ETHIC

Enabling Technologies for Housing Innovation Center

Assessing the Climate Impacts of the U.S. Housing Supply: Identifying Key Climate Impact Factors and Carbon Estimation Strategies

The Enabling Technologies for Housing Innovation Center
a HUD Hispanic Serving Institution Center of Excellence

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1. Introduction

The building sector is a major contributor to global greenhouse gas (GHG) emissions, making it a critical area for addressing climate change. The United Nations Environment Programme (UNEP) reports that the building sector accounts for approximately 37% of global energy-related carbon emissions [1]. In the U.S. – one of the world's largest emitters of GHGs [2], [3] – building construction accounts for 36% of total carbon emissions, with housing stock comprising more than half of this share [4]. Housing construction in the U.S. has been steadily rising since 2011 [5] (Figure 1). Since this trend is expected to increase even more over the coming decades [6], it is critical to analyze how we can combat and adequately mitigate the effects of climate change within the U.S. housing supply chain.

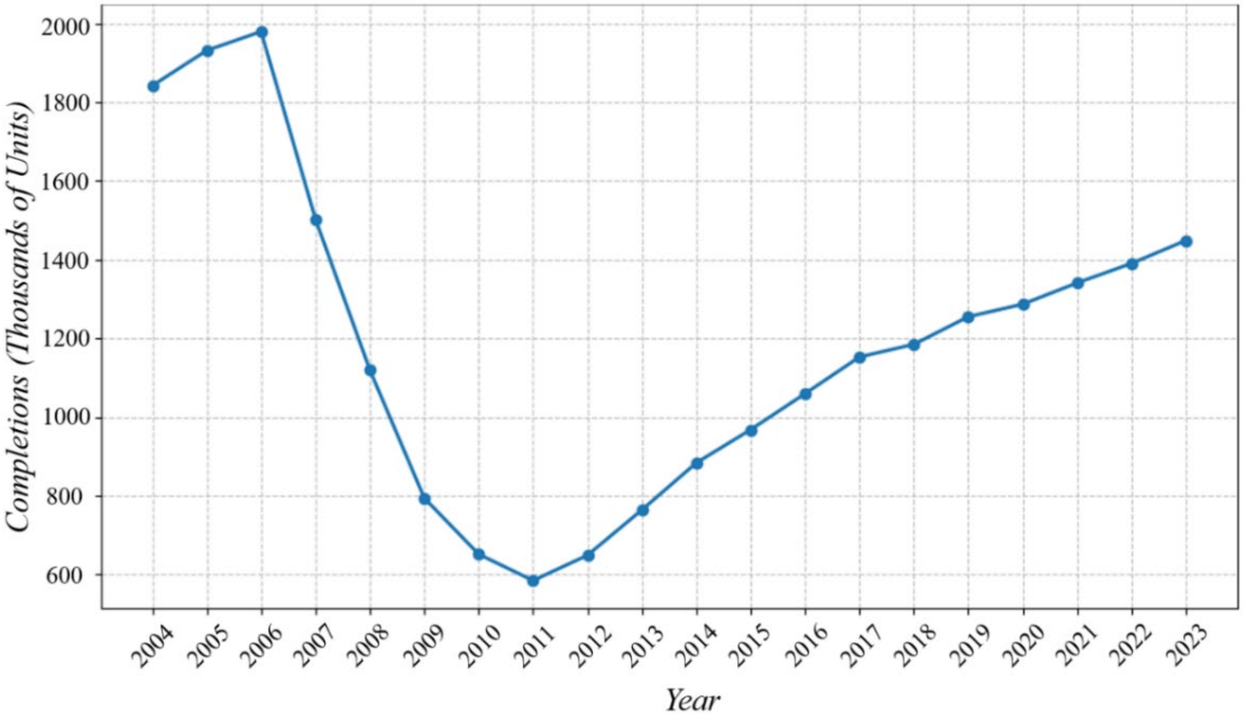

Figure 1. Annual housing construction completions in the U.S. (2004-2023)

It is also important to note that housing infrastructure and climate change are inextricably linked (Figure 2). One of the primary functions of housing is to safeguard and protect humans from the effects of the climate including extreme heat, extreme cold, water, wind, drought, poor air quality, etc. In addition to functioning as a protective shield, housing infrastructure itself must withstand the current and future effects of the climate, maintaining an acceptable physical and operational condition. A positive feedback loop exists between housing infrastructure and the climate: housing contributes to climate change (through the production of GHG emissions), which in turn increases the climate effects burden placed on housing. Characterizing this positive feedback loop is essential if we want to future-proof our housing infrastructure to ensure it continues to protect and safeguard humans from a changing climate.

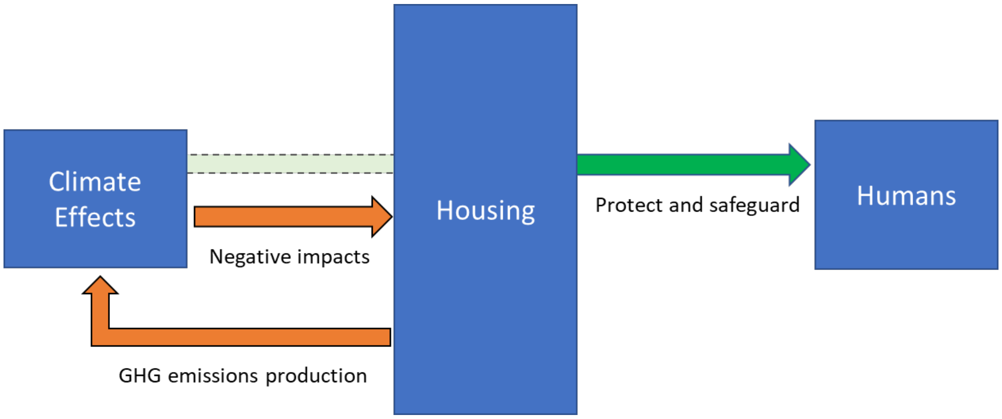

Figure 2. Depicting the relationship between housing, humans and climate effects

This report assesses the current state of GHG emissions associated with U.S. housing supply. It focuses specifically on existing carbon estimation practices and highlights areas requiring further research to support future emission reduction efforts within the housing sector.

2. GHG Emissions of the Building Construction Sector

The GHG emissions of building construction are broadly categorized into operational carbon emissions from building's use phase and embodied carbon emissions associated with the building construction supply chain. Each emission accounted for 75% and 25%, respectively, of the total building sector emissions in 2021 (Figure 3(a)).

The overall life cycle of housing stock can be broadly categorized into five key phases: manufacturing, transportation, construction, operations, and end-of-life. Carbon emissions occur in each of these phases. Figure 4 shows the potential carbon emissions in each phase. Embodied carbon emissions occur at every phase of the lifecycle, while operational carbon emissions only arise from the operation phase of a building.

Operational carbon emissions primarily result from indoor energy consumption activities such as heating, cooling, powering, and water use [4]. These emissions are continuous throughout the building's lifespan and are directly tied to the building's functions. Strategies to mitigate operational carbon emissions include improving the energy efficiency of the building, adopting renewable energy sources, and optimizing building systems. In contrast, embodied carbon emissions occur during the entire lifecycle of a building and are primarily associated with the materials used in its construction [4].

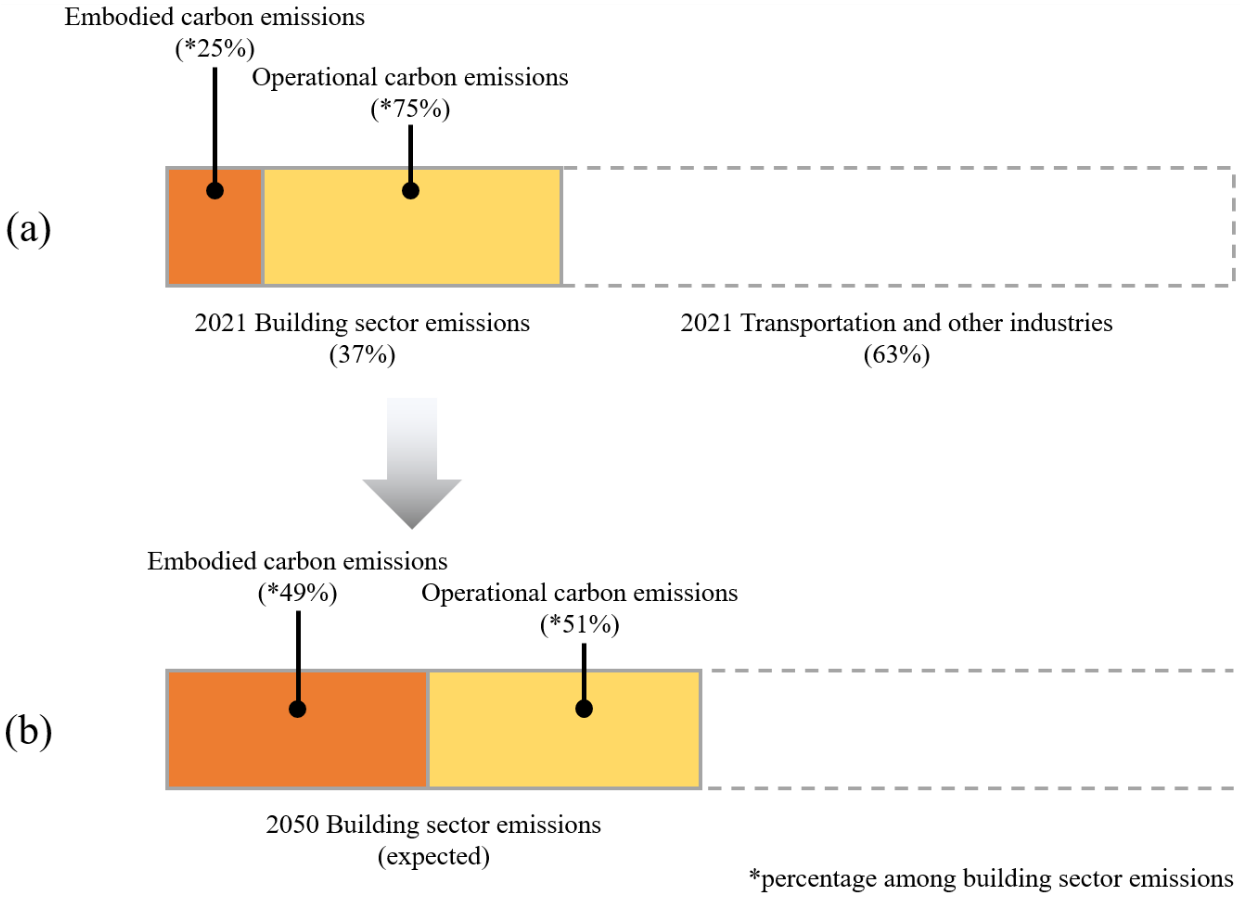

Figure 3. Global share of the building sector in energy-related CO$_2$e emissions: (a) emission rate of 2021 and (b) expected emission rate of 2050

Embodied carbon emissions have an immediate and increasingly significant impact on total building emissions, making its reduction critical for achieving carbon mitigation goals [7]. As shown in Figure 3(b), the share of embodied carbon emissions in the building sector is projected to increase from the current one-quarter to nearly half by 2050, assuming the continuation of current socioeconomic trends [1]. Strategies to reduce embodied carbon emissions include selecting low-carbon materials, retrieving used materials for recycling and reuse, and designing for material efficiency.

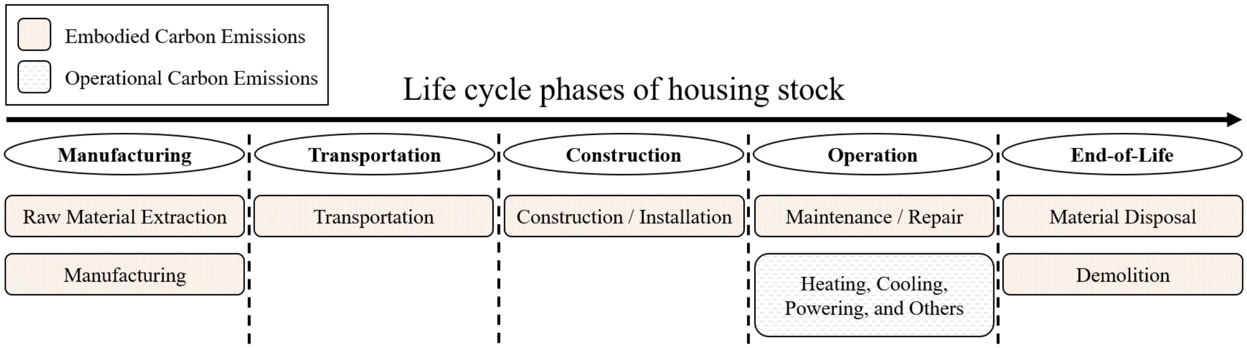

Figure 4. Emission activities in life cycle phases of housing stock

Historically, carbon emissions reduction efforts have primarily focused on operational carbon emissions. As a result, RESNET Home Energy Rating System (HERS) rates indicate that new homes could achieve net-zero operability by 2030 [8]. However, focusing solely on operational emissions fails to address the substantial embodied carbon emissions arising from the building construction supply chain [1], [9], [10]. Additionally, strategies to reduce operational carbon emissions can sometimes result in trade-offs, inadvertently increasing embodied carbon emissions, and vice versa [11].

To effectively reduce GHG emissions within the housing supply chain and minimize emissions starting from the design phase, it is essential to accurately calculate and estimate both operational and embodied carbon emissions. The following section introduces the strategies and practices for estimating carbon emissions in the U.S. housing sector.

2.1. Estimation of Operational Carbon Emissions

Operational carbon emissions are generated exclusively during the use phase of the housing supply chain, with minimal interrelations to other phases. This characteristic simplifies the calculation and estimation process compared to embodied carbon emissions. The operational carbon emissions of housing can be estimated by calculating the activity rate of a unit and multiplying it by the corresponding emission factors.

Activity rates represent the energy consumption of a building and can be accurately collected using utility bills and energy monitoring systems. Energy sources for each activity must then be identified to determine emission factors, which are available through existing datasets or tools. For example, electricity emission factors can be obtained using tools such as the EPA's Emissions & Generation Resource Integrated Database (eGRID) [12]. Table 1 provides examples of widely used datasets for emission factors in the U.S. Once the activity rate and emission factors are determined, operational carbon emissions are calculated giving energy usage converted into carbon emissions.

Additionally, adjustments for renewable energy are made to account for whether a particular building uses renewable energy sources or purchases renewable energy credits. Using this methodology, U.S. operational carbon emissions from housing was calculated to have decreased by 307.3 $MtCO_2e$ during the period of 2000 – 2020. This refers to 4344.9 $kgCO_2e$ per household reduction [13].

Table 1. Emission Factor Dataset Sources in the U.S.

Source	Category	Reference
EPA eGRID	Electricity	[12]
Green-e	Electricity	[14]
Edison Electric Institute GHG database	Electricity	[15]
ASHRAE Standards	Electricity & Fuels	[16]
Wattime	Electricity	[17]
Cambium, NREL	Electricity	[18]
EPA Simplified GHG Emissions Calculator	Fuels, refrigerants, and others	[19]

Historical annual consumption patterns can be applied to future scenarios, or building energy simulation tools can be used to estimate future operational carbon emissions [2]. Globally, there are hundreds of building energy simulation tools available [20]. A prominent example is EnergyPlus [21], developed by the U.S. Department of Energy (DoE). EnergyPlus is an open-source whole-building energy simulation software that analyzes heating, cooling, lighting, and other energy loads, while accounting for complex interactions between building systems and environmental conditions. It allows for the incorporation of advanced HVAC configurations and renewable energy systems, enabling precise estimations of future energy consumption and associated emissions. Another example, BEopt [22], developed by the National Renewable Energy Laboratory (NREL), which is tailored specifically for optimizing housing energy efficiency and cost-effectiveness. BEopt enables users to evaluate energy efficiency measures, renewable energy installations, and retrofit strategies, making it ideal for scenario-based analysis of housing construction.

Despite their capabilities, building energy simulation tools have limitations that hinder their full potential for estimating operational carbon emissions. These tools rely heavily on user inputs and assumptions, which can introduce uncertainty and make them less accessible for non-technical users [23]. Additionally, they do not inherently account for embodied carbon emissions from building materials, which are becoming increasingly significant in life-cycle carbon assessments. As such, future improvements should focus on integrating embodied carbon estimation capabilities and enhancing compatibility with real-time monitoring systems to reduce reliance on static inputs.

2.2. Estimation of Embodied Carbon Emissions

Embodied carbon emissions are generated throughout the entire lifecycle of the housing supply chain. The complexity of accounting for embodied carbon emissions across these diverse stages and industries poses significant challenges. Due in part to this complexity (but also as a result of limited data being reported or required by housing supply stakeholders), there are currently no granular or standardized methods available in the U.S. for assessing embodied carbon emissions across the entire housing supply chain [4], [24]. Despite this, existing research studies can be used to obtain a rough order of magnitude estimate for embodied carbon emissions of the U.S. housing stock.

An analysis of five studies covering 921 homes across the E.U., U.S., and Canada shows an average embodied carbon emission of 184 kilograms of CO_2 equivalent (i.e., with a range of 150 - 210) per square meter of conditioned floor area (kg CO_2e/m^2 cfa) [8]. These calculations were based on construction plans that estimated the material types and quantities for each housing unit. Extrapolating this average to the 219 million square meters of floor area for new single-family housing constructed in the U.S. in 2023 (calculated using 2023 new single-family housing construction data [25] and median size of completed single-family homes in 2023 [26]) yields an annual emission of approximately 40 Mt CO_2e. Since this number may be difficult to understand, this amount is comparable to the total emissions of countries such as Bahrain, Sweden, and Ireland [8]. However, these studies only account for the raw material extraction and manufacturing phases of new housing construction. Also, crucial elements such as mechanical, electrical, and plumbing (MEP) systems are excluded from the calculations due to the limited availability of Environmental Product Declaration (EPD) data. Existing tools for estimating embodied carbon emissions in housing (e.g., BEAM [27] and MCE^2 [28]) also focus primarily on the production and manufacturing of materials to calculate the dominant amount of embodied emissions.

Although material extraction and manufacturing account for approximately 65% to 85% of total embodied carbon emissions in U.S. housing construction [8], other phases also require accurate estimation due to their potential interconnected impact on reducing emissions. For example, reusing materials from the end-of-life phase can substantially lower the demand for material extraction and manufacturing. Similarly, recovered building material stock information can minimize transportation requirements to construction sites. Analyis of these examples highlight the need for conducting a comprehensive evaluation of embodied carbon emissions throughout the entire lifecycle of U.S. housing construction, in order to obtain a more accurate estimate.

To conduct such an estimate, the literature denotes three viable approaches: (1) top-down, (2) bottom-up, and (3) hybrid methodologies. The following sections provide a detailed overview of these methodologies, highlighting their unique advantages and limitations to identify potential applications for estimating embodied carbon emissions across the entire lifecycle of the U.S. housing sector.

2.2.1. Top-down Approach

Top-down approaches rely on macro-level data and aggregated statistics such as national economic accounts and sector-wide emission factors to estimate embodied carbon. A widely used method in this category is Input-Output Analysis (IOA), which examines interconnections between industries and tracks emissions across supply chains. IOA maps how outputs from industries such as material mining contribute to inputs for construction activities. This method is particularly useful for evaluating the overall carbon footprint of multi-national projects and providing insights for national policy development.

However, top-down approaches often lack granularity relying on high-level data, which can result in oversimplifications [29], [30], [31]. They may fail to capture detailed, material-specific, or process-specific emissions, limiting their usefulness for project-level assessments or scenarios requiring precise insights.

2.2.2. Bottom-up Approach

Bottom-up approaches focus on detailed data collection at the material, process, and project level. Compared to top-down methods, bottom-up methods offer greater precision and granularity but face challenges in scalability due to the intensive data requirements. These characteristics make bottom-up approaches particularly effective for project-specific analyses and identifying carbon hotspots within supply chains.

Key methods in this field are the Life-Cycle Assessment (LCA) and Material Flow Analysis (MFA) methods. LCA involves the compilation and evaluation of the environmental impacts associated with all stages of a product’s lifecycle [32]. For embodied carbon estimation, LCA quantifies greenhouse gas (GHG) emissions generated across the lifecycle stages of materials or buildings, providing a detailed and comprehensive understanding of carbon footprints. Zhu et al. [30] show the evaluation of granular data by categorizing embodied carbon emissions into three types: Initial Embodied Carbon (IEC), Recurrent Embodied Carbon (REC), and Demolition Carbon (DC). They applied a Life-Cycle Assessment (LCA) to each category, enabling the calculation of detailed and granular emissions data for every phase of a building’s lifecycle. LCA also allows for scenario-based analyses to estimate and compare the climate impacts of different projects. For example, various housing construction methods can be compared using LCA to optimize the selection of a scenario that minimizes embodied carbon [33], [34].

MFA is a systematic methodology for assessing material flows and stocks within a defined system over a specific time period [35]. MFA focuses on the movement and accumulation of materials over time to evaluate values such as resource efficiency, resource usage, and potential waste generation [9], [36].

While bottom-up approaches offer advantages in precision and granularity, their reliance on detailed inputs for each material and process makes them inherently data-intensive and time-consuming. This limitation restricts their scalability and often confines their scope to narrowly defined boundaries.

2.2.3. Hybrid Approach

Hybrid approaches combine the macroeconomic perspective of top-down models with the detailed material-level precision of bottom-up methods. This dual perspective allows for capturing both the broad supply chain impacts and the specific contributions of individual materials and processes, making it the most effective strategy for embodied carbon estimation [30]. Hybrid approaches are particularly valuable for achieving a holistic understanding of embodied carbon, as they bridge the gap between large-scale policy applications and project-level assessments. For instance, Xie et al. [37] utilized a hybrid framework combining process-based material-specific data with IOA to evaluate the embodied energy and emissions of a green scientific research building in China. Their approach could provide a comprehensive lifecycle perspective on both embodied and operational carbon emissions. Jungclaus et al. [24] employed a hybrid method integrating detailed LCA with archetypal building models to establish theoretical embodied carbon benchmarks for single-family detached housing across diverse U.S. climate zones. While promising, hybrid methods also face significant challenges, including data consistency issues and computational complexities. These challenges necessitate further refinement to enable their widespread application.

3. Discussion and Concluding Remarks

This review highlights the challenges and opportunities in accurately estimating carbon emissions within the U.S. housing sector. The findings emphasize the growing importance of embodied carbon emissions, which are projected to increase in relative significance as operational carbon emissions continue to decline due to advancements in energy efficiency and renewable energy adoption. This review found that the largest share of embodied carbon emissions in housing supply is the ‘manufacturing phase’ including the raw material extraction (Figure 4). However, addressing emissions of other phases is equally critical to reducing the U.S. housing sector’s overall embodied carbon footprint. Therefore, it is essential to develop embodied carbon estimation methods that capture the (complex) connections between lifecycle phases and across diverse housing typologies. Conducting such an estimate will provide a more holistic understanding of emission sources and enable the identification of specific efficient mitigation strategies.

A key challenge identified is the lack of a standardized framework for assessing embodied carbon emissions. Current top-down methods lack the granularity needed to capture material or process-specific insights. In contrast, bottom-up approaches provide detailed assessments but are constrained by intensive data requirements and limited scalability. Hybrid approaches show promise by combining the strengths of both methods, offering a comprehensive lifecycle perspective. However, challenges related to data consistency and computational complexity limit their widespread application. The findings also underscore the need for integrated strategies to address trade-offs between operational and embodied carbon reductions. For instance, efforts to enhance building energy efficiency may inadvertently increase embodied carbon emissions through the use of advanced materials and technologies. Therefore, lifecycle assessments that holistically evaluate both operational and embodied carbon emissions are critical to achieving meaningful carbon reductions.

A final recommendation from this report is that there is a need to prioritize the development of housing-specific benchmarks and databases to improve the accuracy and accessibility of embodied carbon estimation methods. Additionally, there is a need for innovative data collection techniques, such as via machine learning and automated data extraction from construction workflows, to streamline the assessment process. Collaboration between policymakers and industry professionals could also foster the creation of regionally adapted guidelines and standards. Exploring the integration of dynamic modeling tools that account for temporal and spatial variations in emissions could further enhance the precision and relevance of future methodologies.

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