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Carbon Emissions in a Typical New Production Home: A Case Study

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Carbon Emissions in a Typical New Production Home: A Case Study

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Prepared for:

Building Technologies Office

Office of Energy Efficiency and Renewable Energy

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List of Acronyms

BEopt	Building Energy Optimization tool
CO_2	carbon dioxide
CO_2e	carbon dioxide equivalent
DOE	U.S. Department of Energy
EC3	Embodied Carbon in Construction Calculator
EPD	environmental product declaration
NREL	National Renewable Energy Laboratory
SEC	Securities and Exchange Commission

Executive Summary

This report, prepared by IBACOS, is intended to serve as a foundational document for the residential construction industry to understand how a typical home currently performs relative to building decarbonization goals set for 2030 and 2050. The intent is to help homebuilders benchmark their current performance and better understand the largest sources of carbon emissions in their homes.

Specifically, this case study assesses carbon emissions for a single-family residential home plan with respect to (1) the initial embodied carbon emissions associated with construction materials from environmental product declaration (EPD) documents, (2) additional embodied carbon emissions from material replacement and maintenance over time, and (3) the ongoing operational emissions based on energy modeling. These results are presented by material type and category to indicate the primary contributors to the overall emissions. Mechanical, electrical, and plumbing (MEP) systems are excluded from consideration due to EPD documents for those components not being reliably available. There is currently no universally accepted approach for carbon assessments in new construction, so the approach from this case study is defined in the methodology and described in a data set associated with this publication.[1]

It is important to consider the effects of material carbon emissions when considering the overall carbon impact of new construction, and it is the selection of the materials that can make the biggest immediate impact for a builder in meeting U.S. climate goals. Building efficient homes based on guidance from governmental programs will provide ongoing reductions to operational carbon emissions that will continue to lower as utilities adopt cleaner sources of energy.

For more information on this case study, please see the related fact sheet—*New Residential Construction Carbon Emissions* (DOE 2023).

[1] The data set is available in two parts: Operational Carbon Data (Rapport 2023a) and Embodied Carbon Data (Rapport 2023b).

Table of Contents

List of Figures

1 Background

As of 2022, U.S. climate goals include reductions in **greenhouse gas** emissions economy-wide by more than 50% by 2030, a zero emissions power sector by 2035, and a net zero emissions economy by 2050 (White House 2021). Currently, carbon emissions from commercial and residential buildings account for 36% (U.S. Environmental Protection Agency 2022) of total U.S. emissions—with residential buildings representing just over half of this amount—setting the stage for a considerable opportunity to help decarbonize the economy.

At the same time, large investment companies are advancing sustainable investing practices, including environmental, social, and governance policies, to deliver better outcomes for investors, address climate change, and improve employer-employee-community relations. The Proposed Item 1501 of Regulation S-K[2] from the Securities and Exchange Commission (SEC) would require a company to disclose information about its climate-related risks "that are reasonably likely to have a material impact on its business, results of operations, or financial condition." This information about climate-related risks would also require companies to disclose information about greenhouse gas emissions that would include—in the case of homebuilders—the carbon emissions associated with constructing their homes.

As large production homebuilders adapt to these emerging realities, there is a need to understand and assess their current performance against "net zero carbon" goals to enable better decision-making around available paths forward and help them to deliver on their commitments to decarbonize their businesses in environmentally, socially, and fiscally responsible ways. To help with this process, this case study introduces an approach to assess carbon emissions associated with a typical single-family detached home currently being constructed by production homebuilders in communities across the United States. The intent is to help homebuilders benchmark their current performance and better understand the largest sources of carbon emissions in their homes. While this case study is not meant to represent specific homes in a builder's portfolio, it provides a general understanding of where they are today, and a starting point for more customized assessments of emissions associated with their specific homes.

[2] https://www.federalregister.gov/documents/2022/04/11/2022-06342/the-enhancement-and-standardization-of-climate-related-disclosures-for-investors

2 Carbon Emissions in Homes

The following diagram from the Carbon Leadership Forum presents an overview of the two primary components of a home's associated carbon emissions—the **embodied carbon emissions** and **operational carbon emissions**—including the upfront construction of the building through its useful life (including maintenance and repair), and eventual end-of-life demolition or reuse.

Figure 1. Overview of embodied and operational carbon emissions for a building

Figure from Carbon Leadership Forum (2020)

Embodied carbon emissions refer to the greenhouse gas emissions that result from the extraction of raw materials that go into building products, manufacturing of the products, transportation to a job site, construction of a building, the maintenance and repair of that building, and the eventual disposal of the building products. Operational carbon emissions refer to the greenhouse gas emissions associated with the heating, cooling, and energy and water use of the building. For the purposes of this study, operational carbon emissions associated with the water use of the building were not included.

The next diagram, based on a similar graph from EIA's International Energy Outlook (EIA 2017), shows for context the global annual carbon emissions associated with the building and construction sector. Combining the emissions associated with upfront building materials and construction with building operations, this sector represents about 39% of total global emissions, compared to 36% of U.S. emissions.

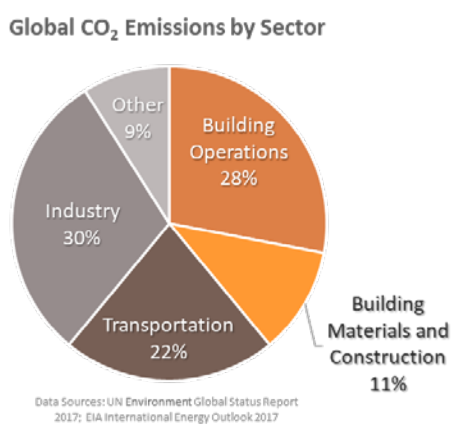


Figure 2. Global carbon emissions associated with the building and construction sector

Figure from UN Environment and International Energy Agency (2017)

3 Methodology

This study analyzes the embodied and operational carbon emissions associated with a typical new, single-story, 1,858 square foot production builder's home located in International Code Council Climate Zones 5 (cold) and 2 (warm). Each home shares a similar layout, with differences in foundation type, insulation, roof structure, and finishes based on typical, climate-specific practices. The house plan was designed to roughly meet the 2015 International Energy Conservation Code[3] requirements for the thermal enclosure and whole building air leakage, with a slab on grade foundation in Climate Zone 2 and a basement foundation in Climate Zone 5. A full list of energy and building specifications can be found in the appendix included with this case study.

Embodied carbon emissions calculations are based on actual material take-offs for foundation, exterior walls, interior walls, floors and roofs, windows, interior finishes, and site elements. Emissions include upfront construction of the home, and projected emissions over a 28-year maintenance and use period from 2022–2050 that include replacement of materials such as asphalt shingles, paint, and carpet. This time period was selected to align with the 2050 decarbonization targets set by the White House at the time of this publication.

Operational carbon emissions are based on modeled annual gas and electric use of the home using the National Renewable Energy Laboratory's (NREL's) Building Energy Optimization (BEopt™) tool, converted to global warming potential using emissions factors available through NREL's Cambium database (NREL 2022; see "Lifetime Operational CO_2e Calculation Methodology" below). Operational carbon emissions were also calculated for a period of use from 2022–2050.

Finishes and interior walls were included in this study because they impact the total embodied carbon emissions, although they do not impact operational carbon emissions.

The following diagram from the New Buildings Institute shows the different life cycle stages of a building and their associated types of carbon emissions (embodied or operational). Red circles indicate the life cycle stages where embodied carbon emissions were calculated for this study, and the green circle indicates where operational carbon emissions were calculated.

[3] https://codes.iccsafe.org/content/IECC2015

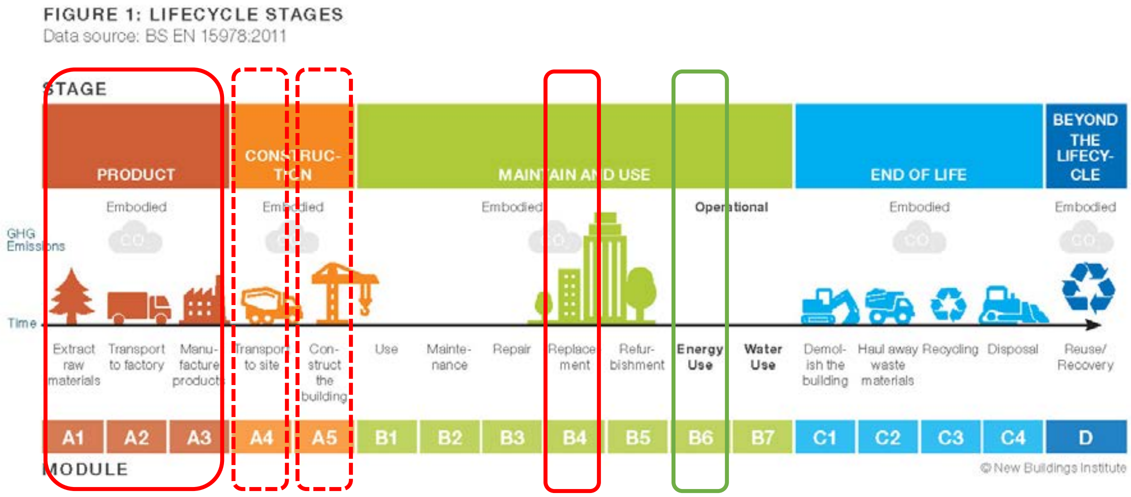


Figure 3. Life cycle stages of a building and associated carbon emissions; red and green borders indicate the stages included in this study

Original figure from New Buildings Institute (2022)

4 Carbon Calculators

Analyzing carbon emissions in residential buildings is an emerging field that uses software tools to calculate embodied and operational carbon emissions based on the specific products and materials in homes, their quantities, associated transportation and construction activities, use of the building over its lifetime (including maintenance, repair, and replacement) and end-of-life demolition or reuse. While these carbon calculators each have a unique methodology to calculate carbon emissions, they all share a similar approach based on established **life cycle assessment** techniques and most rely on data provided by **environmental product declaration (EPD)** documents available from product and material manufacturers and suppliers to assess and calculate the **global warming potential** of a building. Carbon emissions are typically presented in tons (or metric tonnes) of carbon dioxide equivalent (CO_2e).

Two calculators used for the analysis in this case study are the **Embodied Carbon in Construction Calculator (EC3)**[4] tool from Building Transparency and the **One Click LCA Product Carbon Tool**[5] from One Click LCA. These tools utilize available EPDs and LCA reports for different products and materials, but many gaps still exist in their databases.

These calculators are generally accessible to any user, as the inputs align with typical home construction materials and products. That said, where EPD documents are not available for embodied carbon emissions calculations, the tools may produce different results based on the specific assumptions and calculation methodologies used.

For calculating operational carbon emissions, energy use for the home—actual or modeled through an energy evaluation tool such as BEopt—must be input into the calculator.

For the analysis of building life cycle stages A1–A3, both calculators were used in tandem with each other for a "hybrid" calculation approach. Some material inputs were available in one calculator or another, and sometimes in both. Where the same input was available in both calculators, the most conservative output (i.e., higher carbon emissions amount) was selected for the final analysis.

One Click LCA provided default inputs for life cycle stages A4 (Transport to Site) and A5 (Construct the Building) that were used in this analysis. EC3 did not have similar inputs. For life cycle stage B4 (Replacement) manual inputs were made in both tools as in stages A1–A3 calculations.

EPD documents were selected that most closely represented the actual materials and products used to build these homes. In some cases, these selections were not accurately representative of

[4] For more information, see: https://www.buildingtransparency.org/ec3-resources/ec3-faq/.
[5] For more information, see: https://www.oneclicklca.com/.

the actual materials but were the only ones available for use. This introduced significant uncertainty into the results.

At the time of this publication, there were no available EPD documents for elements related to the mechanical, electrical, and plumbing systems in residential buildings, so they were not included in this analysis.

5 Lifetime Operational CO_2e Calculation Methodology

NREL Cambium data was utilized to project operational **carbon dioxide equivalent** (CO_2e) emissions impacts for a constant yearly electric energy load for each house model as calculated by BEopt simulations.

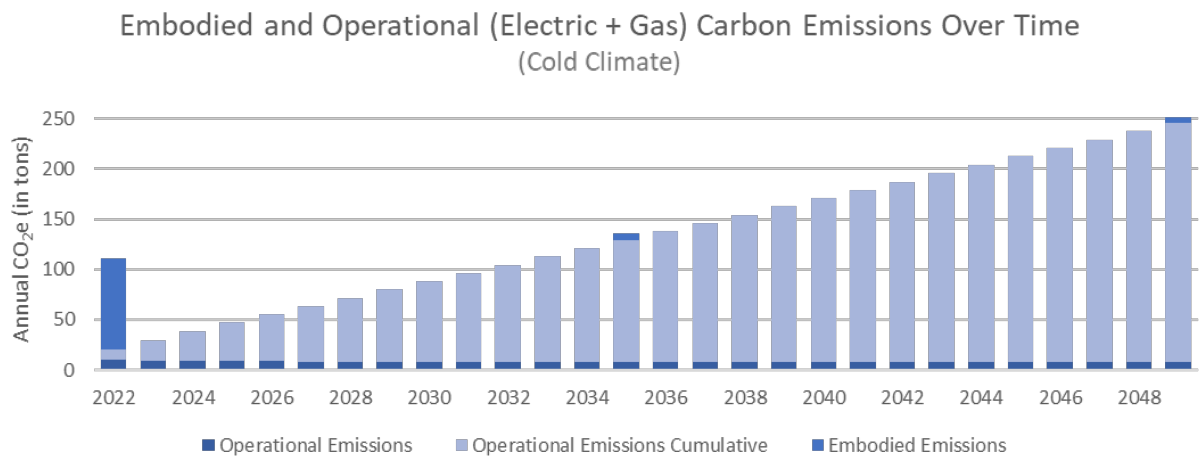
The scope included two homes, one located in a cold climate and one in a warm climate. Cambium data include hourly CO_2 emission rates per megawatt-hour for the two grid locations, specifically the Mid-Case under CO_2 from Direct Combustion from the "Data - Month - Hour" sheet. BEopt modeling produced an hourly kilowatt-hour output for each home, for each day of an entire year that was used to calculate the operational carbon emissions occurring each hour from 2022–2050 (28 years). The Cambium Month-Hour database provided data for every other year, so emissions rates for the in between years were calculated by interpolation. The results were summed from hourly CO_2e impacts to total annual operational CO_2e impacts and presented graphically (Figure 4).

The Cambium Mid-Case applies moderate technology cost reduction trajectories, reference fuel cost trajectories, and representations of enacted policies such as renewable portfolio standards.

Note that for site natural gas usage in the cold climate home, direct hourly Therm outputs from BEopt were used and converted to tons of CO_2e.

6 Overview: Your Home's Carbon Emissions

The following figure shows embodied and operational greenhouse gas emissions for a typical, new production home in a cold (top) and warm (bottom) climate over a 28-year use period (2022–2050). Operational carbon emissions are up to 200% greater than embodied carbon emissions in this period. Embodied carbon emissions include upfront emissions and additional emissions in 2036 and 2050 due to anticipated material replacements.



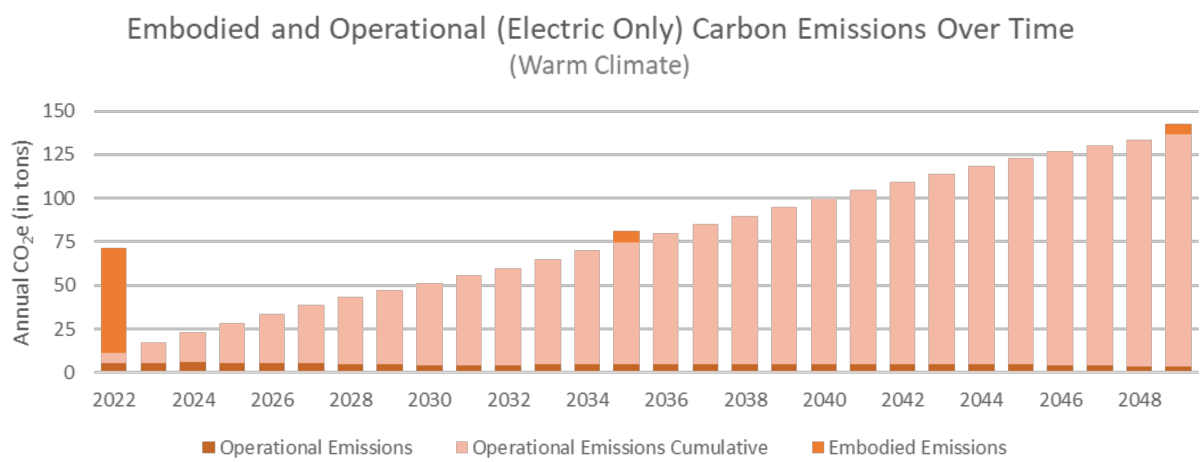


Figure 4. Embodied and operational carbon emissions for a new production home in a cold (top) and warm (bottom) climate over a 28-year useful life (2022–2050)

It is worth noting here that if the electric grid does decarbonize over the next 28 years by adopting cleaner, renewable energy sources such as photovoltaics and wind power, the operational carbon emissions will be lower, assuming the house is all electric. If the house uses gas heat or water heating, then those emissions will persist.

7 Results: Embodied Carbon Emissions

Figures 5, 6, and 7 show embodied carbon emissions associated with the same model home plan in a cold and warm climate. Primary differences between the two houses include foundation type (basement versus slab on grade) and insulation levels. Interior materials and finishes, and exterior cladding materials are similar. As noted above, mechanical, electrical, and plumbing systems have not been included in this analysis because EPD documents are not currently available for these materials.

As shown in Figure 5, the same home in a cold climate has approximately 50% higher total embodied carbon emissions than in a warm climate, primarily due to the larger volume of concrete used in the foundation and to the increased insulation levels in the thermal enclosure.

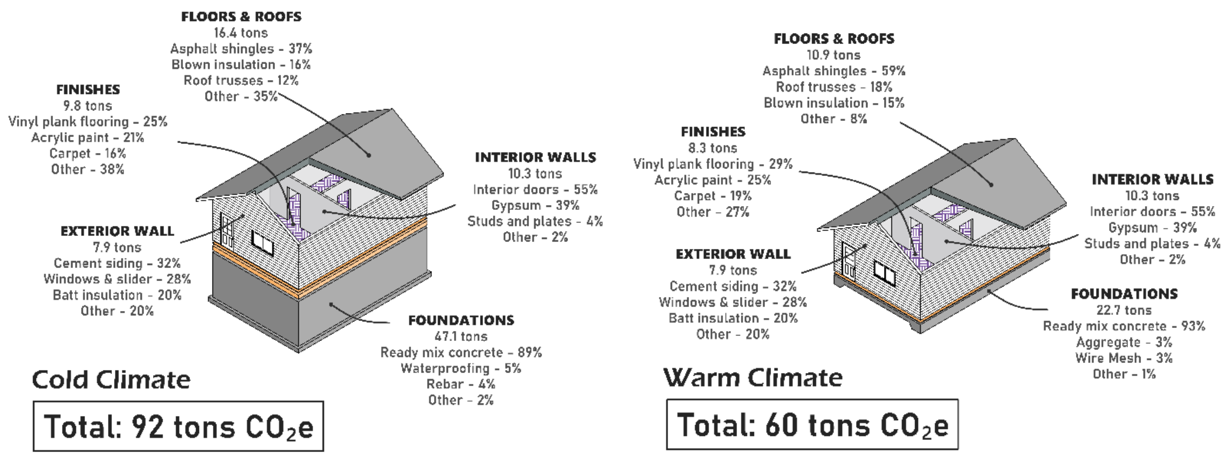


Figure 5. Upfront embodied carbon emissions associated with the construction of a new production home in a cold (left) and warm (right) climate, by building assembly and material

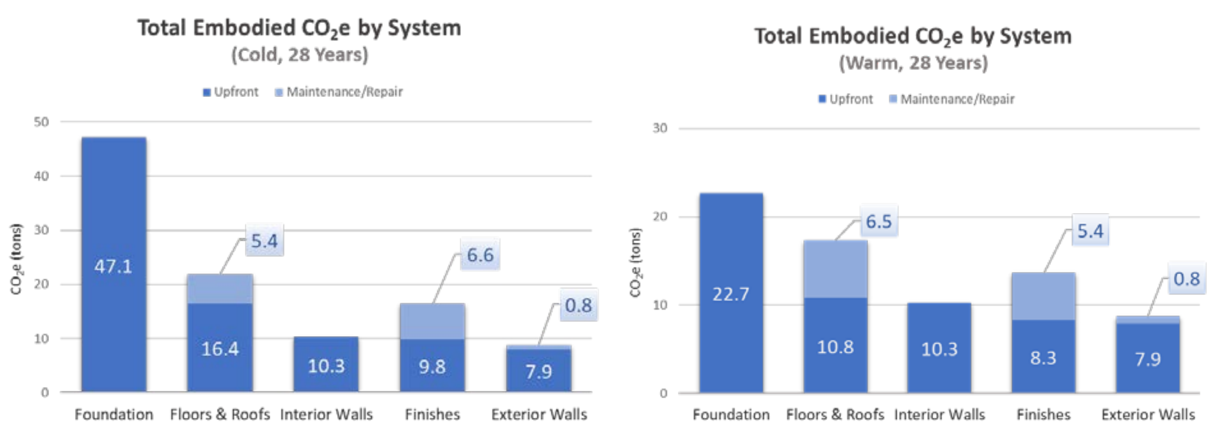


Figure 6. Top five embodied carbon emissions sources over a 28-year period (including upfront, maintenance, and repair emissions) of a new production home in a cold (left) and warm (right) climate, by building assembly

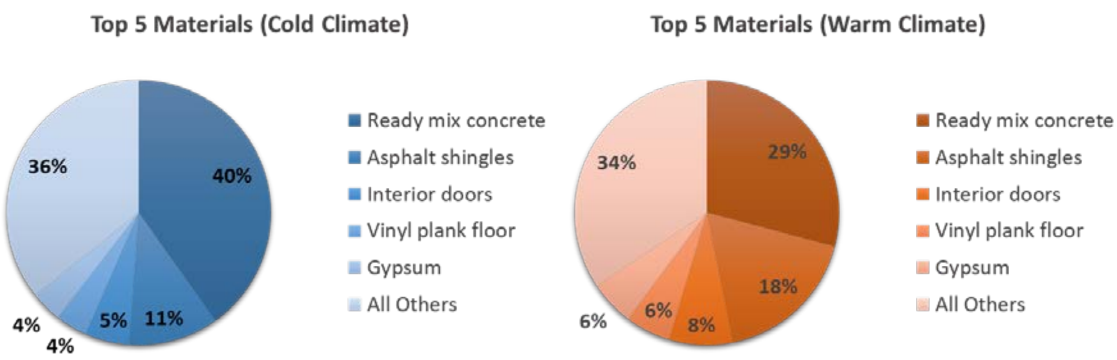


Figure 7. Top five embodied carbon emissions sources over a 28-year useful life (including upfront, maintenance, and repair emissions) of a new production home in a cold and warm climate, by material

It is important to understand that similar homes may produce very different results when calculating their associated carbon emissions. A wide range of factors influence these results, and this case study does not necessarily reflect how a specific builder's homes will perform. Different materials and their quantities can influence the results, and the EPD documents from different manufacturers can include vastly different emissions data for the same material or product type. One carbon calculator may use different default calculations than another, which can significantly influence the calculation results.

8 Operational Carbon Emissions

The operational carbon emissions calculated for this study were based on the home's modeled annual energy use. For the cold climate home, natural gas was used for heating, water heating, and cooking while in the warm climate home, all equipment and appliances used electricity. Gas produces higher direct carbon emissions than electricity when used in these applications, leading to much higher operational carbon emissions from the cold climate home.

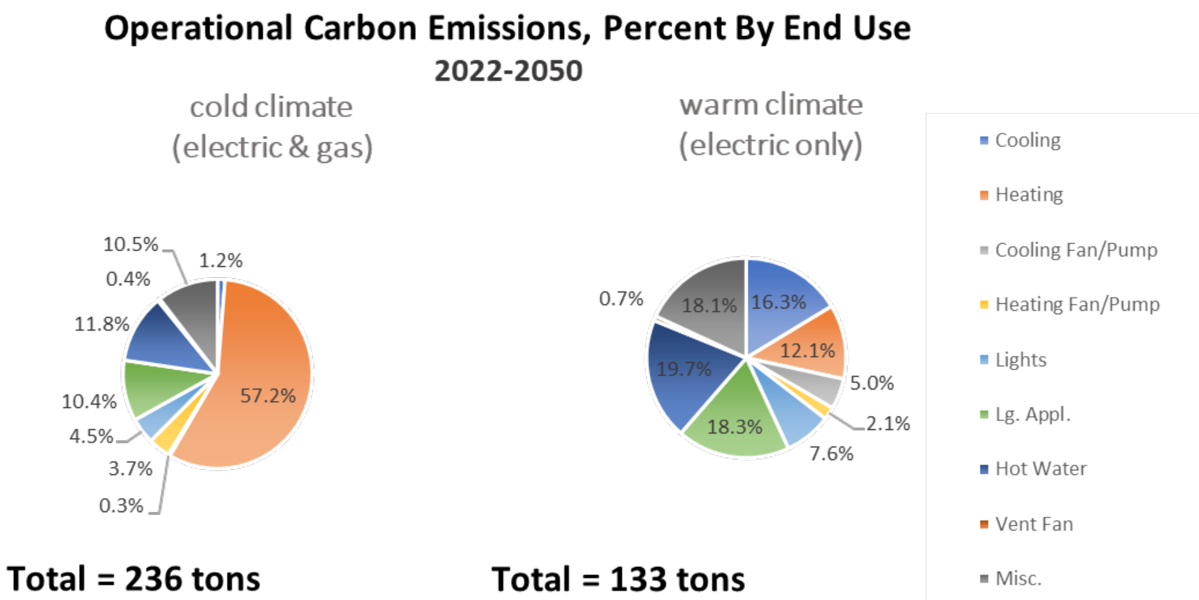


Figure 8. Breakdown of operational carbon emissions for a typical new production home constructed in a cold and warm climate, by end use (carbon emissions factors provided by NREL's Cambium database). Home is constructed in 2022 and operates from 2023–2050.

9 Putting It All Together

For a builder constructing 10,000 homes in a given year to the 2015 building code standard, the cumulative amount of embodied and operational carbon emissions released from these homes over the next 28 years is equivalent to the emissions from about a single year's production of 6 natural gas power plants (EPA 2022 Greenhouse Gas Equivalencies Calculator). Given the current rate of approximately 1.6 million housing starts,[6] if a net zero emissions economy is to be realized by 2050, the residential construction community has a significant role to play in reducing these carbon emissions.

[6] https://www.census.gov/construction/nrc/pdf/newresconst.pdf

10 Opportunity to Improve

Builders can consider taking several important actions right now to reduce the carbon emissions associated with their homes. With nearly 1.6 million units being constructed in the United States each year,[7] the biggest immediate impact a builder can having on meeting U.S. climate goals is to select the materials and construction practices that reduce upfront embodied carbon emissions. Additionally, building energy-efficient homes, such as homes that comply with the U.S. Environmental Protection Agency's Energy Star Residential New Construction[8] program or the U.S. Department of Energy's (DOE) Zero Energy Ready Home[9] program, will provide ongoing reductions to operational carbon emissions that will continue to lower as utilities adopt cleaner sources of energy.

The developers of the carbon calculators used in this study are continuing to grow their databases of EPD documents as these become available in the market and will likely continue to evolve their user "friendliness" to become more useful to the building community. Additional tools, such as the **BEAM Estimator** from Builders for Climate Action and the **EcoCalculator** from Athena Sustainable Materials Institute, are currently available and others will likely enter the market as demand grows for their capabilities.

Ultimately, standard tools and processes will be needed to simplify the upfront analysis of home designs and to enable builders to make more informed decisions for their businesses. The following immediate actions can help builders start to address the needed reductions in embodied and operational carbon emissions associated with their homes:

Embodied Carbon Emissions

- Create specific goals for embodied carbon reductions, and then consider alternative products and construction practices for the biggest areas of embodied carbon emissions in the home. Defining a staged approach to decarbonization will facilitate annual environmental, social, and governance reporting and SEC reporting and engender talking points for your sales team to convey this value to potential buyers.
- Request information from your suppliers and vendors on the environmental impacts of their products that you are using or considering, to let them know this is important to you. If you can get an environmental product declaration (EPD) for each of their products, that would be even better. Currently, EPDs do not exist for all the building materials that go into a new home and making these requests will encourage product manufacturers to provide this information for more effective decision-making.
- Reduce construction waste and hold trade contractors responsible for compliance. Working with off-site manufacturing suppliers—such as roof truss or wall panel

[7] For more information, see: https://www.census.gov/construction/nrc/index.html
[8] For more information, see: https://www.energystar.gov/newhomes
[9] For more information, see: https://www.energy.gov/eere/buildings/zero-energy-ready-home

manufacturers, or even modular manufacturers—is one way to reduce construction waste, as these suppliers have been shown to use materials more efficiently in a factory environment than on-site providers.

Operational Carbon Emissions

- Improving building energy efficiency will impact the long-term operational carbon emissions, so consider improvements to your building enclosure, mechanical systems, appliances, and other areas of your homes to reduce operational energy use; the U.S. EPA Energy Star New Residential Construction program and the U.S. DOE Zero Energy Ready Home program are two such approaches to improve building energy efficiency.
- Work with electric utilities to support homeowner participation in energy efficiency and demand flexibility programs, to help reduce peak load issues and support greater integration of renewable energy sources to the electric grid.

Key Definitions

Life cycle assessment (LCA)
A methodology for assessing environmental impacts associated with all stages of the life cycle of a commercial product, process, or service.

Environmental product declaration (EPD)
A registered document that communicates a building product's environmental impact across its life cycle. An EPD is created using data from a complete LCA and is then verified by a third party. EPDs report out on a product's global warming potential, smog creation, ozone depletion, and water pollution.

Greenhouse gas (GHG)
A greenhouse gas is a gas that absorbs and emits radiant energy within the thermal infrared range, causing the greenhouse effect. The primary greenhouse gases in Earth's atmosphere are water vapor, carbon dioxide, methane, nitrous oxide, and ozone.

Global warming potential
The heat absorbed by any greenhouse gas in the atmosphere, as a multiple of the heat that would be absorbed by the same mass of carbon dioxide (CO_2). Global warming potential is 1 for CO_2. For other gases, it depends on the gas and the time frame.

Carbon dioxide equivalent (CO_2e)
According to the U.S. Environmental Protection Agency, "carbon dioxide equivalent or CO_2e means the number of metric tons of CO_2 emissions with the same global warming potential as one metric ton of another greenhouse gas," and is used to standardize comparison of the global warming potential from different GHG sources.

Embodied carbon emissions
Embodied carbon emissions refer to the greenhouse gas emissions that result from the extraction of raw materials that go into building products, manufacturing of the products, transportation to a job site, construction of a building, the maintenance and repair of that building, and the eventual disposal of the building products

Operational carbon emissions
Operational carbon emissions refer to the greenhouse gas emissions associated with the heating, cooling, and energy and water use of the building.

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