Small Footprints: Lessons from Three Years of Low-Carbon Small Home Design-Build Projects

NAOMI DARLING
Mount Holyoke College
University of Massachusetts Amherst

ROBERT WILLIAMS
University of Massachusetts Amherst

CARL FIOCCHI
University of Massachusetts Amherst

KENT HICKS
University of Massachusetts Amherst

BEN LEINFELDER
University of Massachusetts Amherst

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INTRODUCTION

In recent years, there has been an increasing focus on the role of embodied carbon within the overall carbon footprint of the built environment.(1) Historically, green building certifications and best practices primarily focused on operational energy and the associated operational carbon. Recent research has demonstrated that embodied carbon is a more significant factor than previously thought.(2) As the energy efficiency of buildings and the availability of renewable energy resources has improved, the relative impact of the material carbon emissions (MCE; i.e. cradle-to-gate or A1-A3 emissions) on the total life cycle carbon emissions (A1-C4) of buildings has increased (Figures 1 and 3) (3). As this has become apparent, an increasing array of tools, including Tally(4), EC3(5), and BEAM(6) among others, are now available to architects to assess the embodied carbon impacts of their design decisions. While the basic tenets of low-carbon design are clear – prioritize bio-based construction materials over synthetic, petroleum-based materials – there is still an open question about how carbon accounting is best integrated into the design process. This paper addresses these issues through presenting the results of three iterations of a university-based design-build program dedicated to designing and building high-performance, low-carbon small homes (Figure 4).

DESIGN BUILD PROGRAM

Founded in 2020 (7), this program is a collaboration between the University of Massachusetts Department of Architecture, Building and Construction Technology program, and the Five College Architectural Studies program, with faculty and students from all three (Figure 2). This unique collaboration enables the design-build teams to develop detailed operational energy and embodied carbon calculations while also investing in material and assembly development and testing, beyond the capacity of a single program. Each of the three houses incorporate best practices for high-performance construction and are designed to be net-zero ready. Each year the teams have refined the primary assemblies based on experiences from the prior iteration, including embodied carbon analysis.

MATERIAL CARBON EMISSIONS COMPARISONS

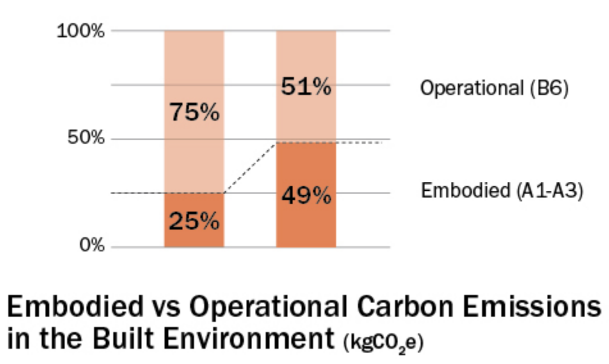

Figure 1. Increasing importance of Embodied Carbon. By authors. Adapted from Architecture 2030.

Figure 2. The 2024 team: undergraduate and graduate level architecture and building construction technology students.

PROJECT

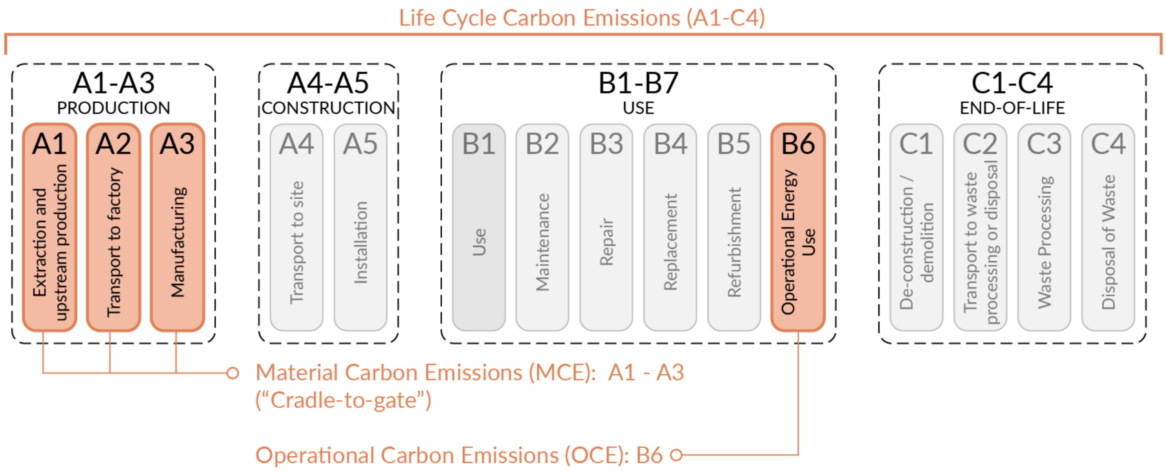

Figure 3. Life Cycle Carbon Emissions - diagram adapted by authors from: ES BN15978:2011.

Figure 4. Three iterations of low carbon small homes

The design-build teams rely on the Building Emissions Accounting for Materials (BEAM) tool developed by Builders for Climate action. Unlike Tally and EC3, which require detailed Revit models and/or bills of materials, BEAM is relatively user friendly, needing only assembly square footages, and is designed for residential applications. Despite the relative ease of use, the design-build team found that beyond following general heuristics for low-carbon design, the embodied carbon calculations are most impactful in refining the projects year-to-year (Figure 5).

The first project, the "Hygge House", included 2x6 framing with dense pack cellulose and an exterior layer of 3" of Gutex brand wood fiberboard insulation. The MCE for the project were about 15% lower than an average new home, relative to building floor area.(8)(Figure 6) In the second year – the "Paper House" – the team further reduced the MCE by nearly 40% relative to average construction, primarily by using reclaimed polyisocyanurate

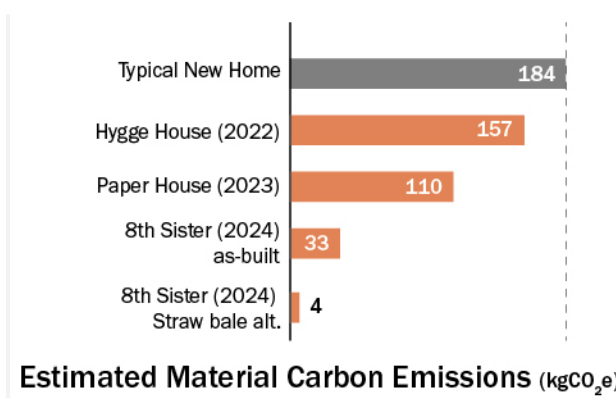

Figure 5. Estimated MCE for 3 years compared to a typical new home

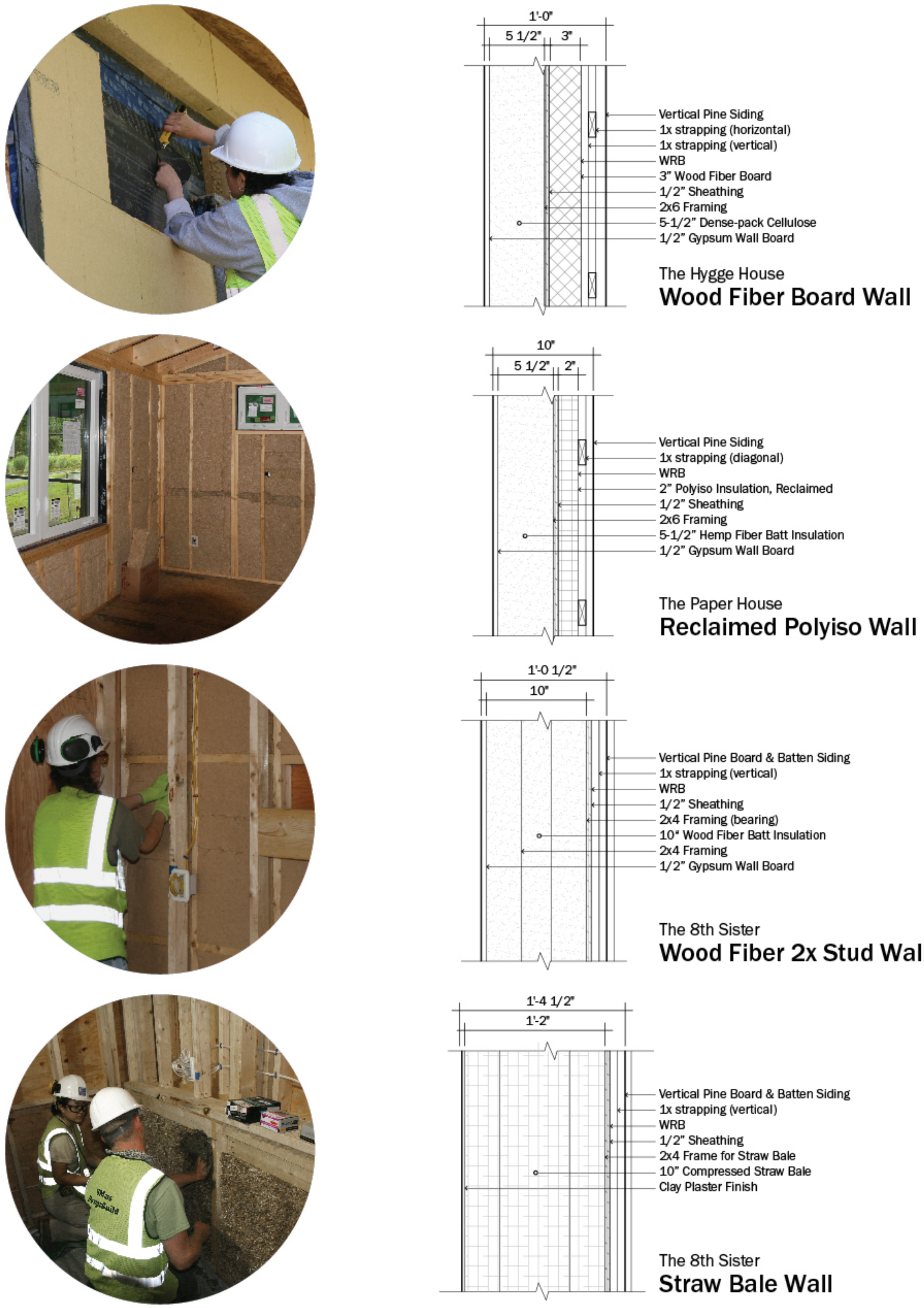

Figure 6. Wall assemblies and photos of walls used in the first 3 homes

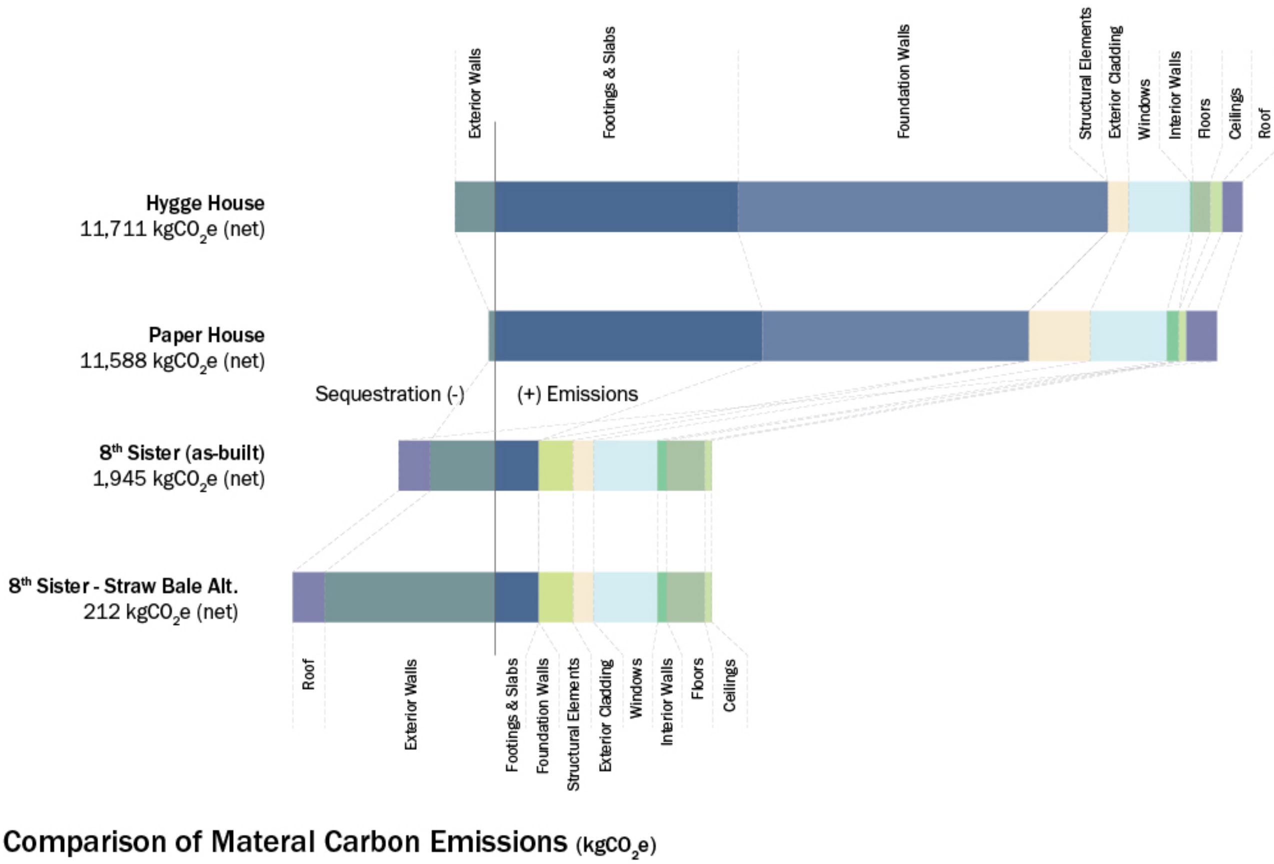

Figure 7. BEAM Comparision of MCE for the first three homes and a projected alternate home

insulation (which was assumed to have an MCE value of 0) along with hemp-fiber and conventional cellulose insulation. Notably, both houses included full basements with concrete foundations, which is the dominant source of embodied carbon emissions (Figure 7).

The most recent iteration – the "8th Sister", constructed in 2024 – incorporated additional bio-based materials and, critically, eliminated full concrete foundations relying instead on simple concrete piers.(9) This one change was the single most impactful decision in reducing MCE. This third house also includes 10" deep double-stud walls with regionally produced TimberHP brand wood fiberboard batt insulation, along with a small test section of compressed straw bale wall insulation (Figure 8). For comparison, the team also modeled an alternate version assuming the straw bale assembly throughout. The as-built house achieves an 82% reduction in MCE while the straw bale alternative would achieve an estimated 98% reduction in MCE relative to average new home construction; quite close to true carbon-zero construction but at the expense of thicker walls that would reduce usable square footage in an already small house. Additional developments can be seen in the roof assemblies. Paper House used a peel and stick membrane that has a slightly higher MCE than the asphalt shingles used on Hygge House. 8th Sister used a wood fiber insulation that has a much lower MCE than even cellulose, giving us a net-negative roof assembly. The remaining high carbon costs are attributed to the windows, suggesting the imperative for window manufacturers to reduce MCE in their products (Figure 9).(10)

It's worth noting that despite the significant relative reductions in MCE over the three years, the absolute embodied carbon impacts are quite low throughout. Paper House has the highest estimated MCE with nearly 12,000 kgCO2e; equivalent to approximately thirteen roundtrip flights from JFK to LAX. (11) The concrete alone is equivalent to approximately ten roundtrip flights. Given the value of a basement with respect to functionality, durability, and maintenance, it's worth asking whether the carbon cost is worth it, especially with advances in reduced GWP concrete mixes.

Figure 8. Straw bale compression assembly. Photo by Josey Wermuth.

Figure 9. Taping around a window opening.

CONCLUSIONS

Working on houses of a similar scale in the same region over multiple years with a focus on reducing both operational and embodied carbon emissions has allowed us to target specific materials and assemblies with the greatest potential for carbon reductions. While these projects offer valuable lessons for other design-build programs and practitioners interested in pursuing true net-zero carbon design, the true value of this work is in recognizing a process of refinement specific to a typology and location. Ultimately, all building is local, constrained by both geography and politics. Simultaneously addressing the housing crisis and climate crisis will require practitioners from all regions to consider models for small, affordable homes with reduced environmental impacts. The model outlined here of iterative refinement, of balancing embodied carbon with operational energy use, and of targeting materials and assemblies with the most impact enables the development of true low-carbon housing to fill the gap in our current national housing shortage. Although through our academic design-build model our refinements happen only incrementally with one small house per year, this process of refinement could happen much more quickly in practice as architects and builders work to supply the large numbers of units of housing needed to fulfill the current demand.

ENDNOTES

1. Chris Magwood and Tracy Huynh, “The Hidden Climate Impact of Residential Construction”, Rocky Mountain Institute, 2023, accessed October 4, 2024, https://rmi.org/insight/hidden-climate-impact-of-residential-construction/.

2. Martin Rock, et al., “Embodied GHG emissions of buildings – The hidden challenge for effective climate change mitigation,” Applied Energy 258 (2020). https://doi.org/10.1016/j.apenergy.2019.114107.

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3. United Nations Environment Programme, Building Materials and the Climate: Constructing a New Future, Nairobi, 2023, accessed October 04, 2024. https://wedocs.unep.org/handle/20.500.11822/43293

   “Why the Built Environment”, Architecture 2030, 2023, accessed October 4, 2024, https://www.architecture2030.org/why-the-built-environment/why-buildings/.

4. “Tally”, Building Transparency, accessed October 10, 2024, https://choosetally.com/.

5. “EC3 User Guide”, Building Transparency, accessed October 10, 2024, https://www.buildingtransparency.org/ec3-resources/ec3-user-guide/.

6. “BEAM Estimator”, Builders for Climate Action, accessed October 10, 2024, https://www.buildersforclimateaction.org/beam-estimator.html.

7. We needed to pause during COVID when students were sent home in March of 2020

8. Assuming an average of 184 kgCO2e/m2 for new residential homes. See Magwood and Huynh 2023.

9. The design team explored both helical piles and conventional concrete piers, ultimately settling on concrete piers because it’s a more familiar construction system and the embodied carbon differences between helical piles and concrete piers was minimal.

10. This research is underway and progress has been made to lower the embodied carbon from the manufacturing of glass. See for example: Scott Colangelo. “Reducing the environmental footprint of glass manufacturing,” International Journal of Applied Glass Science. 2024; 15: 350–366. https://doi.org/10.1111/ijag.16674

11. Based on the Terrapass carbon footprint calculator. “Carbon Footprint Calculator”, Terrapass, 2024, accessed October 4, 2024, https://terrapass.com/carbon-footprint-calculator/.