Unveiling the Hidden Environmental Costs of Modern "Green" Buildings

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Abstract

The aim of this paper is to quantify these two environmental costs – “embodied carbon” and “operational carbon”- in the design of single-family homes and to arrive at a set of guidelines for balancing the two and achieving a truly net zero carbon building. These solutions include the reduction of concrete and the selection of different concrete mixes; the optimization of glazing (windows and glass doors); the substitution of biogenic materials for conventional wall insulation; the use of reclaimed and recycled materials; the reduction of overall building size; the avoidance of other high embodied carbon materials; the use of passive solar; and the adherence to energy code standards for thermal insulation, vapor barriers, air tightness, and other considerations.

To illustrate these best practices this research proposes a case study of a representative single-family home and explores four different design iterations of the same project, making a series of substitutions in that building’s construction to reduce its embodied carbon. The resulting design reduces the environmental cost of this building from highly carbon positive –twice the national average—to significantly carbon- negative. In its construction, this building design sequesters more carbon than it uses.

1. Introduction

The construction and operation of buildings impose a significant environmental burden—greater than any other human activity. As Mouton (2023b, p. 1) states, "Building construction and operation are responsible for around 37% of global, energy-related greenhouse gas (GHG) emissions, along with various other environmental impacts such as waste generation and land use." However, advancements in building envelope construction, air tightness, insulation, and mechanical systems have significantly improved buildings' operational efficiency. According to the United Nations Environment Programme's *2021 Global Status Report for Buildings and Construction*, emissions intensity in buildings—including both construction and operational emissions—decreased by 17.2% from 2015 to 2020 (UNEP, 2021, p. 5). During this period, energy intensity in building operations also declined by 6%, driven in part by an 11% rise in energy efficiency investments, a 13.9% increase in green building certifications, and the adoption of building energy codes in 10 additional countries (Ibid., p. 5).

Progress in "green" building has been insufficient to meet global greenhouse gas reduction targets, with 2020 decarbonization levels reaching only 40% of the necessary 2050 pathway (Ibid., p. 6). This shortfall may stem from an industry-wide focus on reducing operational carbon—emissions from heating, cooling, and building operations—while largely overlooking embodied carbon. Embodied carbon, which includes emissions from material extraction, manufacturing, transportation, and demolition, can account for up to 90% of a building's total emissions, especially in the critical years leading to 2050 (Röck, 2020, p. 7).

Efforts to reduce buildings' environmental impact have largely focused on operational emissions, neglecting other life cycle stages. While these measures have been effective, they have inadvertently increased embodied carbon emissions, both in absolute terms and as a share of total emissions (Mouton, 2023a, p. 1). The rise in construction-related emissions is concerning, suggesting that by overlooking embodied carbon, the green building industry may have unintentionally exacerbated the problem despite advancements in technology and engineering.

2. Literature review

Building codes and green incentives have increasingly prioritized reducing operational carbon, but over a building's lifetime, embodied carbon from production can be nearly twice as impactful on global warming. While energy efficiency measures like improved insulation and heat recovery lower operational emissions, they also increase material use, with production accounting for up to 60% of total emissions in low-energy buildings (Gustavson, 2010, p. 210). Despite this, sustainability frameworks like LEED place far greater emphasis on operational carbon reduction (42%) than on material reuse (6%) (USGBC, 2016, p. 7-8). However, studies show that using recycled materials can cut embodied energy by nearly 50%, highlighting the need for greater focus on material reuse in carbon reduction strategies (Thormark, 2002, p. 429).

While progress has been made in reducing operational carbon, research increasingly highlights the significance of embodied emissions. The issue extends beyond underestimating construction-related emissions—some advanced building techniques have actually led to higher overall emissions. Although building standards helped reduce embodied carbon from nearly 600 $kgCO_2/m^2$ in 2000 to 300 $kgCO_2/m^2$ in 2015, emissions for "new advanced buildings" have since risen to approximately 500 $kgCO_2/m^2$ (Röck, 2022, p. 4). This trend suggests that energy-efficient buildings may unintentionally contribute to higher embodied carbon, offsetting their operational carbon savings.

Röck et al. categorize new buildings into "New Standard" (code-compliant but not high-performing) and "New Advanced" (high-efficiency) buildings, finding that while standard buildings have reduced total carbon emissions, advanced buildings are seeing an increase. This trend is significant when considering the overall environmental impact of buildings over their lifetimes. Notably, nearly two-thirds of embodied carbon emissions occur upfront—during material production and construction—averaging about 340 $kgCO_2e/m^2$, or 63% of total life cycle embodied emissions (Röck, 2022, p. 10).

Lise Mouton and her team compared two exemplary Passive house buildings, Solar House in Switzerland and be2226 in Austria, to highlight the magnitude of embodied carbon emissions in construction. Both buildings feature low surface area to volume ratios, small south-facing windows for passive heat gain, and thick insulating envelopes, allowing them to operate without building-wide heating or cooling systems. The Solar House uses timber framing, rammed earth, and flax insulation, while be2226 is built with pre-stressed concrete floors, hollow brick walls, and lime plaster. Both buildings rely on passive solar gains and internal loads for heating, demonstrating Passive house principles of efficiency. Despite their operational efficiency, the embodied carbon emissions from their construction are significant and have been extensively studied, particularly be2226, which is considered a model building (Mouton, 2023b, p. 3).

The PEF4Buildings study, part of the European Commission's testing of the Environmental Footprint (EF) method, compared two office buildings as case studies, including the be2226 in Austria. Despite its high efficiency, be2226 is not considered an environmental success. A comparison between be2226 and the SolarHouse revealed that the upfront embodied carbon emissions of be2226 were more than double those of the SolarHouse, with 555 $kgCO_2e/m^2$ for be2226 versus 247 $kgCO_2e/m^2$ for SolarHouse (Mouton, 2023b, p. 5). A life cycle analysis of 73 construction elements showed that production phases (A1-A3) were the primary contributors to environmental impact, particularly cement-based construction due to its energy-intensive production process, which generates nearly one ton of CO_2 for every ton of concrete produced.

Cement-based construction is the most mass-intensive for all building types, requiring significant insulation to offset total construction emissions—ranging from 449 to 608 kg/m^2 when using straw insulation. In contrast, bamboo-based construction is far less mass-intensive, needing only 65 to 110 kg/m^2 of straw to achieve climate neutrality, even with bamboo transported from Asia (Carcassi, 2022, p. 5219). A building with a concrete skeleton is approximately 6.5 times more environmentally costly than one with a bamboo frame. Reducing embodied carbon is crucial, as its emissions are a one-time "carbon expense," whereas operational emissions are ongoing. Embodied emissions, occurring early in the building lifecycle, create a "carbon spike" that could use up the remaining GHG budget needed for future low-carbon energy production, jeopardizing climate neutrality by 2050. The time value of carbon emissions suggests that carbon released now may be more impactful than future emissions, emphasizing the urgency of reducing embodied carbon in the short term to avoid long-term climate damage.

3. Methodology

To reduce embodied carbon in buildings, two key strategies are essential: 1) using bio-based, carbon-sequestering or low-carbon materials, and 2) designing smaller buildings that require fewer resources for construction, maintenance, and disposal. The production stage of building materials has a far greater environmental impact than transportation or assembly, making it crucial to focus on material choices. A review of 73 building assemblies shows that the production stage (A1-A3) is the most significant contributor to life cycle emissions (Mouton, 2023, p. 5). Some of the most environmentally damaging materials include galvanized steel, extruded aluminum, glass, spray polyurethane insulation, and concrete, with galvanized steel being the most carbon-intensive. Reducing the use of these high-impact materials is essential to lowering the embodied carbon footprint of buildings (Lewis, 2022, p. 336-337).

Some building materials are either carbon neutral or carbon negative, offering significant environmental benefits. For example, expanded polystyrene insulation has low carbon emissions (49 $kgCO_2e/m^3$), while straw bales and dimensional lumber are carbon-negative, sequestering 128 $kgCO_2e/m^3$ and 615 $kgCO_2e/m^3$, respectively (Lewis, 2022, p. 336-337). By replacing environmentally costly materials like concrete, steel, and glass with these bio-based alternatives, buildings can be redesigned with drastically lower embodied carbon footprints. For instance, using straw bale, wood fiber, and cellulose insulation, and replacing steel with mass timber can create buildings that are both low in embodied carbon and operationally efficient.

Bio-based materials, such as straw, have been used in construction for centuries and are proven to be effective insulators. Straw, a waste product from agriculture, is affordable and widely available. In the case of the be2226 and SolarHouse buildings, replacing traditional insulation with straw and blown-in hemp reduced the embodied carbon footprint by up to 58%. At a larger scale, using straw insulation could act as a significant carbon sink, reducing the global warming potential (GWP) of a building by 24%, nearly matching the operational emissions over the building's lifespan (Mouton, 2023b, p. 9).

Straw insulation offers substantial carbon savings, both in terms of operational and embodied carbon, especially in different climates. A study in Iran showed that straw bale buildings reduced energy consumption by 57.49% to 83.12% compared to conventional buildings, with the most significant savings occurring in colder climates. In these regions, replacing traditional brick walls with straw bale walls could reduce both embodied and operational carbon emissions by up to 75%.

While timber construction is also carbon-sequestering, its long growth cycle (45-120 years) limits its carbon-offsetting potential. In contrast, straw, as a fast-growing crop, offers a much more effective and efficient carbon sink, as it can be harvested in under a year and used in construction, making it a superior bio-based material for low-embodied carbon buildings.

Biogenic insulation alone is not enough to offset the environmental impact of buildings with high embodied carbon structures, such as those made of concrete and brick. While timber-based buildings like the SolarHouse meet climate targets, buildings like the be2226 do not. To reduce embodied carbon, it's essential to reduce the use of concrete and steel, minimize glazing areas, and use biogenic materials for insulation and structural components.

However, the most effective way to reduce both embodied and operational carbon emissions is to design smaller, more efficient buildings. This can involve creating multi-use spaces, like combining bedrooms and offices, and avoiding excessive living areas. Smaller buildings are more environmentally efficient, and reducing square footage is crucial for meeting climate goals.

The trend of increasing single-family home sizes from the 1940s to the 2000s, with homes growing by 60% while household sizes have decreased, contrasts with the potential benefits of smaller homes. Designing the same number of rooms in a smaller space can significantly reduce both environmental and financial costs. For example, a smaller home can be 53% cheaper and 40% less impactful in terms of embodied carbon, saving both money and reducing carbon emissions (figure 1).

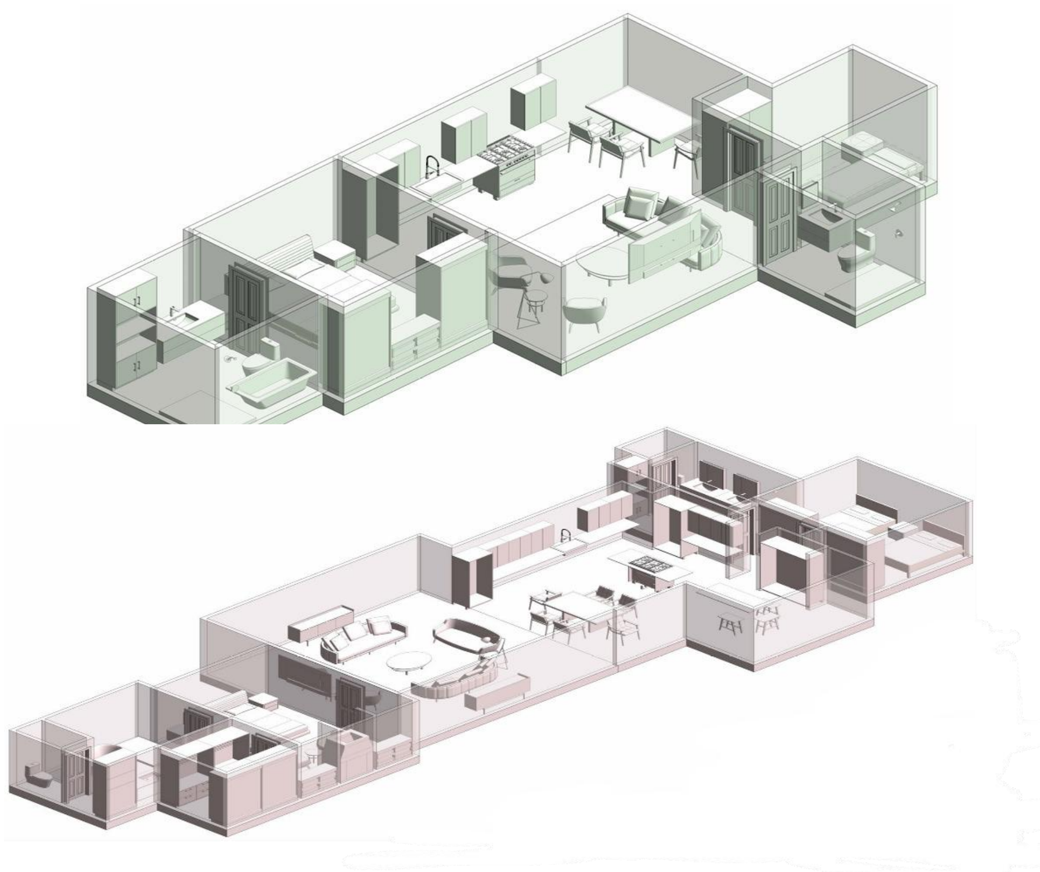

Figure 1: Comparative Axonometric of Two-Bedroom Apartments

4. Research Procedure

The case study examines the redesign of a single-family home to achieve low or negative embodied carbon. Using an iterative design process, four home models were created, each progressively reducing embodied carbon by modifying building materials. The BEAM software was used to calculate embodied carbon for different components, with material data sourced from Revit. The final design aimed to minimize both embodied and operational carbon emissions.

The study explores four home designs—High, Medium, and Low Embodied Carbon, plus Ultra-low Operational Carbon—each maintaining the same interior layout and program. The design includes four bedrooms, 3.5 bathrooms, offices, storage, and outdoor spaces. The research demonstrates that reducing embodied carbon does not compromise design quality and can also lower operational carbon emissions. The home is sited on Martha's Vineyard, Massachusetts, on a steep, north-facing hill with views of Vineyard South. It is positioned between tree stands for privacy, minimizing exposure to nearby trails and roads.

4.1 High Embodied Carbon Design

The High Embodied Carbon design features a compact floor plan, smaller than the national average, with multi-purpose spaces to optimize efficiency. The entryway integrates with the kitchen, some bedrooms double as offices, and a den serves as an additional bedroom. Outdoor living areas reduce embodied and operational carbon costs. The second floor is stepped back to maximize views while minimizing visibility from the neighboring home. Trees and a vegetated roof enhance privacy and screening.

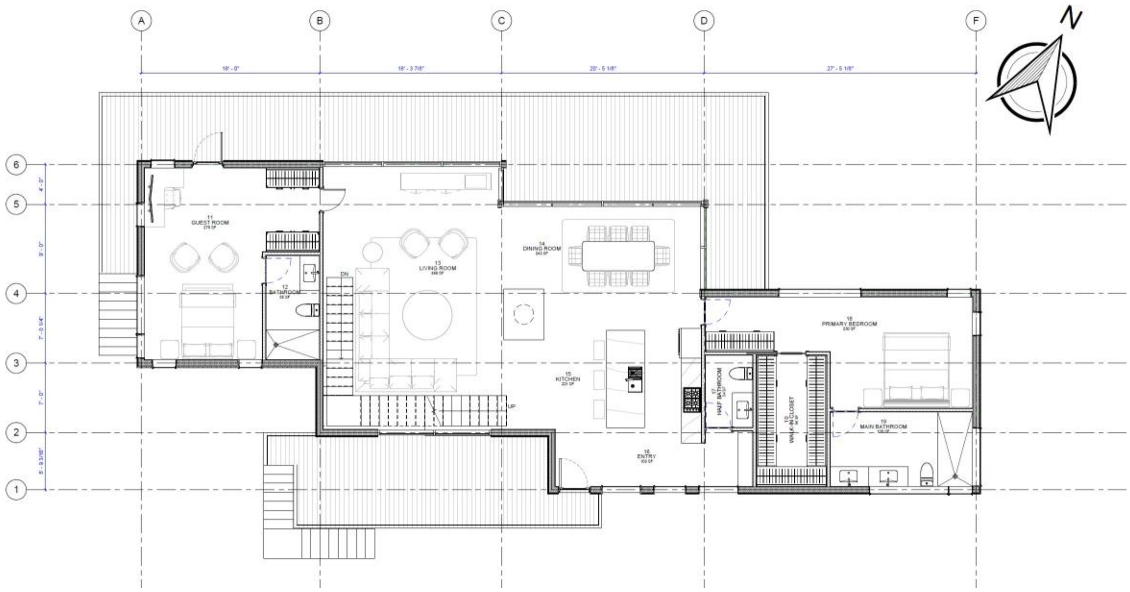

Figure 2: High Embodied Carbon Design, First Floor Plan

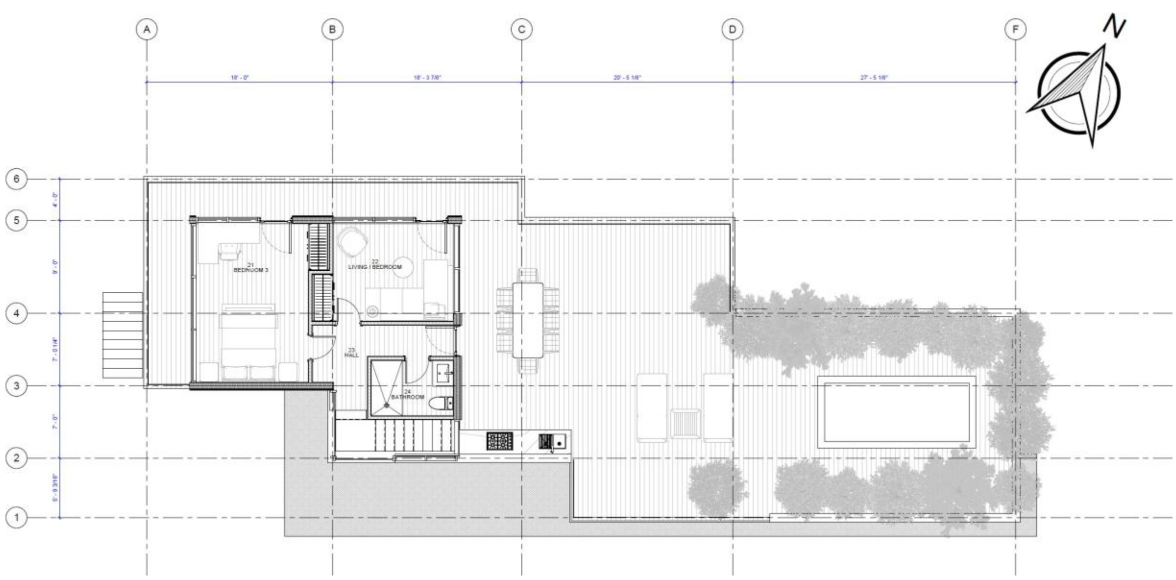

Figure 3: High Embodied Carbon Design, First Floor Plan

The angled roof and wide overhangs of the second floor serve to offer shade and overhead protection for an outdoor kitchen, outdoor dining, and large outdoor living area, as well as to visually balance the composition of the building.

Figure 4: High Embodied Carbon Design, South Perspective

Figure 5: High Embodied Carbon Design, North Perspective

To reduce embodied carbon, the foundation design was minimized, limiting the lower level to a garage, mechanical and storage rooms, and a stairwell enclosure. Expanding the foundation by 833 square feet would increase embodied carbon by approximately 7,468 kgCO2e (55%). The primary contributors to embodied carbon in the foundation are concrete and reinforcing bar (rebar).

Despite having an embodied carbon cost more than double the average American home (77,973 kgCO2e vs. 31,600 kgCO2e), the building performs 20% better than the Stretch Code, which is 45% stricter than the base energy code. This highlights a key issue with modern “Advanced Standard” homes—they meet high energy efficiency standards but still have significant environmental impacts. Given an average operational carbon footprint of 3,255 kgCO2e per year, the home's embodied carbon equals 24 years of operational emissions.

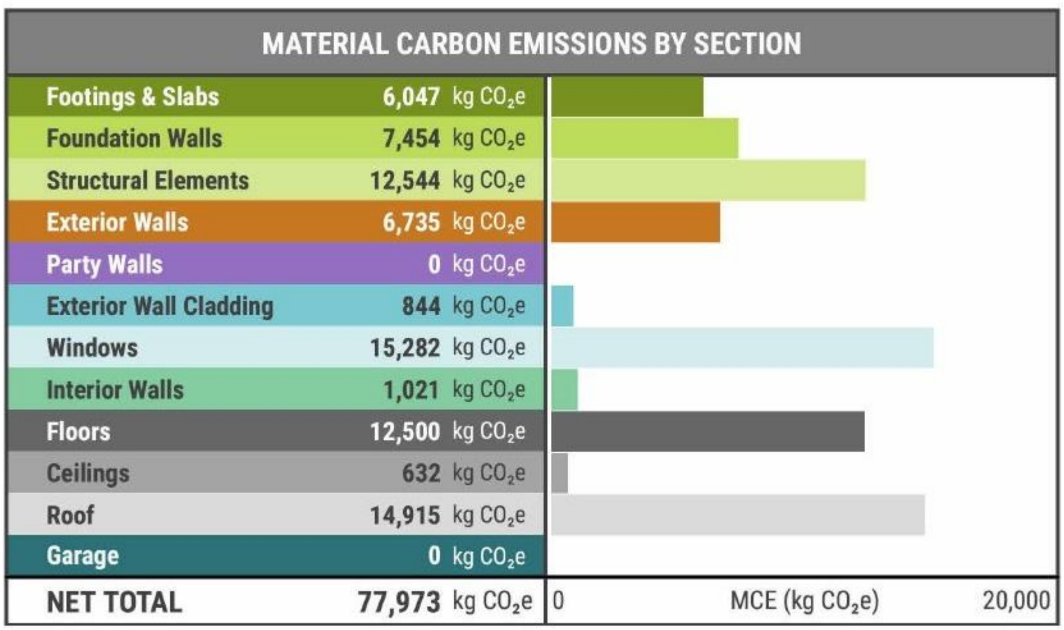

Figure 6: Building Emissions Accounting for Materials (BEAM), High Embodied Carbon Design

4.2 Medium Embodied Carbon Design

To reduce high embodied carbon emissions, the building was redesigned to meet, rather than exceed, Stretch Code insulation standards (R-30 floor, R-60 roof, R-15 walls). Changes included reducing glazing, eliminating the garage slab, and minimizing structural steel. These adjustments lowered embodied carbon by 23,771 kgCO2e (over 30%) compared to the high-carbon version. Key reductions came from cutting concrete use by 44% by replacing the garage slab with stone pavers and modifying garage walls. Further reductions could be achieved by using fly ash or slag instead of Portland cement. Insulation changes—reducing spray foam and incorporating mineral wool—further decreased embodied carbon by 17%. A base-code design could save an additional 7,000 kgCO2e, achieving a total reduction of ~37%. These changes are largely invisible and could also be cost-saving.

The biggest reduction in embodied carbon came from decreasing glazing and the associated structural steel needed for large spans and open corners. This change lowered embodied carbon from 27,826 kgCO2e to 15,230 kgCO2e—a 45% reduction. Modern homes often use wide spans supported by mass timber or steel, but reducing window spans cuts both glazing and structural material needs. Glazing alone accounts for 20% of the carbon budget (15,282 kgCO2e with a wood frame), while aluminum or fiberglass frames would increase emissions to 26–29% of the total.

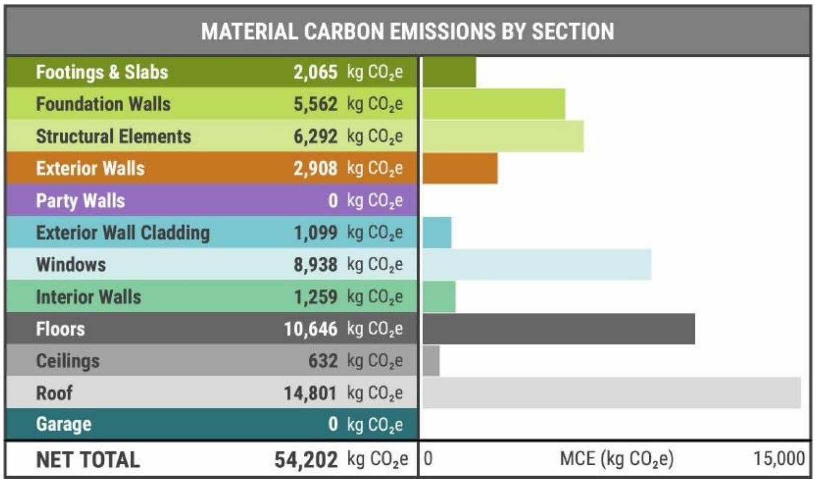

Figure 7: BEAM, Medium Embodied Carbon Design

Figure 8: Medium Embodied Carbon Design, South Perspective View

Figure 9: Medium Embodied Carbon Design, North Perspective View

Despite reducing insulation levels, the medium embodied carbon design maintains comparable or slightly better operational efficiency than the high embodied carbon version. The updated design achieves a 20.9% better-than-code rating, improving from the previous 20.2%. This suggests that reducing glazing and steel use has a greater impact on energy performance than excessive insulation.

The medium embodied carbon home remains highly carbon-intensive, emitting about 72% more CO_2 in production than a standard single-family home. To further reduce embodied carbon, the design was revised again, keeping the same layout but significantly cutting glazing and replacing all spray foam and mineral wool insulation with straw bales. This change represents the largest reduction in embodied carbon but also has the most noticeable visual impact.

4.3 Low Embodied Carbon Design

To eliminate the carbon costs of concrete, the foundation and footings were redesigned as stacked stone, with no concrete in the project at all, thereby removing 7,627 $kgCO_2e$ of embodied carbon.

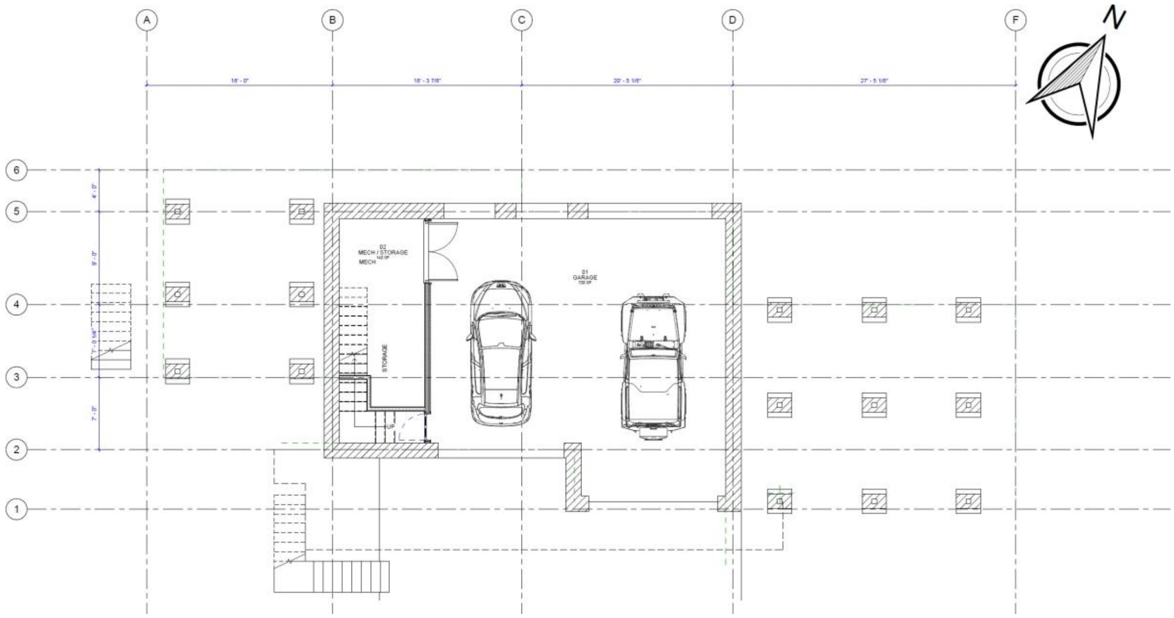

Figure 10: Low Embodied Carbon Design, Garage & Foundation Floor Plan

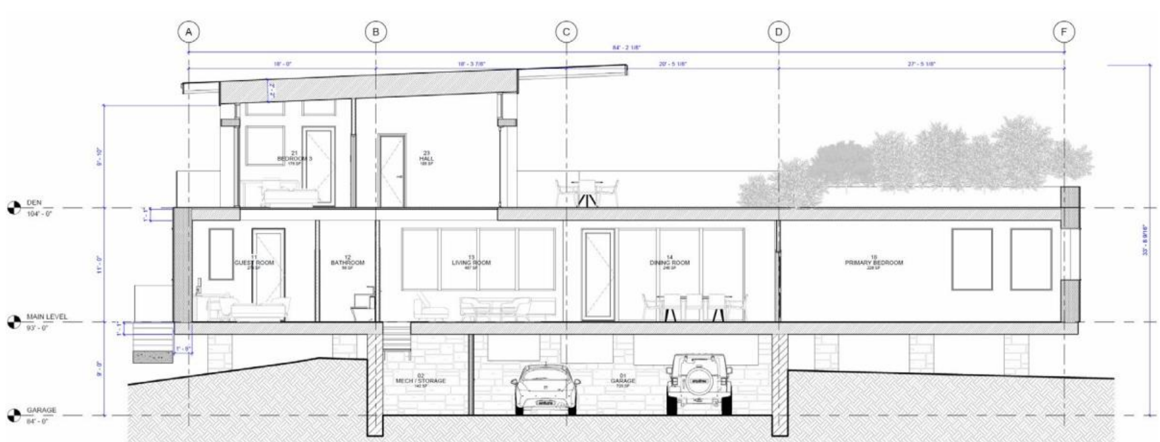

Figure 11: Low Embodied Carbon Design, Long Section

Glazing reductions lowered embodied carbon by 1,213 kgCO2e (19%). To improve thermal performance, double-pane windows were upgraded to triple-pane, adding a modest 212 kgCO2e (2%) in emissions. Key views were preserved while reducing glazing in bedrooms and bathrooms, enhancing privacy despite the semi-rural setting. The primary living space still feels open with substantial views. Additionally, the second-floor roof overhang was replaced with a fabric screen instead of a solid roof.

Figure 12: Low Embodied Carbon Design, South Perspective View

Figure 13: Low Embodied Carbon Design, North Perspective View

The changes are most noticeable in the floor plans, where the exterior envelope expands significantly, increasing from 2x6 framing to over 20-inch exterior walls (excluding furring, rain screen, and utility chase). However, the perspective views appear less altered, with the floor plans still offering options for deep windowsills, despite the larger wall dimensions.

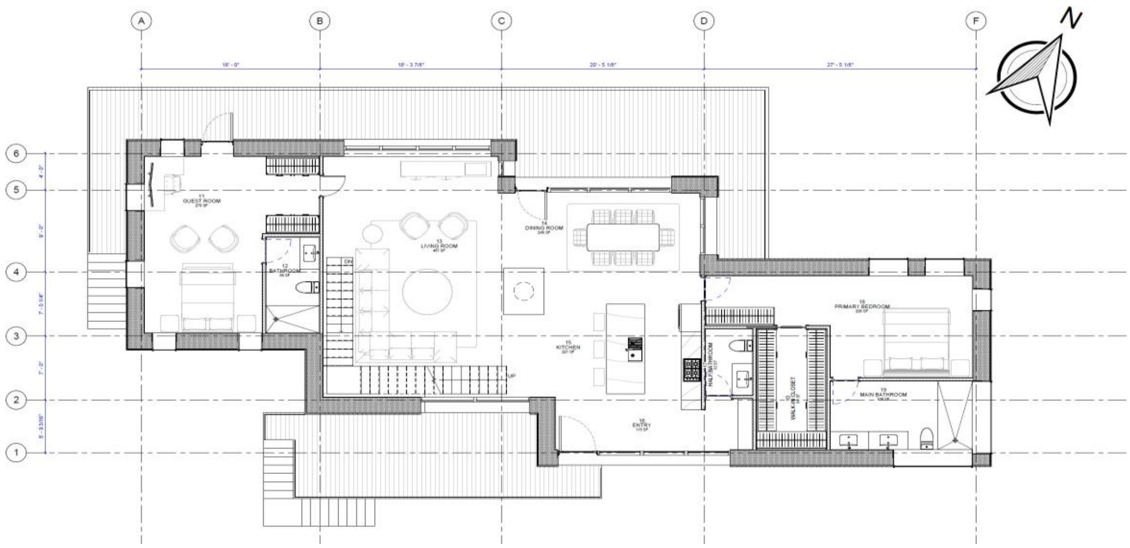

Figure 14: Low Embodied Carbon Design, First Floor Plan

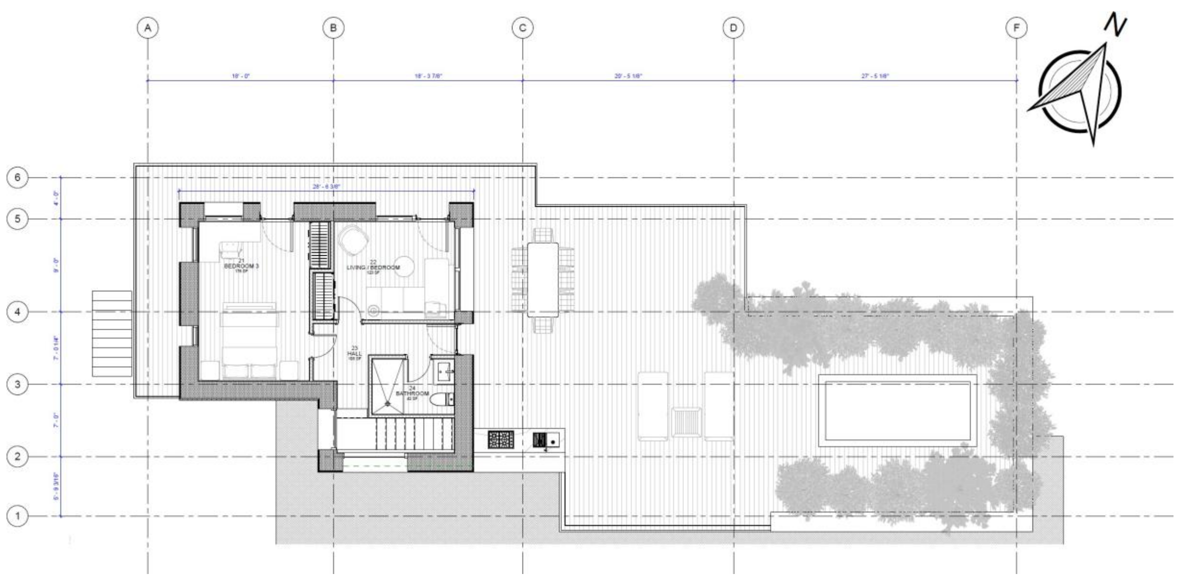

Figure 15: Low Embodied Carbon Design, Second Floor Plan

The significant reduction in embodied carbon is primarily due to the use of straw bale insulation, which acts as a massive carbon sink, sequestering 50,339 kgCO2e—almost equal to the entire carbon emissions of the medium embodied carbon building. This design achieves net zero carbon emissions, surpassing the Paris Agreement's 2050 goals for carbon-neutral homes.

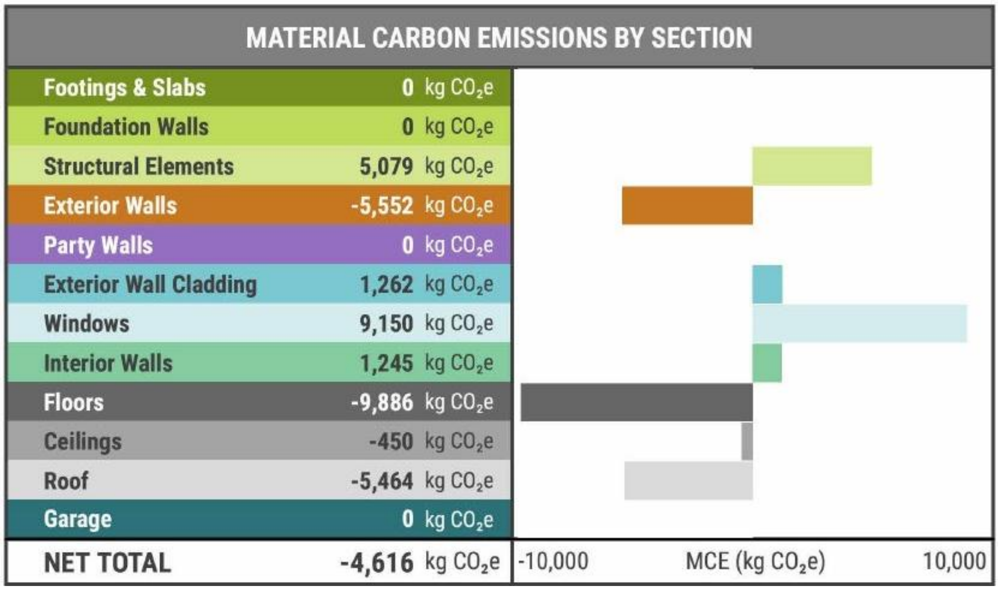

Figure 16: BEAM, Low Embodied Carbon Design

With the improved insulation from triple-pane windows and increased R-values (R-61.6 roofs, R-56 walls, and R-36.4 floors), the operational carbon costs of this building surpass both the medium and high embodied carbon designs by about 22%. It achieves a 24.6% better-than-code rating, improving energy efficiency significantly compared to the previous designs.

Conclusion

Despite the focus on "green" building practices, current codes and incentive programs fail to address the critical issue of embodied carbon emissions. These emissions are as significant as operational carbon and are often overlooked. Case studies show that embodied carbon can have more than twice the impact of operational carbon. Even high-performance buildings can still emit substantial operational carbon in their early years. By redesigning buildings to reduce embodied carbon, their environmental impact can be greatly reduced or even eliminated. Key strategies include using low or negative carbon materials (e.g., straw insulation, bamboo, and mass timber), reducing the use of high-carbon materials (e.g., steel, glass, concrete), and designing smaller, more efficient buildings.

This research highlights key design decisions for reducing embodied carbon in buildings. The most significant change is replacing closed cell spray foam insulation with biogenic insulators like straw bales. Eliminating concrete in slabs, footings, and foundations is also crucial. Reducing glazing addresses the environmental impact of glass and steel, while shortening structural spans and using carbon-sequestering insulated walls further reduce emissions. Although these design strategies may compromise views and increase costs (e.g., using stonework instead of concrete for below-grade structures), they aim to lower overall costs associated with steel, glass, and large basements. Despite these changes, the redesigned buildings maintain a similar appearance while achieving vastly different environmental impacts.

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