 30% less than mixed fuel homes.
- Due to the larger impact of cumulative operational carbon emissions (67% of the total carbon emissions overall), all electric homes are still expected to result in substantially fewer total carbon emissions than homes with fossil fuels, even when normalized by conditioned floor area.

Figure 45: Average Embodied and Operational Carbon Emissions over 25 Years by Home Fuel Use (Tons of CO_2e)

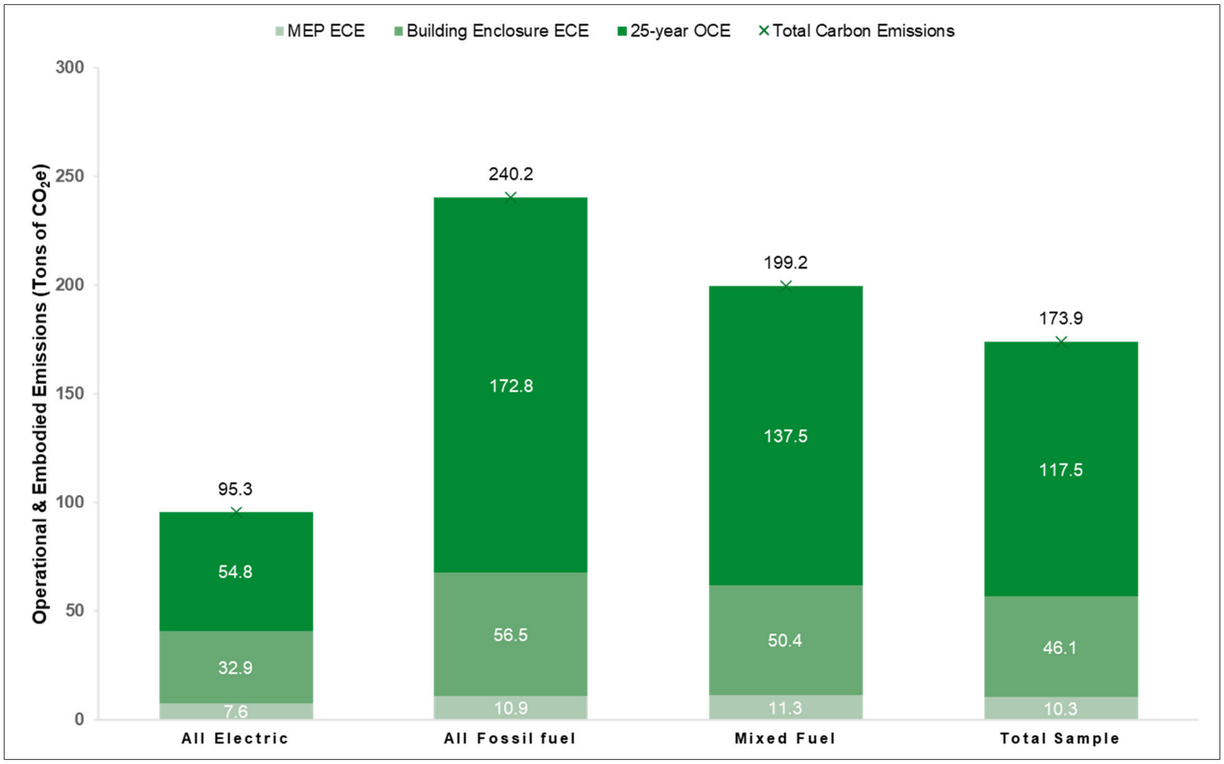


Figure 46: Average Embodied and Operational Carbon Emissions over 25 Years by Home Fuel Use, Normalized by Conditioned Floor Area (kg CO_2e/m^2)

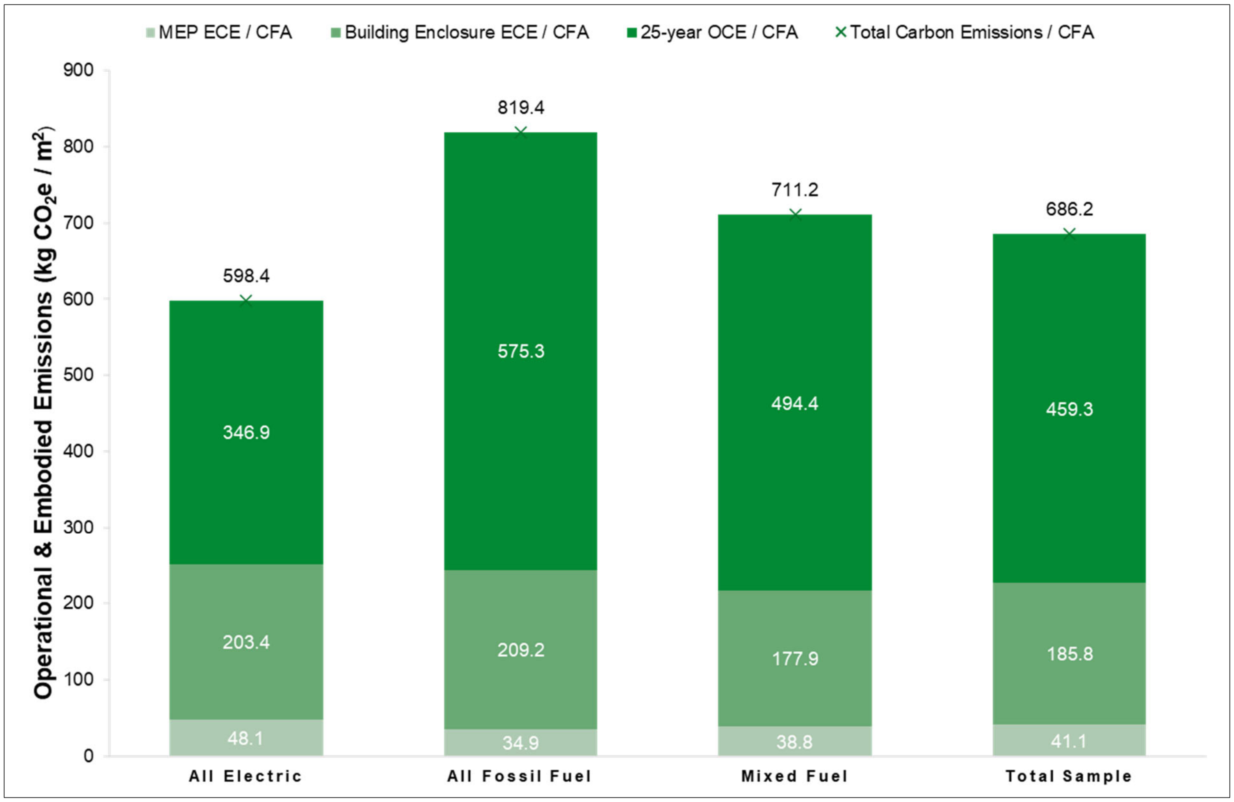


Figure 47: Emissions Time Series by Fuel Type

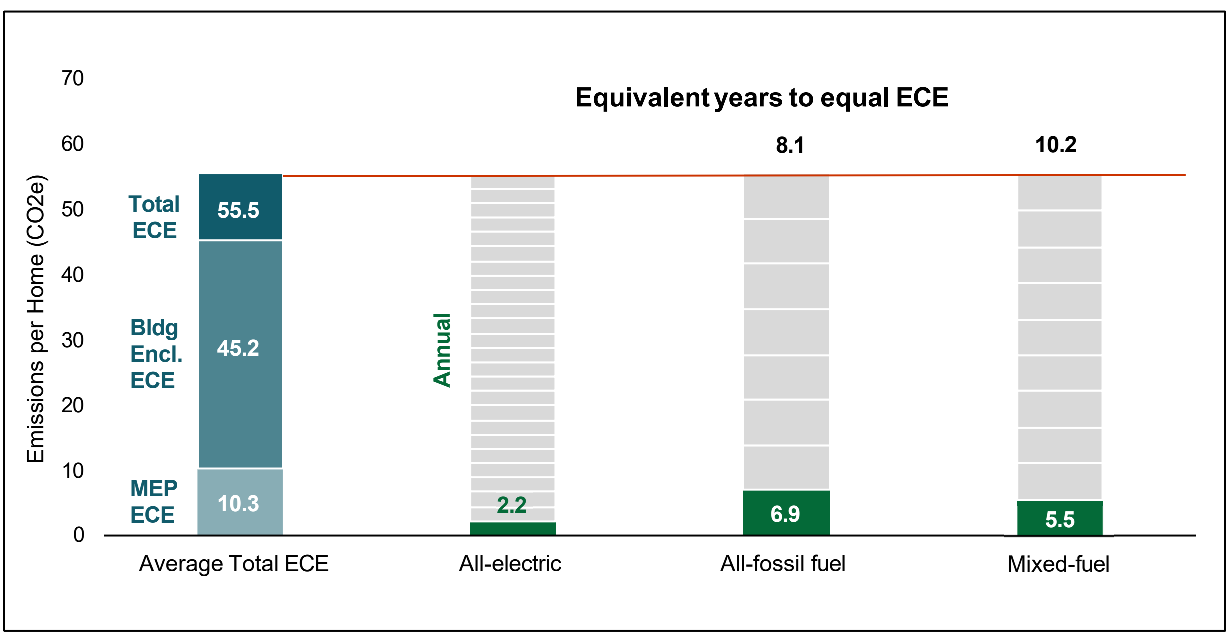


Table 45: Gross ECE by Home Fuel Type (Tons CO_2e) (Includes Building Enclosure and MEPs)

	All Electric	All Fossil Fuel	Mixed Fuels	Total Sample
n-value	*26*	*4*	*70*	***100***
Mean	40.5	67.5	61.7	**56.4**
Median	39.9	68.2	56.2	**52.7**
Min	18.5	44.3	23.8	**18.5**
Max	68.5	89.1	144.3	**144.3**
Std. Deviation	14.3	20.1	25.0	**24.3**

Table 46: Total Net ECE by Home Fuel Use (Tons CO_2e)

	All Electric	All Fossil Fuel	Mixed Fuels	Total Sample
n-value	*26*	*4*	*70*	***100***
Mean	38.8	67.0	61.0	**55.5**
Median	39.4	68.2	54.2	**50.7**
Min	18.5	42.5	23.8	**18.5**
Max	67.9	89.1	143.9	**143.9**
Std. Deviation	13.2	20.8	25.2	**24.5**

Table 47: Gross ECE of Building Enclosure Only by Home Fuel Use (Tons CO_2e)

	All Electric	Mixed Fuels	All-Gas	Total Sample
n-value	*26*	*70*	*4*	***100***
Mean	32.9	50.4	56.5	**46.1**
Median	31.3	46.5	59.1	**42.8**
Min	13.6	19.3	38.6	**13.6**
Max	61.8	123.2	69.3	**123.2**
Std. Deviation	12.55	21.07	14.55	**20.46**

Table 48: Net ECE of Building Enclosure Only by Home Fuel Use (Tons CO_2e)

	All Electric	Mixed Fuels	All-Gas	Total Sample
n-value	*26*	*70*	*4*	***100***
Mean	31.2	49.7	56.1	**45.2**
Median	30.9	45.0	59.1	**41.1**
Min	13.6	19.3	36.8	**13.6**
Max	56.0	46.2	69.3	**69.3**
Std. Deviation	11.4	21.3	15.3	**20.6**

Table 49:Total MEP-related ECE by Home Fuel Use (Tons CO_2e)

	All Electric	All Fossil Fuel	Mixed Fuels	Total Sample
n-value	*26*	*4*	*70*	***100***
Mean	7.60	10.94	11.32	**10.33**
Median	7.99	9.11	10.37	**9.26**
Min	3.78	5.74	4.02	**3.78**
Max	12.01	19.79	23.66	**23.66**
Std. Deviation	2.279	6.325	4.647	**4.499**

Table 50: HERS® Rating by Home Fuel Use

	All Electric	All Fossil Fuel	Mixed Fuels	Total Sample
n-value	*26*	*4*	*70*	***100***
Mean	48.6	50.5	50.0	**49.6**
Median	50.0	51.0	51.0	**50.0**
Min	37.0	48.0	42.0	**37.0**
Max	58.0	52.0	60.0	**60.0**
Std. Deviation	5.35	1.91	3.61	**4.10**

Table 51: Carbon Index by Home Fuel Use

	All Electric	All Fossil Fuel	Mixed Fuels	Total Sample
n-value	*26*	*4*	*70*	***100***
Mean	49.0	87.8	76.7	**69.9**
Median	49.0	86.0	79.5	**74.0**
Min	39.0	82.0	49.0	**39.0**
Max	68.0	97.0	100.0	**100.0**
Std. Deviation	5.97	6.50	12.73	**16.81**

Table 52: Annual Energy Consumption by Home Fuel Use [MBtu]

	All Electric	All Fossil Fuel	Mixed Fuels	Total Sample
n-value	*26*	*4*	*70*	***100***
Mean	35.94	93.43	80.90	**69.71**
Median	33.56	79.06	77.70	**70.69**
Min	18.67	59.30	30.80	**18.67**
Max	65.19	156.29	177.37	**177.37**
Std. Deviation	10.86	43.56	28.20	**32.44**

Table 53: EUI per CFA by Home Fuel Use [kBtu/ft^2]

	All Electric	All Fossil Fuel	Mixed Fuels	Total Sample
n-value	*26*	*4*	*70*	***100***
Mean	20.88	29.49	27.21	**25.65**
Median	20.28	28.91	25.94	**23.96**
Min	13.19	21.50	12.76	**12.76**
Max	29.22	38.63	47.77	**47.77**
Std. Deviation	4.291	8.466	8.015	**7.739**

Table 54: Total First-Year Operational CO_2e Emissions by Home Fuel Use [Tons]

	All Electric	All Fossil Fuel	Mixed Fuels	Total Sample
n-value	*26*	*4*	*70*	***100***
Mean	2.82	7.82	6.37	**5.51**
Median	2.62	6.75	6.20	**5.49**
Min	1.44	4.41	2.45	**1.44**
Max	5.20	13.36	15.14	**15.14**
Std. Deviation	0.876	3.907	2.325	**2.659**

Table 55: CO_2e Emissions per Total Floor Area by Fuel Type [kg CO_2e/m^2]

	All Electric	All Fossil Fuel	Mixed Fuels	Total Sample
n-value	*26*	*4*	*70*	***100***
Mean	17.58	26.08	22.98	**21.70**
Median	17.31	24.53	22.77	**20.32**
Min	10.95	19.73	10.73	**10.73**
Max	24.56	35.52	39.28	**39.28**
Std. Deviation	3.631	7.199	6.712	**6.533**

Table 56: Heating CO_2e Emissions by Fuel Type [Tons]

	All Electric	All Fossil Fuel	Mixed Fuels	Total Sample
n-value	*26*	*4*	*70*	***100***
Mean	1.26	4.84	3.68	**3.10**
Median	1.13	4.17	3.62	**3.16**
Min	0.38	2.59	1.04	**0.38**
Max	2.96	8.45	10.19	**10.19**
Std. Deviation	0.615	2.531	1.651	**1.854**

Table 57: Water Heating CO_2e Emissions by Fuel Type [Tons]

	All Electric	All Fossil Fuel	Mixed Fuels	Total Sample
n-value	*26*	*4*	*70*	***100***
Mean	0.21	0.81	0.69	**0.57**
Median	0.15	0.77	0.75	**0.56**
Min	0.10	0.48	0.11	**0.10**
Max	0.60	1.24	1.78	**1.78**
Std. Deviation	0.134	0.318	0.379	**0.392**

Figure 48: 25-Year Forecast of Operational Carbon Emissions by Home Fuel Use

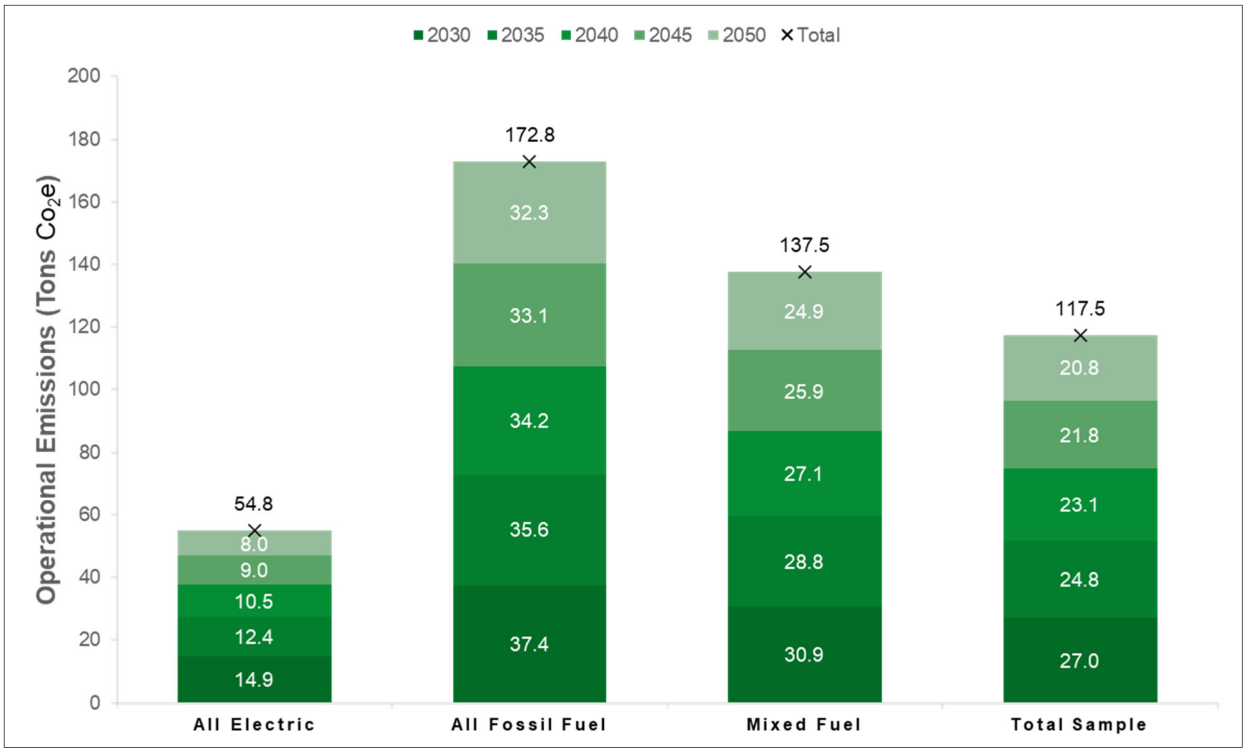
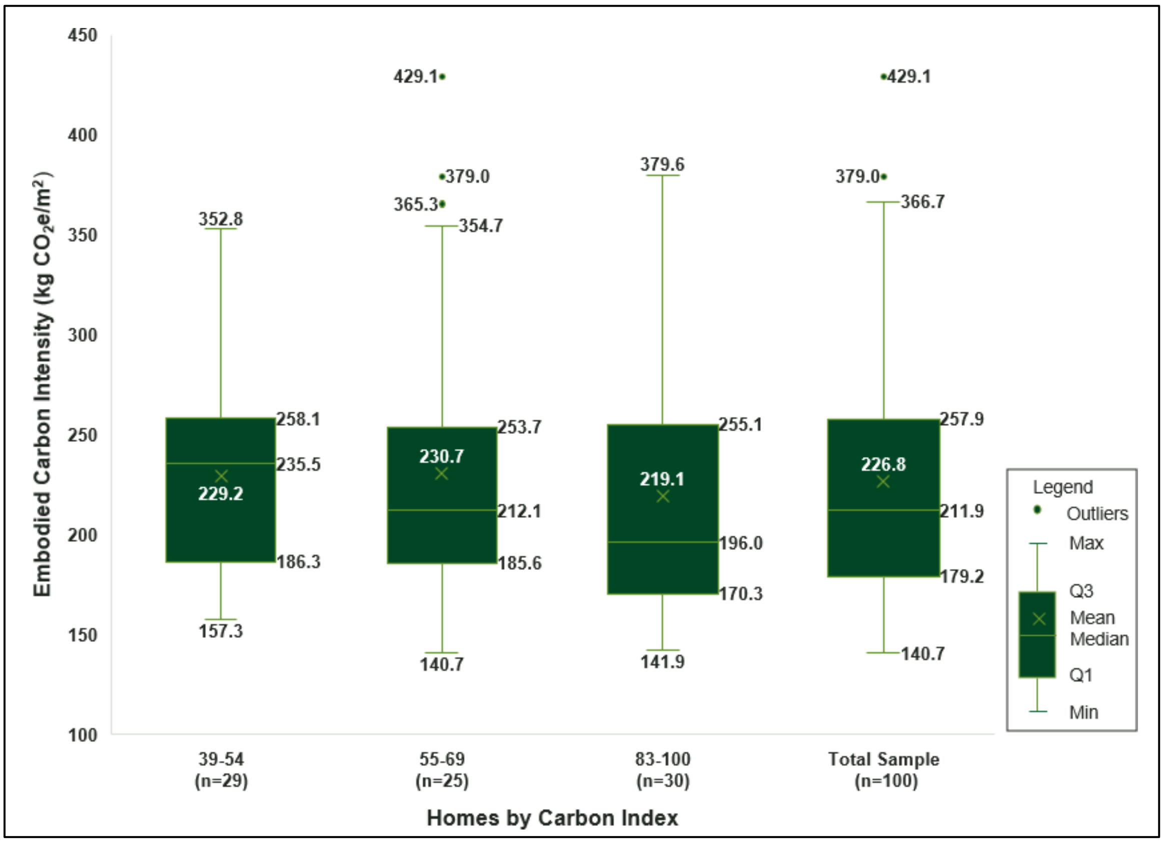


Table 58: 25-Year Cumulative Forecast of Operational Carbon Emissions by Home Fuel Use

(tons)	All Electric	All Fossil Fuel	Mixed Fuel	Total Sample
n-value	*26*	*4*	*70*	***100***
Mean	57.7	180.6	143.9	**123.0**
Median	54.9	155.6	140.4	**125.3**
Min	30.6	101.8	51.6	**30.6**
Max	107.0	309.3	349.6	**349.6**
Std. Deviation	16.09	90.73	55.93	**63.71**

The RESNET® Carbon Index is a scale that measures the homes' operational carbon impacts relative to a 2006 IECC reference home. It uses hourly energy consumption projections from a HERS® Index calculation and emissions rates by fuel type to give the home a score on a similar scale used for the HERS® score, where 100 is the reference home. [45] The higher the Carbon Index score, the more carbon that home emits (Figure 49). Higher or lower HERS® Carbon Index scores did not yield trends in building ECI.

Figure 49: ECI Results by Carbon Index Score (kg CO_2e/m^2)
(Includes Building Enclosure and MEP)



45 https://www.resnet.us/about/hers-carbon-rating-index/

Appendix E Results by Primary Heating Equipment Type

This appendix provides additional information on embodied carbon emissions, operational energy consumption, and operational energy emissions based on the primary heating equipment type.

The appendix provides additional data for interested readers. Some results may need additional analyses and assessments to fully contextualize the results. However, due to time and resource constraints, these data segmentations were not further explored in this study. It is recommended that deeper, specific analysis is conducted to supplement the findings presented in the main body of the report with these additional segmentations to provide alternative perspectives on embodied carbon and operational carbon emission impacts.

Some general observations for the combined cumulative operational emissions and embodied carbon emissions by primary heating equipment type:

- Homes with air source heat pumps have far fewer total carbon emissions than any other primary heating type, with 13% lower MEP ECE, 19% lower building enclosure ECE, and 45% lower operational carbon emissions than the overall averages. The highest total carbon emissions are homes with propane boilers, with 18% higher MEP ECE, 27% higher building enclosure ECE, and 68% higher operational carbon than the overall average.
- When normalized by the conditioned floor area of the home, the differences are smaller. Homes with an air source heat pump still represent the fewest total carbon emissions, with 11% higher MEP ECE, 4% higher building enclosure ECE, and 27% lower operational carbon emissions than the overall averages. Homes with propane furnaces have the highest total carbon emissions, with 5% lower MEP ECE, 3% lower building enclosure ECE, and 22% higher operational carbon emissions than the overall average.

Figure 50: Average Embodied and Operational Carbon Emissions over 25 Years by Primary Heating Type (Tons of CO_2e)

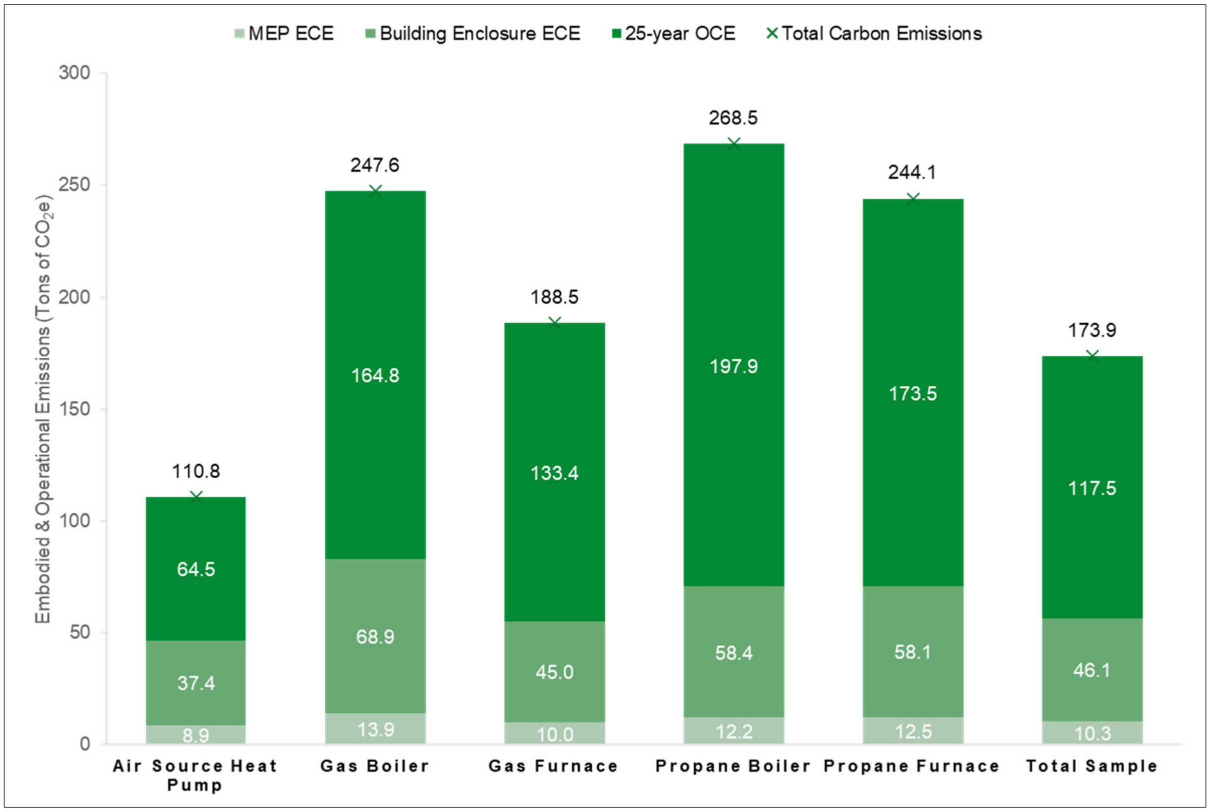


Figure 51: Average Embodied and Operational Carbon Emissions over 25 Years by Primary Heating Type, Normalized by Conditioned Floor Area (kg CO_2e/m^2)

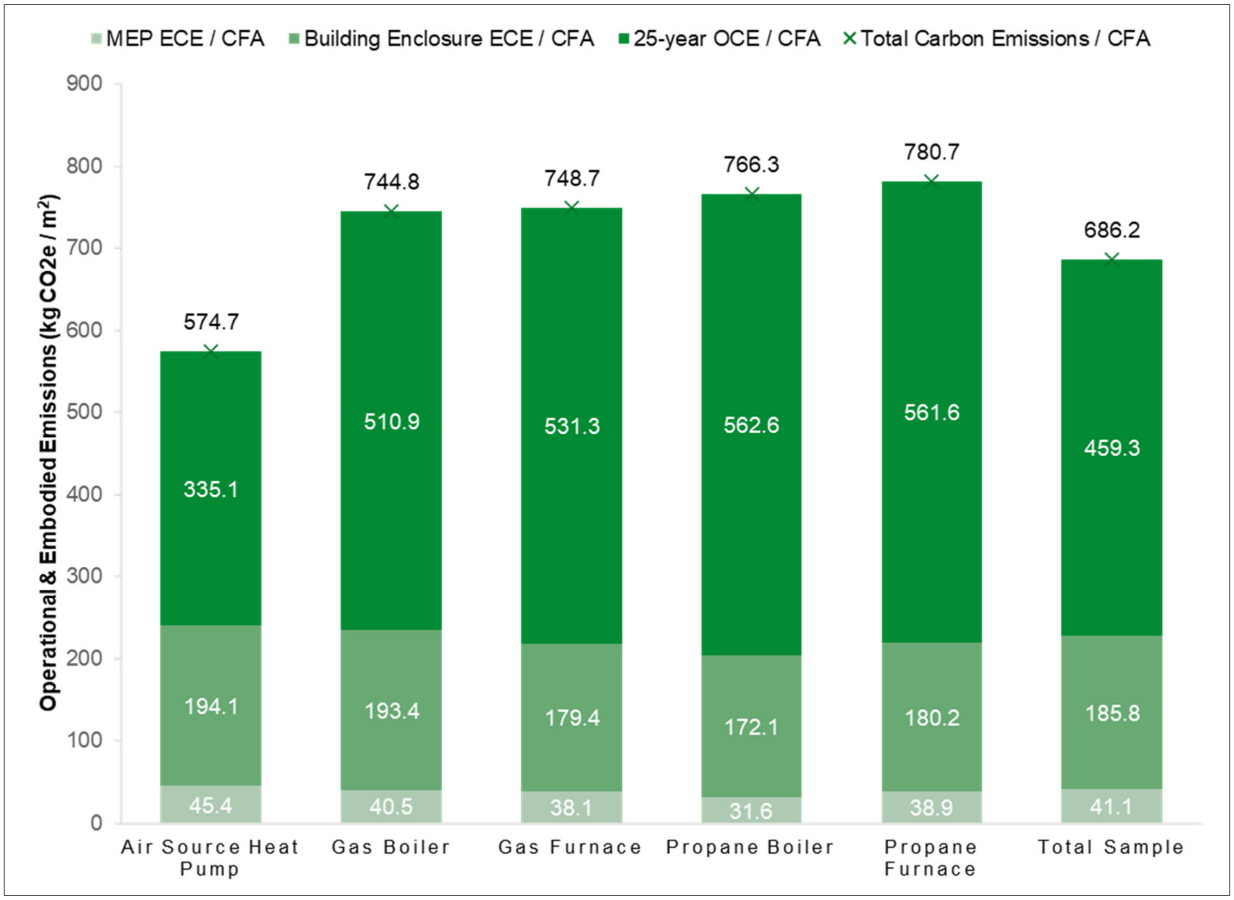


Table 59: Gross ECE by Primary Heating Type (Tons CO_2e)
(Includes Building Enclosure and MEPs)

	Air Source Heat Pump	Gas Furnace	Propane Furnace	Gas Boiler	Propane Boiler	Total Sample
n-value	*40*	*32*	*21*	*4*	*3*	***100***
Mean	46.4	55.0	70.6	82.8	70.6	**56.4**
Median	41.9	54.9	60.3	81.6	78.5	**52.7**
Min	18.5	28.6	30.2	23.8	44.3	**18.5**
Max	99.0	94.5	140.2	144.3	89.1	**144.3**
Std. Deviation	18.44	15.98	29.10	49.80	23.40	**24.29**

Table 60: Total Net ECE by Primary Heating Type (Tons CO_2e)

	Air Source Heat Pump	Gas Furnace	Propane Furnace	Gas Boiler	Propane Boiler	Total Sample
n-value	*40*	*32*	*21*	*4*	*3*	***100***
Mean	45.2	54.3	69.8	82.7	70.0	**55.5**
Median	40.2	54.0	60.3	81.6	78.5	**50.7**
Min	18.5	28.6	29.1	23.8	42.5	**18.5**
Max	99.0	94.5	140.2	143.9	89.1	**143.9**
Std. Deviation	18.40	16.11	29.50	49.63	24.42	**24.51**

Table 61: Gross ECE of Building Enclosure Only by Primary Heating Equipment (Tons CO_2e)

	Air Source Heat Pump	Gas Furnace	Propane Furnace	Gas Boiler	Propane Boiler	Total Sample
n-value	*40*	*32*	*21*	*4*	*3*	***100***
Mean	37.3	45.0	58.1	68.9	58.4	**46.1**
Median	34.3	46.1	50.9	66.5	67.4	**42.8**
Min	13.6	24.4	23.0	19.3	38.6	**13.6**
Max	77.3	80.2	116.6	123.2	69.3	**123.2**
Std. Deviation	14.88	13.50	24.79	42.97	17.21	**20.46**

Table 62: Net ECE of Building Enclosure Only by Primary Heating Type (Tons CO_2e)

	Air Source Heat Pump	Gas Furnace	Propane Furnace	Gas Boiler	Propane Boiler	Total Sample
n-value	*40*	*32*	*21*	*4*	*3*	***100***
Mean	36.2	44.2	57.3	68.8	57.8	**45.2**
Median	33.5	43.7	50.9	66.5	67.4	**41.1**
Min	13.6	24.4	21.9	19.3	36.8	**13.6**
Max	77.3	80.2	116.6	122.8	69.3	**122.8**
Std. Deviation	221.0	13.6	25.2	42.8	18.3	**20.6**

Table 63: Total ECI per Total Floor Area by Primary Heating Type (kg CO_2e/m^2)

	Air Source Heat Pump	Gas Furnace	Propane Furnace	Gas Boiler	Propane Boiler	Total Sample
n-value	*40*	*32*	*21*	*4*	*3*	***100***
Mean	234.3	220.8	213.7	284.8	202.0	**226.8**
Median	234.1	203.6	193.2	290.6	189.8	**211.9**
Min	147.1	140.6	151.5	208.2	141.8	**140.7**
Max	429.1	379.0	379.6	350.0	274.3	**429.1**
Std. Deviation	61.0	60.1	59.3	50.5	54.7	**61.6**

Table 64: Total MEP-related ECE by Primary Heating Type (Tons CO_2e)

	Air Source Heat Pump	Gas Furnace	Propane Furnace	Gas Boiler	Propane Boiler	Total Sample
n-value	*40*	*32*	*21*	*4*	*3*	***100***
Mean	8.94	10.01	12.52	13.93	12.21	**10.33**
Median	8.16	9.41	11.23	15.09	11.09	**9.26**
Min	3.78	4.20	7.16	4.49	5.74	**3.78**
Max	22.24	17.82	23.66	21.06	19.79	**23.66**
Std. Deviation	4.185	3.296	4.958	7.037	7.093	**4.499**

Table 65: Total First-Year CO_2e Operational Emissions by Primary Heating Type [Tons]

	Air Source Heat Pump	Gas Furnace	Propane Furnace	Gas Boiler	Propane Boiler	Total Sample
n-value	*40*	*32*	*21*	*4*	*3*	***100***
Mean	3.36	6.07	7.88	7.44	8.95	**5.51**
Median	3.14	6.10	7.10	7.08	7.51	**5.49**
Min	1.44	3.19	5.13	3.62	5.98	**1.44**
Max	6.75	8.73	15.14	11.99	13.36	**15.14**
Std. Deviation	1.287	1.374	2.676	3.635	3.895	**2.659**

Table 66: CO_2e Operational Emissions per Conditioned Floor Area by Primary Heating Type [kg CO_2e/m^2]

	Air Source Heat Pump	Gas Furnace	Propane Furnace	Gas Boiler	Propane Boiler	Total
n-value	*40*	*32*	*21*	*4*	*3*	***100***
Mean	17.33	24.14	25.49	23.09	25.51	**21.70**
Median	16.56	24.18	24.49	22.25	21.28	**20.32**
Min	10.73	15.35	16.53	17.19	19.73	**10.73**
Max	32.01	38.15	39.28	30.68	35.52	**39.28**
Std. Deviation	4.335	6.158	6.117	6.110	8.707	**6.533**

Table 67: Heating CO_2e Emissions by Primary Heating Type [Tons]

	Air Source Heat Pump	Gas Furnace	Propane Furnace	Gas Boiler	Propane Boiler	Total Sample
n-value	*40*	*32*	*21*	*4*	*3*	***100***
Mean	1.48	3.58	4.85	4.35	5.59	**3.10**
Median	1.43	3.63	4.47	3.74	4.49	**3.16**
Min	0.38	1.70	2.60	1.88	3.84	**0.38**
Max	3.78	5.43	10.19	8.03	8.45	**10.19**
Std. Deviation	0.735	0.876	1.741	2.650	2.495	**1.854**

Table 68: Water Heating CO_2e Emissions by Water Heater Type [Tons]

	Heat Pump Water Heater (electric)	Tank Water Heater (electric)	Tank Water Heater (natural gas)	Tank Water Heater (oil)	Tank Water Heater (propane)	Instantaneous (natural gas)	Instantaneous (propane)	Total Sample
n-value	*38*	*6*	*6*	*1*	*7*	*26*	*16*	***100***
Mean	0.17	0.49	0.90	1.11	1.11	0.70	0.95	**0.57**
Median	0.15	0.50	0.88	1.11	0.94	0.67	0.92	**0.56**
Min	0.10	0.28	0.56	1.11	0.66	0.38	0.62	**0.10**
Max	0.37	0.76	1.20	1.11	1.78	1.13	1.31	**1.78**
Std. Deviation	0.049	0.178	0.247	N/A	0.454	0.210	0.162	**0.392**

Figure 52: 25-Year Forecast of Operational Carbon Emissions by Primary Heating

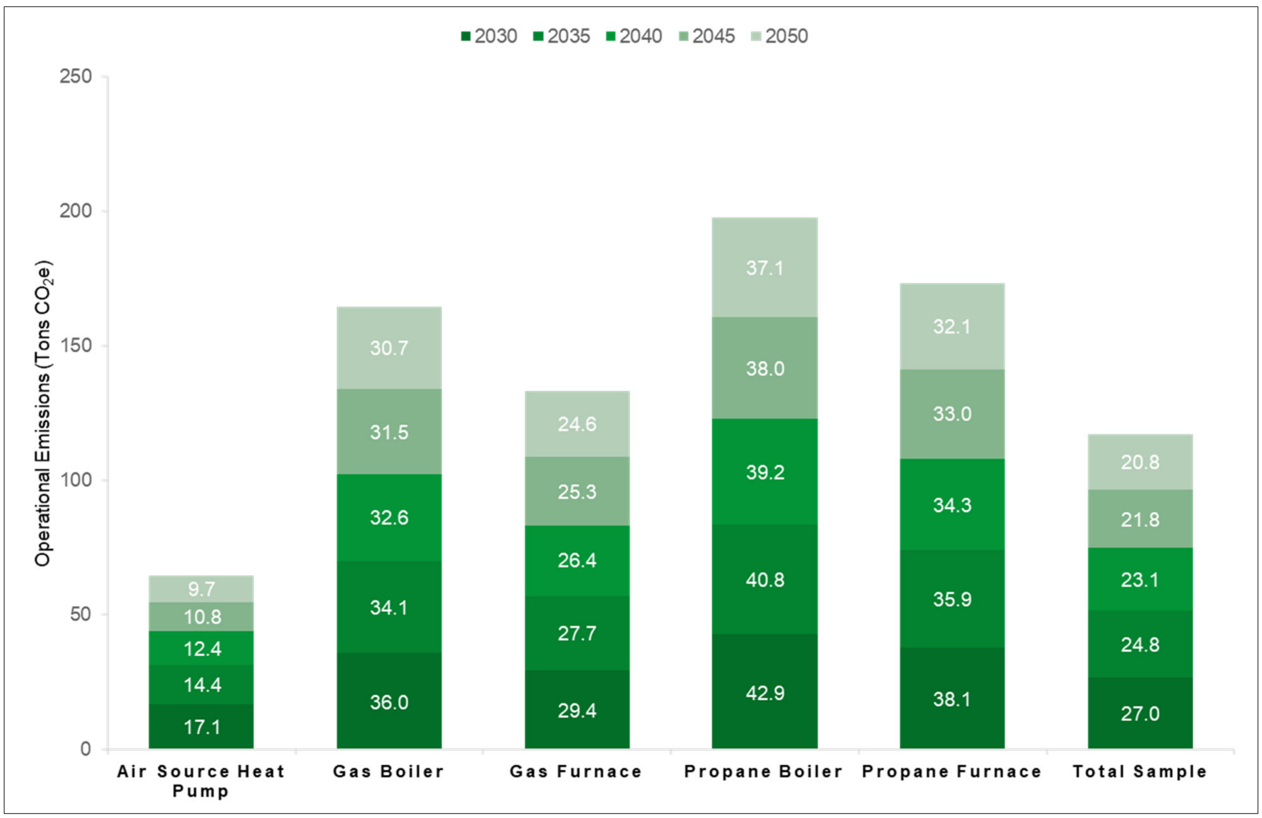


Table 69: 25-Year Cumulative Forecast of Operational Carbon Emissions by Primary Heating

(tons)	Air Source Heat Pump	Gas Boiler	Gas Furnace	Propane Boiler	Propane Furnace	Total Sample
n-value	*40*	*4*	*32*	*3*	*21*	***100***
Mean	67.8	172.2	139.5	206.8	181.4	**123.0**
Median	64.3	163.0	140.3	174.2	164.2	**125.3**
Min	30.6	83.6	73.8	137.1	117.6	**30.6**
Max	144.2	279.1	200.5	309.3	349.6	**349.6**
Std. Deviation	24.45	84.81	31.59	90.61	61.96	**63.71**

Appendix F Results by Foundation Type

This appendix provides additional information on embodied carbon emissions, operational energy consumption, and operational energy emissions based on the foundation type of the home.

The appendix provides additional data for interested readers. Some results may need additional analyses and assessments to fully contextualize the results. However, due to time and resource constraints, these data segmentations were not further explored in this study. It is recommended that deeper, specific analysis is conducted to supplement the findings presented in the main body of the report with these additional segmentations to provide alternative perspectives on embodied carbon and operational carbon emission impacts.

Some general observations for the combined cumulative operational emissions and embodied carbon emissions by primary heating equipment type:

- Homes with a slab foundation have low total carbon emissions, with 32% less MEP ECE, 32% less building enclosure ECE, and 33% less operational emissions than the overall average.
- Homes with more than one foundation type (e.g., a basement with both conditioned and unconditioned spaces) have the highest total carbon emissions, with 16% higher MEP ECE, 12% higher building enclosure ECE, and 25% higher operational emissions than the overall average.

When normalized by conditioned floor area, conditioned basements have low total carbon emissions, with 4% less MEP ECE, 6% less building enclosure ECE, and 15% less operational emissions than the overall average. Unconditioned basements stand out as having high total carbon emissions per conditioned floor area, with 6% higher MEP ECE, 16% higher building enclosure ECE, and 17% higher operational emissions than the overall average.

Note that homes with crawl spaces and those built over garages have low sample sizes, and therefore they are not considered significant for this discussion.

Figure 53: Average ECE vs 25-Year Operational Carbon Emissions by Foundation Type (Tons of CO_2e)

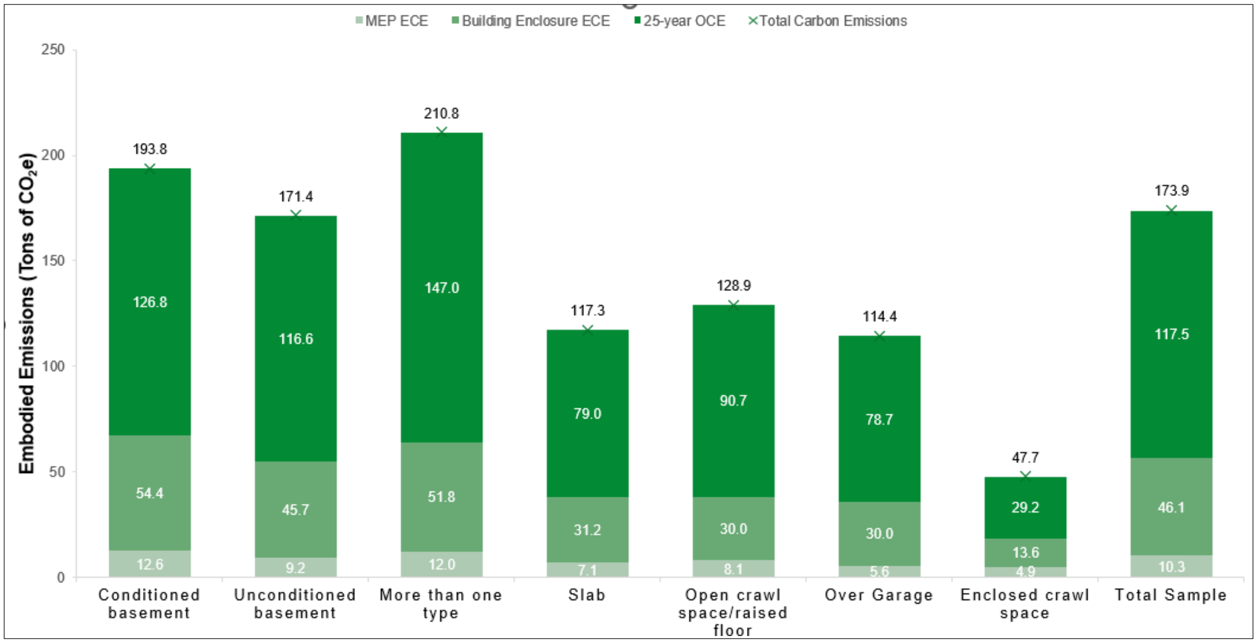


Figure 54: Average Embodied Carbon Emissions and Operational Emissions by Foundation Type, Normalized by Total Floor Area (kg CO_2e/m^2)

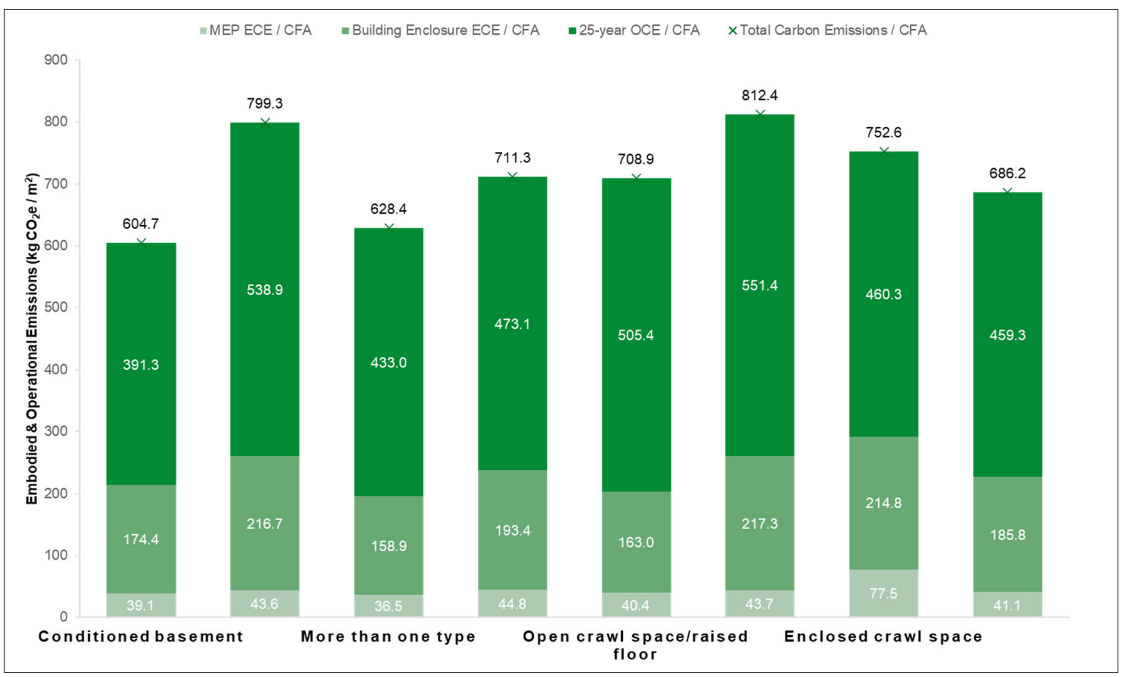


Figure 55: Emissions Time Series by Foundation Type

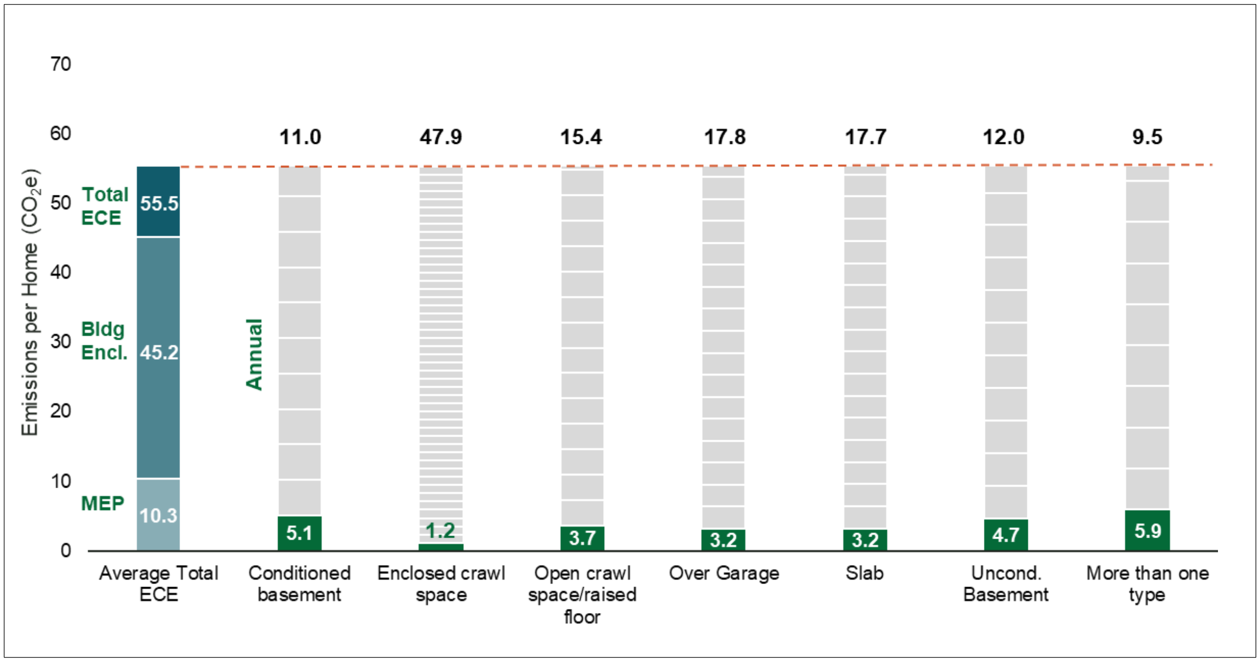


Table 70: Gross ECE by Foundation Type (Tons CO_2e)
(Includes Building Enclosure and MEPs)

	Conditioned Basement	Enclosed Crawl	More Than One Type	Open Crawl	Slab	Unconditioned Basement	Over Garage	Total Sample
n-value	*31*	*1*	*21*	*4*	*15*	*25*	*3*	***100***
Mean	67.0	18.5	63.8	38.1	38.3	54.9	35.6	**56.4**
Median	62.7	18.5	57.2	36.5	40.2	55.7	29.0	**52.7**
Min	28.6	18.5	24.4	29.9	21.6	28.4	23.8	**18.5**
Max	140.2	18.5	144.3	49.8	56.2	94.2	54.1	**144.3**
Std. Deviation	25.86	---	29.03	9.79	9.65	15.36	16.19	**24.29**

Table 71: Net ECE by Foundation Type (Tons CO_2e) (Includes Building Enclosure and MEPs)

	Conditioned Basement	Enclosed Crawl	More Than One Type	Open Crawl	Slab	Unconditioned Basement	Over Garage	Total Sample
n-value	*31*	*1*	*21*	*4*	*15*	*25*	*3*	***100***
Mean	66.0	18.5	63.0	37.9	37.1	53.9	35.6	**55.5**
Median	60.8	18.5	57.2	36.3	39.4	53.2	29.0	**50.7**
Min	28.6	18.5	21	29.1	21.5	28.4	23.8	**18.5**
Max	140.2	18.5	143.9	49.8	55.9	93.5	54.1	**143.9**
Std. Deviation	26.12	---	29.61	10.09	9.94	15.44	16.18	**24.51**

Table 72: Gross ECE of Building Enclosure Only by Foundation Type (Tons CO_2e)

	Conditioned Basement	Enclosed Crawl	More Than One Type	Open Crawl	Slab	Unconditioned Basement	Over Garage	Total Sample
n-value	*31*	*1*	*21*	*4*	*15*	*25*	*3*	***100***
Mean	54.4	13.6	51.8	30.0	31.2	45.7	30.0	**46.1**
Median	51.9	13.6	49.3	30.1	31.4	45.9	23.6	**42.8**
Min	24.4	13.6	20.4	23.0	15.9	23.4	19.3	**13.6**
Max	116.6	13.6	123.2	37.1	48.7	80.5	47.0	**123.2**
Std. Deviation	21.39	0.00	24.84	6.83	8.98	13.92	14.88	**20.46**

Table 73: Net ECE of Building Enclosure Only by Foundation Type (Tons CO_2e)

	Conditioned Basement	Enclosed Crawl	More Than One Type	Open Crawl	Slab	Unconditioned Basement	Over Garage	Total Sample
n-value	*31*	*1*	*21*	*4*	*15*	*25*	*3*	***100***
Mean	53.4	13.6	51.0	29.8	30.0	44.8	30.0	**45.2**
Median	49.5	13.6	48.4	30.1	31.2	43.1	23.6	**41.1**
Min	24.4	13.6	17.2	21.9	15.9	23.4	19.3	**13.6**
Max	116.6	13.6	122.8	37.1	48.3	79.8	47.0	**122.8**
Std. Deviation	21.50	0.00	25.40	40.43	9.17	14.04	14.87	**20.6**

Table 74: ECI By Foundation Type (kg CO_2e/m2)

	Conditioned Basement	Enclosed Crawl	More Than One Type	Slab	Unconditioned Basement	Open Crawl	Over Garage	Total Sample
n-value	*31*	*1*	*21*	*15*	*25*	*4*	*3*	***100***
Mean	220.3	228.6	229.4	230.1	227.9	223.7	252.2	**226.7**
Median	211.8	228.6	214.9	239.7	197.5	203.9	268.8	**211.9**
Min	147.1	228.6	157.9	140.6	151.3	183.1	201.5	**140.6**
Max	366.7	228.6	350.0	353.7	429.1	303.9	286.4	**429.1**
Std. Deviation	57.7	---	53.1	55.2	78.9	47.1	36.5	**61.6**

Table 75: Carbon Index and HERS® Ratings by Foundation Type

	Mean Carbon Index	Mean HERS® Rating	Total Sample
Conditioned Basement	67.4	48.5	**31%**
Unconditioned Basement	76.8	51.0	**25%**
More than one type	71.7	49.3	**21%**
Slab	62.7	49.3	**15%**
Open crawl space / Raised floor	70.3	51.3	**4%**
Over Garage	67.3	50.0	**3%**
Enclosed Crawl Space	53.0	53.0	**1%**

Table 76: CO_2e Emissions per Total Floor Area by Foundation Type (kg CO_2e/ft^2)

(Tons)	Conditioned Basement	Enc. Crawl	More Than One Type	Open Crawl	Slab	Uncon-ditioned Basement	Over Garage	Total Sample
n-value	*31*	*1*	*21*	*4*	*15*	*25*	*3*	***100***
Mean	18.46	22.73	20.54	23.58	23.39	24.86	25.64	**21.70**
Median	16.54	22.73	20.47	23.26	20.83	24.96	27.13	**20.32**
Min	10.73	22.73	12.92	15.57	14.68	13.89	19.12	**10.73**
Max	38.15	22.73	28.66	32.21	39.28	36.40	30.68	**39.28**
Std. Deviation	6.398	N/A	4.097	8.498	7.734	5.879	5.924	**6.533**

Figure 56: 25-Year Forecast of Operational Carbon Emissions by Foundation Type

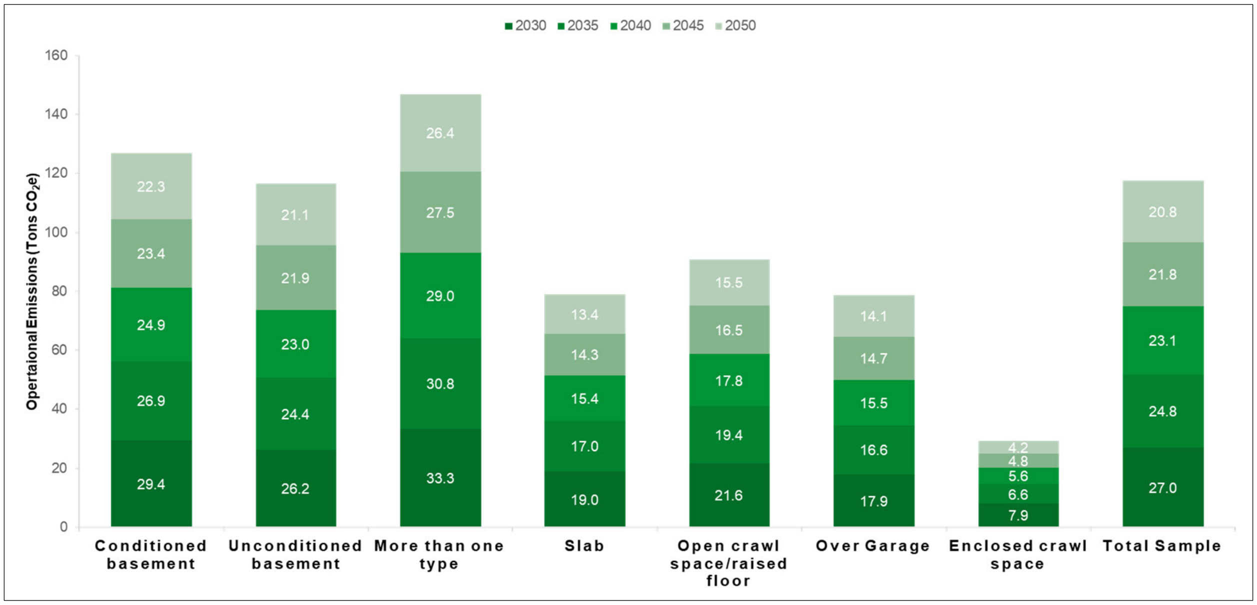


Table 77: 25-Year Cumulative Forecast of Operational Carbon Emissions by Foundation Type

(Tons)	Conditioned Basement	Enc. Crawl	More Than One Type	Open Crawl	Slab	Uncon-ditioned Basement	Over Garage	Total Sample
n-value	*31*	*1*	*21*	*4*	*15*	*25*	*3*	***100***
Mean	132.8	30.6	153.8	95.0	82.9	121.9	82.4	**123.0**
Median	132.6	30.6	139.4	93.9	63.2	139.8	83.6	**125.3**
Min	48.3	30.6	50.3	74.8	43.5	37.1	36.6	**30.6**
Max	349.6	30.6	309.3	117.6	171.3	169.5	126.9	**349.6**
Std. Deviation	68.59	---	79.12	18.22	42.22	41.71	45.15	**63.71**

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