# When Operations Met Materials, An Emissions Story

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## ABSTRACT

The Intergovernmental Panel on Climate Change (IPCC) has issued carbon reduction recommendations that are being actively reflected in state and local decarbonization initiatives across the United States. Achieving these ambitious goals, however, requires broadening the scope of decarbonization strategies in both new and existing buildings. Currently, energy efficiency programs targeting new construction, renovations, and retrofits occupy a strategic position to influence material choices within projects. By incorporating low-embodied carbon materials, these programs have potential for immediate decarbonization.

Building on a presentation delivered at the previous IEPEC conference, which highlighted the potential for energy efficiency programs to address embodied carbon, this paper discusses the findings of a pilot study conducted in Massachusetts that examines both operational energy consumption and embodied carbon emissions from building materials. Specifically, it estimates embodied carbon emissions prior to building occupation, operational emissions estimates over time, who is positioned to conduct embodied carbon assessments, and how these can be incorporated into industry standard practice.

In this study, we explored the embodied carbon implications of newly constructed single-family homes, enlisting Home Energy Rating System (HERS) raters active in the state and training them to estimate embodied emissions by integrating HERS energy models with an embodied carbon estimation tool.

This research underscores the importance of integrating embodied carbon within energy efficiency programs to accelerate comprehensive decarbonization. By providing robust data and actionable insights, the study offers a replicable model for developing embodied carbon baselines that can guide policy, inform building practices, and inspire scalable solutions across sectors.

### Introduction

This paper summarizes the results from a pilot study analyzing the embodied carbon and operational carbon of newly constructed single-family homes in Massachusetts conducted by Stephans and Company, Ekotrope, Builders for Climate Action, and NMR Group Inc. on behalf of the Massachusetts Clean Energy Center (MassCEC), NationalGrid, and Eversource (NMR Group Inc. 2025). The study sought to quantify both embodied carbon emissions – those associated with the raw material extraction, transportation to manufacturing, and the manufacturing of construction materials (A1-A3 of the building lifecycle in Figure 1) – and operations (B6).

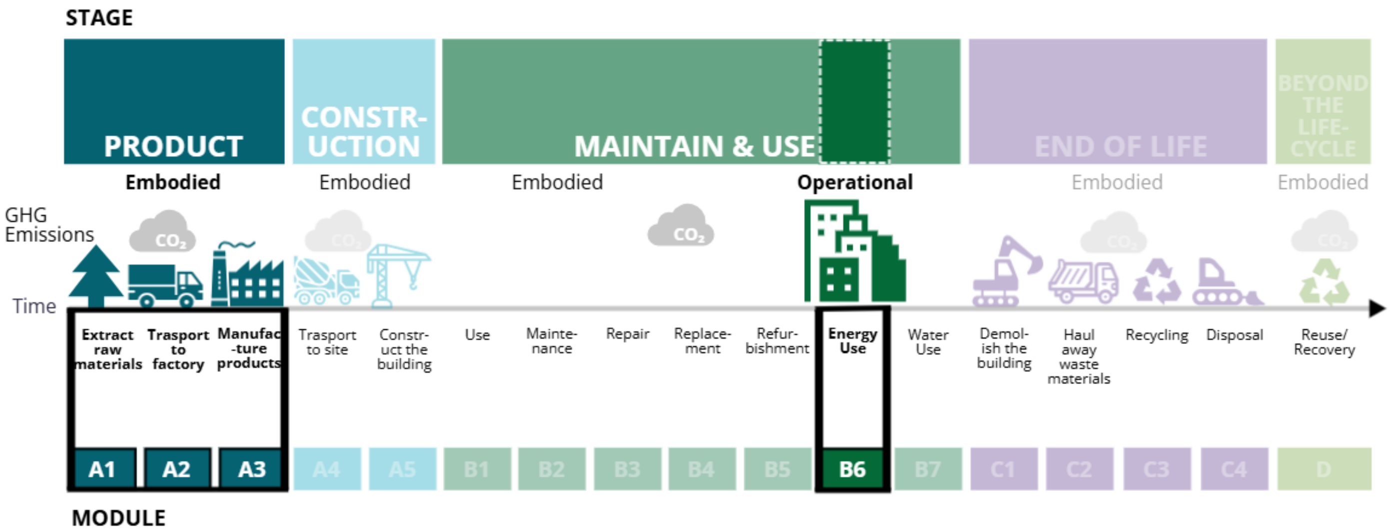


Figure 1. Building lifecycle emissions and pilot study module focus.

The project had four primary components:

1. Developing and testing a semi-automated beta software integration that links energy modeling outputs from Ekotrope, a RESNET accredited software, with embodied carbon estimates from the Building Emissions Accounting for Materials (BEAM) tool.
2. Recruiting and training Home Energy Rating System (HERS) raters in embodied carbon assessment methods, leveraging their existing data collection and modeling workflows.
3. Establishing foundational frameworks, training modules, and quality assurance (QA) processes to enable raters to consistently integrate operational and embodied carbon accounting.
4. Analyzing combined carbon impacts to identify patterns, understand potential reduction strategies, and evaluate the point at which cumulative operational emissions equal upfront material-related emissions.

The findings demonstrate a practical pathway for embedding embodied carbon assessment into existing energy efficiency programs, offering actionable strategies for policymakers, utility program designers, and building industry professionals seeking to reduce the full carbon footprint of new residential construction.

## Background

The Northeast Home Energy Rating System Alliance (NEHERS) formed the Embodied Carbon Working Group in the spring of 2020 with two primary goals:

1. Advocate for the development of a RESNET standard on embodied carbon; and
2. Explore the potential role of HERS raters in collecting the data needed to support embodied carbon tracking in the U.S. residential sector.

In 2017, buildings were responsible for *nearly half* of global carbon emissions, 28%, from operations, and 21% from the embodied carbon associated with the production and distribution of building materials (Racusin 2020). While the building industry has made significant progress in reducing operational emissions, the use of high embodied carbon materials has the potential to offset these efficiency gains. Unlike operational emissions, which accrue over time and can be reduced with changes to the generation mix, embodied cardon emissions are fixed by the time materials are manufacture. Since embodied carbon is released before a home is occupied, its reduction is critical to meeting near-term climate targets. Integrating embodied carbon alongside operational carbon assessments allows for the identification of 'low-hanging fruit' in upfront carbon savings—an essential step toward achieving global carbon targets by 2030 and beyond.

When NEHERS began this effort, no formal building code mechanisms for reporting embodied carbon existed. Committees such as ASHRAE 90.2 were beginning to explore the issue, but no consistent methodology had been adopted. Meanwhile, commercial-sector-focused tools and databases—such as the Carbon Leadership Forum's resources—were expanding rapidly. Grassroots initiatives, including Builders for Climate Action and New Frameworks, highlighted the urgency of addressing embodied carbon in residential construction, which represents nearly 50% of new floor area in the U.S (Webster 2020).

HERS raters were identified as a key asset in this effort. Preliminary estimates suggested that 60%-90% of the data points required for embodied carbon assessments were already being collected for operational carbon modeling through the HERS rating process, depending on the home's design features. By supplementing this existing workflow with targeted material-specific inputs, raters could deliver comprehensive carbon profiles covering both operational and embodied emission impacts.

In pursuit of this vision, NEHERS began advocating for a dedicated RESNET standard. By late 2022, the initiative had gained broad support from stakeholders across North America. In fall 2023, NEHERS formally recommended the creation of a standard for embodied carbon assessments in residential construction. On July 11, 2023, the RESNET Board of Directors approved the formation of Standard Development Committee 1550, comprising 35 experts—including HERS raters, architects, software developers, residential builders, and building material manufacturers. As of this writing, the proposed standard is undergoing its final round of public review, comment, and revisions.

Also in fall 2023, NEHERS secured funding from the MassCEC for the 100-Home Embodied Carbon Study. The pilot study was designed as the first large-scale test of whether typical HERS raters could assess embodied and operational carbon in tandem. Project objectives included developing a workflow for integrating Ekotrope, with the BEAM tool, creating training curriculums, establishing QA processes, and beginning to define a Massachusetts-specific baseline for embodied carbon emissions in residential new construction.

Additionally, at the 2022 IEPEC conference, the primary author of this paper delivered a presentation on the intersection of energy-efficiency programs, embodied carbon, and the opportunity to further drive near-term decarbonization through existing energy-efficiency programs by targeting low-embodied carbon insulation materials (Manning 2022). That paper's co-author, also from NMR Group Inc., and the primary author from this paper further explored this potential at the 2022 ACEEE Summer Study, emphasizing how existing program frameworks and industry professionals (e.g., HERS raters) could be leveraged to assess embodied carbon conditions (Woundy 2022). These presentations and papers sparked discussion among program administrators of energy-efficiency programs, especially in jurisdictions where traditional energy savings goals were being supplanted by decarbonization goals or mandates.

This work coincided with policy momentum in Massachusetts. Over several years, stakeholder groups produced white papers and proposed language codes, culminating in the February 14, 2025, amendment to the Massachusetts Stretch Energy Code. This update introduced embodied carbon credits for both residential and commercial construction. In addition, the Massachusetts Program Administrators of Mass Save concurrently worked to include embodied carbon into their recent 2025-2027 three-year plan, which has an emphasis on delivering decarbonization results in addition to traditional energy efficiency savings. These efforts, however, were not adopted into the final three-year plan for Mass Save.

## Study Objectives and Research Questions

The pilot study was designed to explore the feasibility of incorporating embodied carbon analysis into the existing workflow of residential energy modeling, with a focus on HERS raters. The study design sought to bring both operational and embodied carbon into the same lens, with the aim of combining new applications with real-world practices. While there were discrete objectives, each was interrelated in supporting a broader objective: to test 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. Key outcomes of the study effort include:

- The first operational 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 a semi-automated workflow between Ekotrope and BEAM.
- Creation of a dedicated HERS rater training curriculum to support education.
- Design and implementation of a QA framework to enable repeatability and scalability
- Initial development of a Massachusetts-specific embodied carbon baseline for newly constructed single-family homes.

These outcomes were developed specifically to evaluate feasibility within the study's structure, leveraging new homes that already had completed HERS ratings and energy models. It demonstrates the potential to incorporate embodied carbon assessments into the HERS rater workflow and a foundation to build further learnings, tools, and industry awareness. In practical implementation, embodied carbon assessments would occur concurrently with HERS rating, not retroactively. This would allow the HERS rater to inform reductions in both operational and embodied carbon emissions during the pre-construction and construction process.

This paper summarizes findings related to the following subset of research questions that the pilot study aimed to inform and answer:

- What are the embodied carbon emissions associated with the materials used in newly constructed single-family homes in Massachusetts?
- What is the total carbon footprint, both embodied and operational, associated with constructing and operating a new single-family home, for a 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 cost is required of HERS Raters to integrate embodied carbon assessments into their workflow?
- What structural or process-related barriers must be addressed to make embodied carbon assessments a mainstream component of residential energy rating practices?

## Methodology

This pilot study was designed to evaluate the feasibility of incorporating embodied carbon assessments into existing HERS workflows for newly constructed single-family homes. The approach combined identifying supplemental data collection requirements required for embodied carbon assessments, with the development of a semi-automated beta integration worksheet that derived outputs from Ekotrope energy modeling software into inputs for the BEAM tool to estimate embodied carbon emissions. This process established study-specific protocols for consistent data between models. The study also involved the recruitment and technical training of HERS raters on embodied carbon assessment procedures, follow-up surveys, and an analysis of the modeled energy consumption and associated operational emissions along with estimates of embodied carbon emissions.

**Study scope and sample.** The study analyzed 100 newly constructed single-family homes in Massachusetts, all of which had certified HERS ratings with complete Ekotrope energy models. Projects were recruited through the 15 participating HERS Raters, with a selection criteria focused on:

- Availability of complete project documentation to support both operational and embodied carbon modeling. Project documentation can include building plans, material specification sheets, and assembly details.
- Diversity of single-family home types, primary heating equipment, and fuel sources to ensure meaningful variation in the dataset.
- Geographic spread across Massachusetts to capture a range of construction practices.

While not randomly selected, homes were chosen to reflect diverse real-world construction practices, system types, and design choices. The pilot approach ensured that data collection and assessment processes could be grounded in actual market conditions while still aligned with study objectives.

**Workflow Development.** A central objective was to create and test a practical workflow for integrating operational and embodied carbon assessments. The workflow linked two primary tools.

1. Ekotrope: A RESNET-accredited software platform used by HERS Raters to generate energy models and operational emissions estimates. Ekotrope was selected given it is a cloud-based software that is commonly used in Massachusetts and supports energy code compliance for both base and stretch energy codes in the state.
2. BEAM (Building Emissions Accounting for Materials): an embodied carbon estimation tool developed by Builders for Climate Action. This tool was selected for its focus on residential construction materials

The study team developed a beta integration process that transferred an estimated 60%-70% of the required material and assembly data directly from Ekotrope to BEAM, with the remaining data collected through targeted rater inputs. This semi-automated process reduced manual entry while preserving flexibility for different home designs.

**Training and Quality Assurance.** Participant HERS Raters received dedicated training covering embodied carbon concepts and terminology, material data collection methods, use of the Ekotrope-to-BEAM integration worksheet and workflow. The study also established a QA protocol to review model inputs, verify data consistency, and ensure methodological alignment across participant raters. The QA process included over 160 total checks.

**Emissions Accounting.** The analysis produced two main emission metrics for each home:

- Embodied Carbon Emissions (ECE): Greenhouse gas emissions associated with material production, transportation to the manufacturing facility, and production, calculated in metric tons of $CO_2$e. These emissions occur prior to occupation of the building. ECE associated with the materials used in the building enclosure are estimated with the BEAM tool and the ECE estimated from the mechanical, electrical, and plumbing (MEP) systems use the RESNET Draft Standard 1550.[1] The associated report provides detailed information on the types of materials modeled within each of the home's assemblies. ECE is expressed in terms of gross ECE, which does not account for any biogenic carbon storage properties within a material (e.g., cellulose, wood fiber insulation), and net ECE which accounts for the material emissions after any carbon storage is accounted for. Net ECE is presented in the findings of this paper.

- Operational Carbon Emissions (OCE): Estimated annual and cumulative emissions from home energy use, based on modeled results from Ekotrope. Emissions factors for fossil fuels were aligned with RESNET fuel emission factors.[2] The emission factors associated with electricity generation were forecasted using the National Renewable Energy Lab (NREL) 2024 Cambian dataset, which provides estimates for annualized long-run marginal emission rates by grid region.[3] This study leverages values from the New England grid region.

Total carbon impact was assessed over a 25-year operational horizon (2025-2050), with both ECE and OCE expressed in absolute terms and as carbon intensity metrics normalized by conditioned floor area.

**Analytical focus areas of the study.** The study explored several key questions including the distribution of embodied carbon across material categories (e.g., concrete, insulation, mechanical systems); carbon emission by home type, home fuel usage, primary heating equipment type, and foundation type; the relationship between embodied carbon and operational emissions over time; identification of a 'breakeven points' where cumulative operational emissions equal upfront embodied emissions; and identification of commonly used materials that could lead to ECE reductions (e.g., cellulose vs. spray foam insulation).

**Limitations.** The study acknowledges several sources of uncertainty including the potential for sampling bias Due to the pilot 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 this sampling approach introduced meaningful bias compared to other newly constructed homes from the same period. Reliance on industry-average data for some materials, particularly when product specific data was unavailable in the project documentation, absence of refrigerant leakage impacts in MEP modeling, and use of projected (rather than measured) operational energy consumption and forecasted emissions profiles. In addition, the ECE estimates do not account for any repairs, equipment replacement, or renovations that may occur within the 25-year period of the home. We expand upon these limitations and sources of uncertainty in the report.

## Results

We present a selection of results from the pilot study, focusing on carbon emissions in three primary areas: (1) the ECE associated with the building enclosure—including the thermal envelope as well

[1] https://www.resnet.us/about/standards/minhers/draft-pds-01-resnet-1550-embodied-carbon/
[2] https://www.resnet.us/about/hers-carbon-rating-index/
[3] https://www.nrel.gov/analysis/cambium

as connected assemblies such as attached garages (AG), unconditioned spaces, and partition walls; (2) the ECE of MEP systems; and (3) cumulative operational emissions over a 25-year period. Additional findings examine ECE relative to home performance metrics (i.e., HERS scores). We also highlight feedback from participating HERS Raters regarding the added time, process modifications, and structural barriers associated with integrating embodied carbon assessments into their standard workflow. While the reporting for this study is still on-going, the report will include additional results by home type, fuel type, primary heating equipment, and foundation type. Although these findings extend beyond the traditional scope of energy-efficiency programs, they offer actionable insights for utility programs and policymakers working to evolve from a focus on kilowatt-hour and therm savings toward broader decarbonization goals.

**Cumulative Embodied Carbon and Operational Carbon Emissions over 25-Years**

Over a 25-year period, the combined impact of upfront ECE and cumulative operational emissions for the sampled homes averaged nearly 174 metric tons of $CO_2e$ (Figure 2). Almost one-third of this total (32%) was attributed to embodied carbon, with the building enclosure contributing 26% and the MEP systems contributing 6%. Larger homes generally exhibited higher ECE, though variation in materials played a role. Most materials used in the sample reflected common construction practices; nascent or biogenic materials, aside from cellulose insulation and limited use of wood fiber board, were largely absent. Additional details on specific materials and their associated impacts are not featured in this paper, but concrete, insulation, cladding, and materials associated with MEPs represent the largest ECE material categories. There are a wide variety of choices for these materials, with some products exhibiting high-levels of ECE and others exhibiting low-ECE, or even carbon storing potential.

Importantly, these ECE values represent only the initial manufacturing stage, including raw material extraction, transport to the production facility, and product manufacturing; they do not account for equipment replacements or renovations throughout the building's life. While operational emissions dominated over the full 25-year timeframe, embodied carbon emissions are realized before a building is even occupied. On average, it took 13.3 years of operational emissions to equal the magnitude of the upfront ECE. This finding underscores the value of targeting ECE reductions to achieve near-term decarbonization goals, particularly those set for 2030.

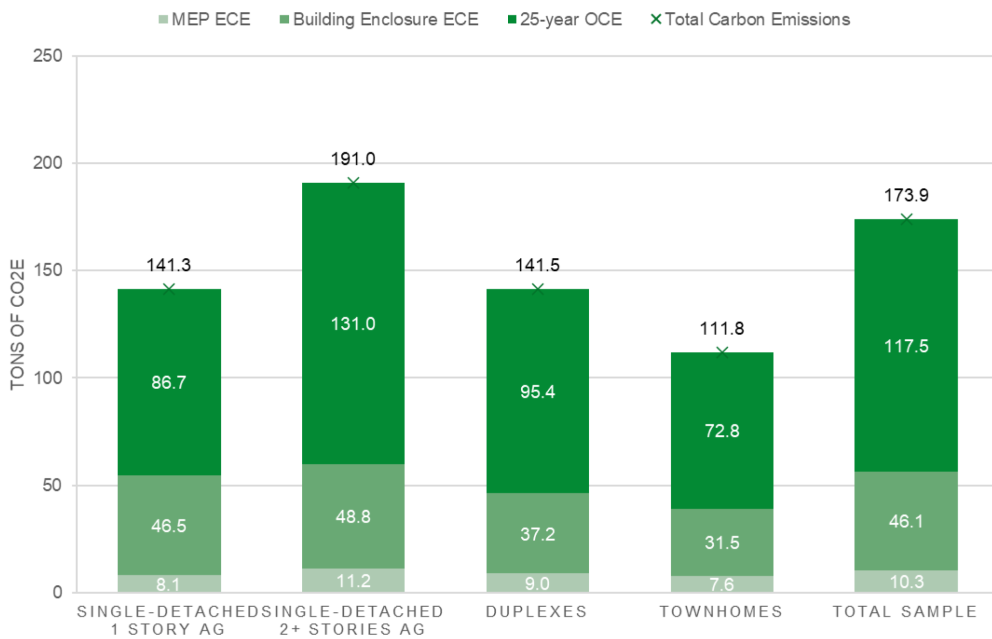


Figure 2. Average embodied and operational carbon emissions over 25 years by home type (tons of $CO_2e$).

**Embodied Carbon Emissions and Home Performance (HERS Scores)**

Embodied Carbon Intensity (ECI) measures the net ECE per unit of building area, expressed as kilograms of $CO_2e$ per square meter of conditioned floor area (CFA). For reference, the HERS Index represents a home's energy performance relative to a 2006 IECC baseline home, with lower scores indicating higher performance. Across the 100-home sample, HERS scores ranged from 37 to 60.

The average ECI was 226.8 kg $CO_2e$ per square meter of CFA, with no observed correlation between a home's energy performance (HERS score) and its ECI (Figure 3). In other words, high-performance homes, those with lower HERS scores, did not consistently exhibit higher carbon intensity due to the use of carbon-intensive materials, nor did they demonstrate systematically lower ECI through widespread use of carbon-storing materials. These findings suggest that achieving high operational efficiency does not inherently require higher ECE, and that both performance goals can be pursued in tandem.

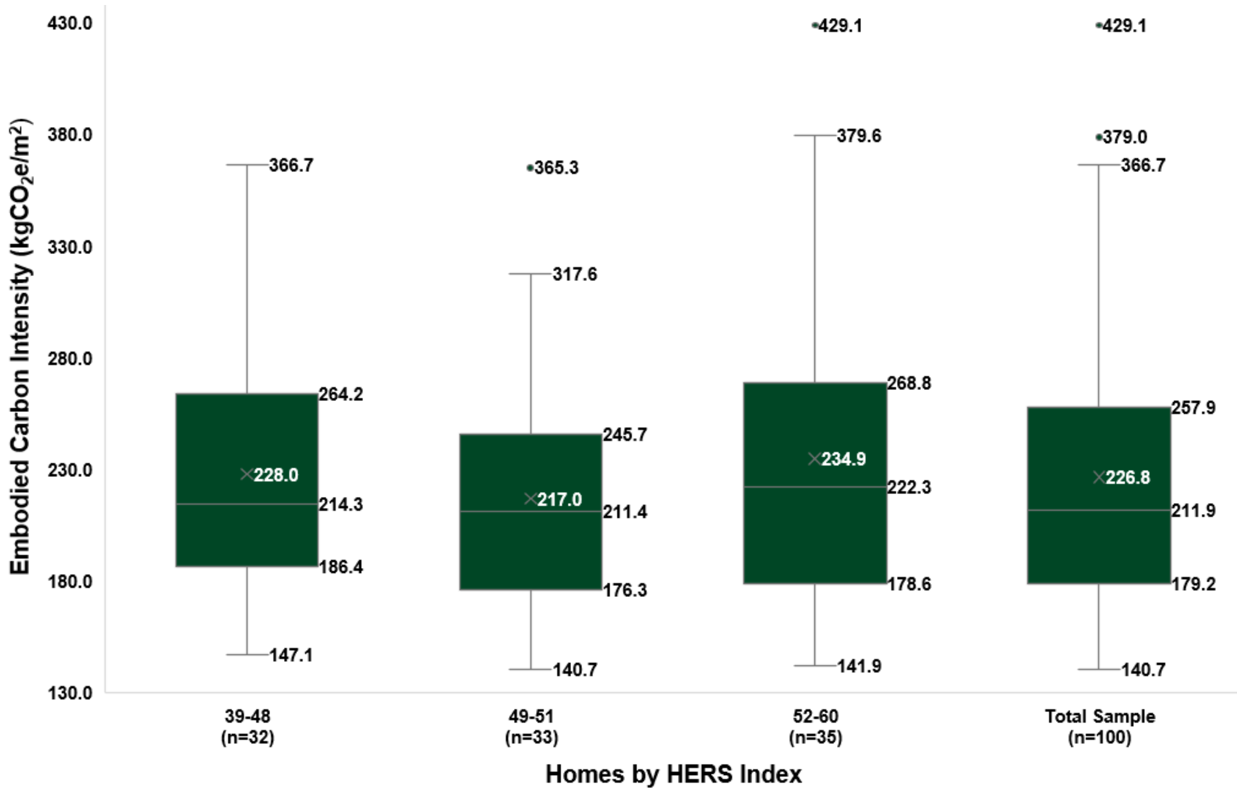


Figure 3. Total net ECI by HERS Index (kg $CO_2e/m^2$ of CFA), includes building enclosure and MEP systems.

**Practical Insights from Study Participants**

All but one participating HERS Rater reported improved productivity over the course of the study when estimating ECE per project. On average, participants reduced completion time from 3.5 hours to 2.7 hours, a 23% decrease in time, after completing between five and ten projects (Figure 4). By the end of the study, three participants were able to complete both the integration worksheet and transcribe that into the BEAM model in under two hours. However, respondents noted that larger or more complex homes required additional time. Time impacting the HERS Raters workflow was mentioned by nearly half of the HERS Raters but that did not discourage most of their likeliness to recommend low embodied carbon materials to builders and homeowners for future projects.

Although this pilot was conducted as a post-mortem analysis rather than during the initial HERS rating process, the results provide insight into the additional workload embodied carbon assessments may require. They also demonstrate the potential for future efficiency gains through a true software integration, with potential for built-in QA/QC checks, and concurrent assessment of operational and embodied carbon. Conducting these analyses in tandem, with seamless data transfer between platforms, would allow HERS Raters to deliver actionable insights to builders, designers, and homeowners. Building capacity to identify opportunities to reduce both ECE and OCE, and evaluate potential cost, design, and performance trade-offs.


Figure 4. Respondent reduction in time to complete embodied carbon assessment.

HERS Raters identified time requirements, scope expansion, and software integration as the primary considerations for incorporating ECE assessments into their workflow (Figure 5). Increased time demands were linked to the need for additional data collection and the complexity of unique home designs. Expanding the scope of analysis requires raters to assess the entire building, including areas outside the conditioned space and beyond the thermal envelope, as well as to conduct a more detailed examination of individual materials.

To make ECE assessments practical and scalable, enhanced software integration is essential. Improved interoperability between energy modeling and embodied carbon tools would streamline data transfer, minimize redundancy, and reduce the risk of transcription errors. One participant also noted that successful integration would require closer alignment with clients, ensuring that builder practices, architectural specifications, and homeowner budgets are considered early in the design process to support both operational and embodied carbon reduction goals.

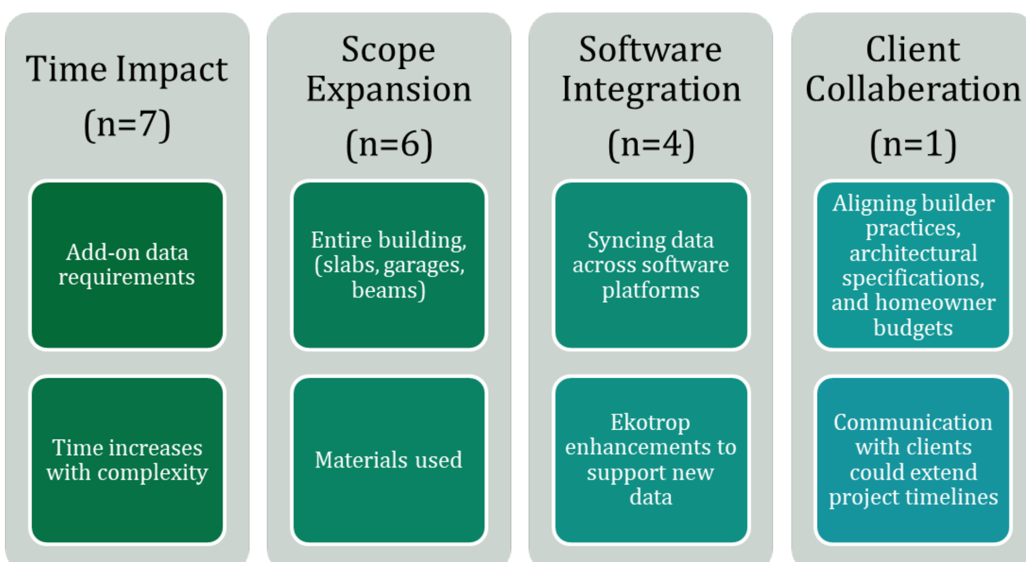


Figure 5. Change in workflow for embodied carbon assessments and analysis (n=12).

## Key Findings from the 100-Home Pilot Study

The 100-home pilot study revealed that ECEs are a substantial portion of a home's total carbon impact, accounting for an average of 55.5 metric tons $CO_2e$ per home, or roughly 32% of total emissions (174 tons) when combined with 25-years of operational emissions. ECE varied widely depending on home size, design features, structural systems, and materials used. Notably, high operational performance did not guarantee low ECE, underscoring the need for programs and policies to address both operational and embodied emissions in tandem. In addition, the time component plays an important role, in that addressing ECE can influence emissions before occupation of the building, while emission that results from operational use (or any energy savings) accrue over time.

One of the most encouraging findings was that HERS Raters are well positioned to integrate ECE assessments into their workflow with modest additional effort. Approximately 60–70% of the data required for ECE calculations in the BEAM tool were already available in HERS energy models. With targeted training and modest workflow refinement, raters can successfully complete embodied carbon assessments without significant disruption to their standard process. The semi-automated integration developed between the Ekotrope energy modeling platform, and the BEAM tool significantly reduced manual data handling and transcription errors. However, full automation through API-based integration remains an important next step to streamline the process, further reduce costs, and make embodied carbon assessments scalable across the residential construction sector.

Finally, this study comes at a time of strong policy momentum. Massachusetts' 2023 Stretch Energy Code now includes embodied carbon provisions for both residential and commercial construction. The residential provision provides a three-point HERS score credit to homes that incorporate low-ECE concrete or low-ECE insulation materials. Although embodied carbon measures were not included in the final 2025–2027 Mass Save Plan, alignment between code requirements, policy goals, and the potential for utility programs to integrate ECE metrics presents a near-term opportunity for accelerating adoption.

## Recommendations to Advance Decarbonization and Embodied Carbon Assessments

Findings from this pilot demonstrate both the feasibility and value of integrating embodied carbon assessments into the HERS Rater workflow. Building on these insights, we recommend the following actions to advance adoption, improve precision, and scale the practice across the residential sector.

1. **Advance software integration between operational and embodied carbon tools.** Automating data transfer between RESNET-accredited energy modeling platforms (e.g., Ekotrope) and embodied carbon calculators (e.g., BEAM) should be a top priority. Open API development and stakeholder collaboration can minimize manual data entry, reduce errors, and enable real-time carbon analysis during the design phase.
2. **Incorporate embodied carbon into utility program frameworks and codes.** Utility programs such as Mass Save, as well as state code agencies, should begin piloting embodied carbon credits or reporting requirements for residential new construction, noting there is already an approved mechanism in the Massachusetts stretch energy code. This pilot's workflow and results can serve as a template for early implementation, allowing programs to measure and incentivize both operational and embodied carbon reductions.
3. **Incentivize low-carbon and carbon-storing materials.** Policy makers and program administrators should design incentives that reward the use of low-ECE or carbon-storing materials where thermal performance is equivalent. Examples include tiered incentives for cellulose insulation, wood-fiber products, and low-carbon concrete, as well as penalties or disincentives for high-carbon-intensity alternatives.

4. **Develop targeted guidance for builders and designers.** Produce concise, practical guidance materials that identify cost-effective, low-ECE substitutions for common high-carbon building products. These guides should focus on materials readily available in mainstream supply chains, while also highlighting biogenic options with strong carbon-storage potential.
5. **Expand and refine the embodied carbon data ecosystem.** Broader availability of residential-scale Environmental Product Declarations (EPDs), particularly for MEP systems, is needed to improve analysis accuracy. Public databases and industry partnerships can help ensure that product-specific data are accessible, consistent, and representative of market-available materials.
6. **Continue baseline development through expanded sampling and longitudinal tracking.** While this study established an initial Massachusetts-specific baseline, expanding the sample size to other regions, climates, and housing types would provide more representative benchmarks. Ongoing annual tracking could establish trends, support policy alignment, and help programs evaluate the long-term impact of design and material choices.
7. **Integrate embodied carbon into climate policy targets.** State and municipal climate action plans should explicitly include embodied carbon in performance metrics, targets, and reporting. This integration will help ensure that near-term decarbonization goals capture the significant upfront emissions from construction.
8. **Support workforce training and scope evolution for HERS Raters.** Offer structured training modules that prepare raters to collect the additional data points needed for ECE analysis, interpret results, and communicate actionable recommendations. Training should also address how to manage expanded project scopes, including unconditioned spaces and detailed material specification review.
9. **Align early project collaboration to reduce both operational and embodied carbon.** Encourage early coordination among builders, architects, raters, and homeowners to identify carbon reduction opportunities before construction begins. This alignment can help integrate material choices, design strategies, and budget considerations into a coherent low-carbon plan.

By taking these steps, the residential construction sector can move from treating embodied carbon as an emerging niche issue to embedding it in mainstream practice, positioning raters, builders, and program administrators to address the full climate impact of new homes.

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