



# Embodied Carbon Pathways to 2050 for the United States

REPORT | AUGUST 2025



## About the Carbon Leadership Forum

The Carbon Leadership Forum is a nonprofit dedicated to accelerating the transformation of the building sector to radically reduce the greenhouse gas emissions attributed to materials (also known as embodied carbon) used in buildings and infrastructure. We research, educate, and foster cross-collaboration to bring the embodied carbon of buildings and infrastructure down to zero.

## About the University of Washington (UW) Life Cycle Lab

The Life Cycle Lab at UW's College of Built Environments leads research to advance life cycle assessment (LCA) data, methods, and approaches to enable the optimization of materials, buildings, and infrastructure. Our work is structured to inform impactful policies and practices that support global decarbonization efforts. We envision a transformed, decarbonized building industry – better buildings for a better planet.

## About RMI

RMI (founded as Rocky Mountain Institute) is an independent, nonpartisan nonprofit founded in 1982 that transforms global energy systems through market-driven solutions to secure a prosperous, resilient, clean energy future for all. In collaboration with businesses, policymakers, funders, communities, and other partners, RMI drives investment to scale clean energy solutions, reduce energy waste, and boost access to affordable clean energy in ways that enhance security, strengthen the economy, and improve people's livelihoods. RMI is active in over 60 countries.

## Authors

This project is a collaborative, multi-organization effort led by the following individuals:

- Milad Ashtiani, University of Washington Life Cycle Lab
- Meghan Lewis, Carbon Leadership Forum
- Rachelle Habchi, Carbon Leadership Forum
- Aurora Jensen, Carbon Leadership Forum
- Matt Jungclaus, Building Insights LLC
- Audrey Rempher, RMI
- Rebecca Esau, RMI

Author contributions: Writing - original draft: M.A., R.H., M.L., A.R. M.J.; Writing - review and editing: A.J. M.L., M.J., R.E.; Conceptualization: M.L., M.A., R.E.; Methodology: M.A., M.L., R.E., A.R., M.J.; Data Collection: R.H., A.J., M.A., A.R., M.J.; Analysis: M.A., R.H., M.L., R.E., A.R., M.J.; Visualization and Graphics: M.L., M.J., S.R.

## Citation

Ashtiani, M., Jungclaus, M., Habchi, R., Jensen, A., Rempher, A., Esau, R., and Lewis, M. (2025). *Embodied Carbon Pathways to 2050 for the United States*. Carbon Leadership Forum. Seattle, WA. URL

## Copyright

*Embodied Carbon Pathways to 2050 for the United States* is licensed under a Creative Commons Attribution 4.0 International License.

Cover image by Alex Moliski from Pexels: <https://www.pexels.com/photo/scenic-path-in-mount-rainier-national-park-28954737/>

## Acknowledgments

The research team would like to thank the Breakthrough Energy Foundation and the ClimateWorks Foundation for supporting this research. Additionally, we would like to thank additional staff from the Carbon Leadership Forum, RMI, and the UW Life Cycle Lab that engaged with this project during its initiation, helped develop background research for its execution, and/or provided technical review: Anthony Hickling, Brook Waldman, Stephanie Carlisle, Victor Olgyay, and Kate Simonen. Sindhu Raju, CLF Program Assistant, supported the publication production and data visualization. Jack Rusk (C-Scale) also provided valuable feedback on the modeling framework early in the project.

# EXECUTIVE SUMMARY

Embodied carbon – the greenhouse gas (GHG) emissions generated by the manufacturing, transportation, installation, maintenance, and disposal of construction materials used in buildings, roads, and other infrastructure – is a critical and often overlooked solution for addressing climate change.

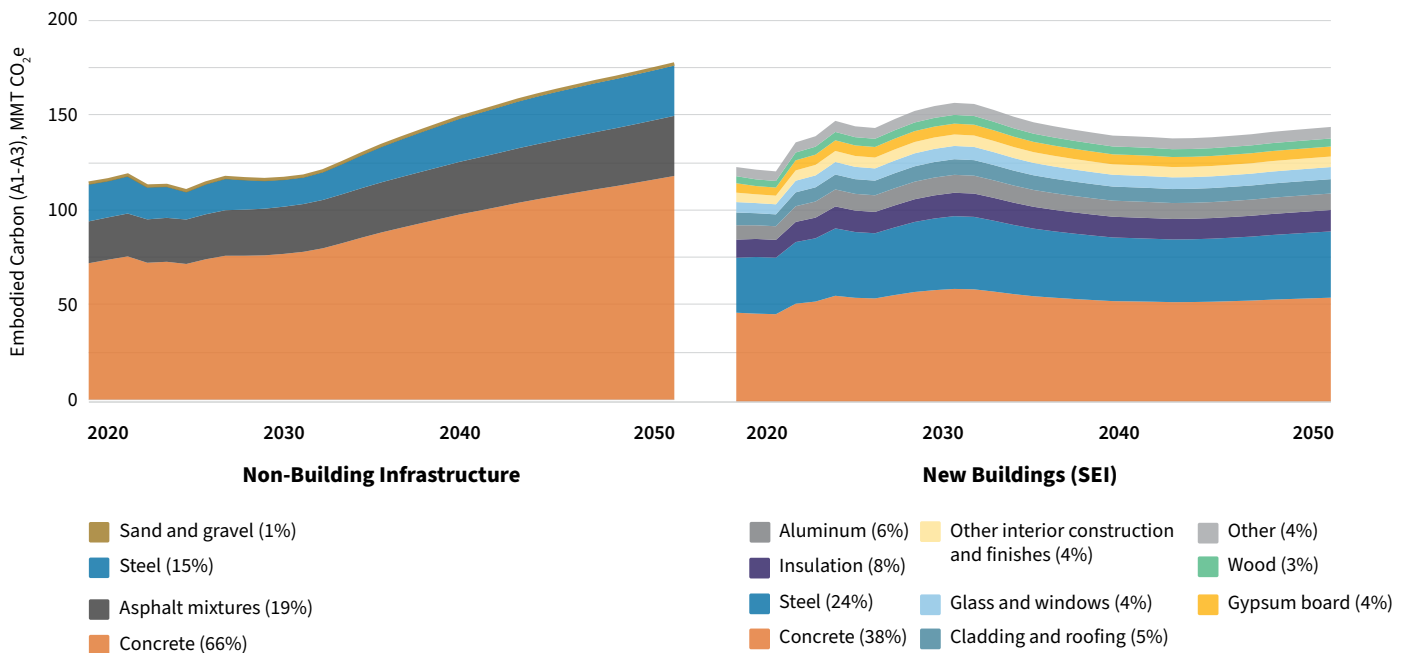
The United States needs a 50% reduction by 2030 to align with a 1.5°C goal (Rhodium Group, 2023) and is not on track to meet this target. Rapid decarbonization of the US industrial and building sectors through energy efficiency, electrification, low-carbon material use, and material-efficient design is crucial to closing the emissions gap and preserving a livable climate. With limited time to act to avoid the worst consequences of climate change and increasing federal headwinds, focusing efforts on the highest potential strategies and associated policies is critical.

*Embodied Carbon Pathways to 2050 for the United States*, a collaboration between the Carbon Leadership Forum (CLF), RMI, and the University of Washington (UW) Life Cycle Lab, provides an assessment of embodied carbon from US construction materials and explores pathways to align with a 1.5°C global warming limit.

## Comparing Business-as-Usual and 1.5°C-aligned Targets

This research begins by establishing a “business-as-usual” (BAU) trajectory for 30 key construction materials through 2050 and evaluates how far this baseline deviates from science-based targets. The analysis in this report focuses on the emissions from the raw material supply and extraction, transportation, and manufacturing of construction materials (A1-A3) used in the construction of new buildings and infrastructure in the United States. For buildings, the analysis focuses on structure, foundations, enclosure, and some interiors, and non-building infrastructure focuses on asphalt, concrete, sand and gravel, and steel.

**US cradle-to-gate embodied carbon from buildings and infrastructure is projected to increase 35% by 2050 under a BAU scenario**, with concrete alone accounting for over 50% of emissions (see Figure ES-1). This trajectory significantly exceeds carbon budgets aligned with the 1.5°C target.

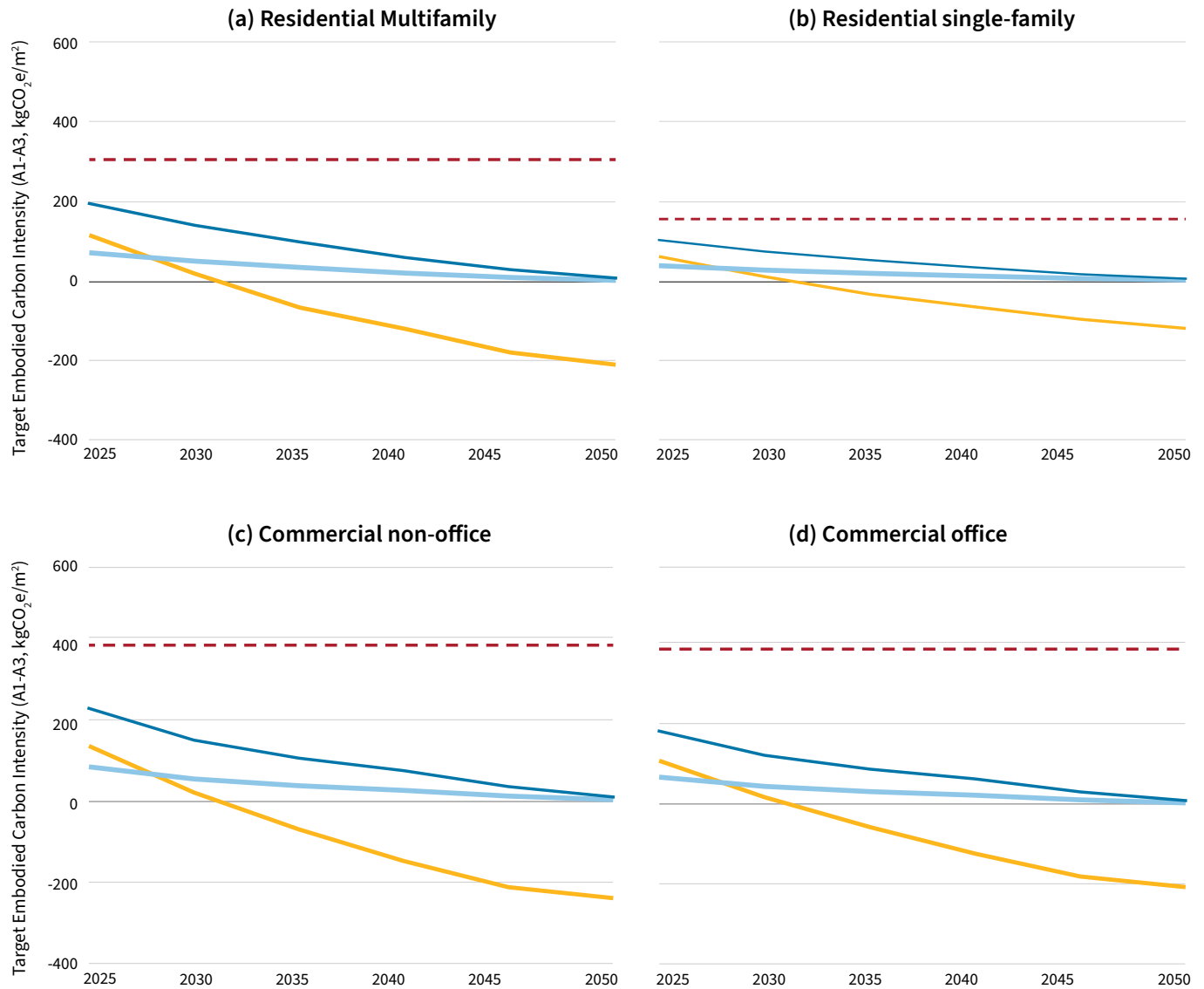


**Figure ES-1. Projected business-as-usual embodied carbon from extraction and manufacturing in the United States, 2020-2050.** (Left) Concrete, steel, asphalt, and sand and gravel, excluding newly constructed buildings. (Right) construction materials used in new building construction (including structure, enclosure, and interiors).

**Science-based targets are ambitious but within reach for some sectors today.** Downscaled carbon budgets for U.S. buildings were developed using three attribution principles: grandfathering, equal per capita, and ability to

pay. All methods require aggressive emissions reductions immediately. Multifamily housing targets are most achievable today, whereas commercial buildings require a lot of progress to reach targets.

**Legend**    - - - Benchmark ECI    — Downscaled via Grandfathering > Grandfathering (G/G)    — Downscaled via Ability to Pay > Grandfathering (A/G)    — Downscaled via Equal per Capita > Grandfathering (E/G)



**Figure ES-2. Target ECIs (kgCO<sub>2</sub>e/m<sup>2</sup>) for each building typology from 2020-2050 based on downscaled 1.5°C-aligned scenarios for the United States for residential multifamily (a), residential single-family (b), commercial non-office (c), and commercial office (d).**

## Scenario Analysis

Six modeled pathways evaluate the potential of strategies and policies to close the gap between BAU and 1.5°C-aligned trajectories. Only the “Best Case” scenario—combining aggressive adoption of all best practices and rapid development and deployment of emerging technologies—approaches the necessary reductions by 2050. Scenarios focused on design innovation and energy strategies also showed substantial promise.

Key takeaways include:

- **A portfolio of strategies is required:** No single intervention is sufficient. The most impactful strategies in the scope of this analysis were:
  - Cement and clinker substitution in concrete
  - Use of low-carbon electricity in steel production
  - Structural design optimization and material substitution
  - Cement kiln energy efficiency and carbon capture and storage (CCS)
  - Reuse / refurbishment of existing concrete buildings and infrastructure
- **Scaling best practices now while investing in emerging technologies is key:** Speed of adoption matters. Immediate scale-up of current best practices is crucial and will be responsible for the majority of reductions for the next twenty years. Deeper reductions from emerging technologies will start to play a larger role post-2040 and will be critical for closing in on targets approaching 2050.
- **Design matters:** Structural design optimization and material substitution strategies for new buildings offer meaningful near-term gains and are currently deployable. Design optimization of concrete and steel structures for material efficiency is particularly important in reducing emissions over the next decade. This scenario would have even more potential if research was available on design strategies for non-building infrastructure, which was mostly unexplored in current research and roadmaps. Based on the significance of design opportunities for buildings, this has large potential.
- **Cement and concrete are central:** Because of its volume and emissions intensity, decarbonizing concrete is critical to achieving reductions at scale.

Across scenarios, cement and clinker substitution in concrete was the top strategy across the entire construction sector. Cement kiln energy efficiency and CCS were also critical.

- **Policy levers can drive change:** The report assesses 32 federal, state, local, and private sector policy tools. The most impactful policies include:
  - Building-level embodied carbon standards (e.g., kgCO<sub>2</sub>e/m<sup>2</sup> limits in codes)
  - Financing and incentives for facility upgrades and raw material substitution
  - Product-level emissions standards (e.g. Clean Product Standards, product-level GWP limits in zoning and building codes)
  - Carbon pricing (e.g., cap-and-trade, border adjustments)

## Conclusion

This report serves as a call to action, urging the industrial and construction sectors to continue progress towards global targets. The embodied carbon of key construction materials used in buildings and infrastructure in the United States is significant and requires deployment of a large range of strategies. While challenges remain, existing technologies and strategies can deliver meaningful reductions in the near term. Success will depend on rapid policy action, cross-sector collaboration, and sustained investment in both proven and emerging solutions.

# Contents

<b>EXECUTIVE SUMMARY</b>	<b>4</b>
<b>1. Introduction</b>	<b>8</b>
1.1 Scope	8
<b>2. Projecting Business-as-Usual Material Consumption and Embodied Carbon in the US</b>	<b>10</b>
2.1 Projecting US building floor area additions	10
2.2 Projecting BAU material consumption for buildings and infrastructure	11
2.3 Projecting BAU embodied carbon from 2020-2050	13
<b>3. Embodied carbon targets toward 1.5°C</b>	<b>17</b>
3.1 Downscaling the Global Carbon Budget to Buildings in the US	17
3.2 Allocating the US Carbon Budget to Buildings by Typology	19
3.3 Pathways to 1.5°C in the US Building Sector	21
<b>4. Pathways to 2050: Reduction Strategies and Policies</b>	<b>24</b>
4.1 Assessing available emissions reduction strategies	24
4.2 Assessing embodied carbon reduction policies	28
4.3 Scenario Development	30
<b>5. Opportunities and limitations</b>	<b>44</b>
<b>6. Conclusion</b>	<b>45</b>
<b>References</b>	<b>46</b>

# 1. Introduction

Embodied carbon - the greenhouse gas (GHG) emissions generated by the manufacturing, transportation, installation, maintenance, and disposal of construction materials used in buildings, roads, and other infrastructure - is a critical and often overlooked solution for addressing climate change.

The industrial sector is the largest contributor to global GHG emissions, contributing to approximately 30% of global emissions (Carbon Leadership Forum (CLF), 2020). Construction materials used in buildings and infrastructure account for more than half of industrial emissions and are therefore key to reducing emissions from this sector (Carbon Leadership Forum (CLF), 2020). In the United States, industrial emissions also account for 30% of total GHG emissions (US EPA, 2025). Embodied carbon from the construction of buildings represents at least 5% of US emissions (US DOE, 2024).

Limiting global warming to 1.5°C is crucial to preventing the most severe impacts of climate change, including irreversible ecosystem loss, extreme weather events, and widespread human and economic harm (IPCC, 2023; IPCC 2018). The Intergovernmental Panel on Climate Change (IPCC) states that limiting warming to 1.5°C above pre-industrial levels requires global greenhouse gas emissions to reach net zero by around 2050 (IPCC, 2023).

The United States needs a 50% reduction by 2030 to align with a 1.5°C goal (Rhodium Group, 2023) and is not on track to meet this target. There remains an urgent need for more ambitious mitigation across all sectors. Rapid decarbonization of buildings through energy efficiency, electrification, low-carbon material use, and material-efficient design is crucial to closing the emissions gap and preserving a livable climate.

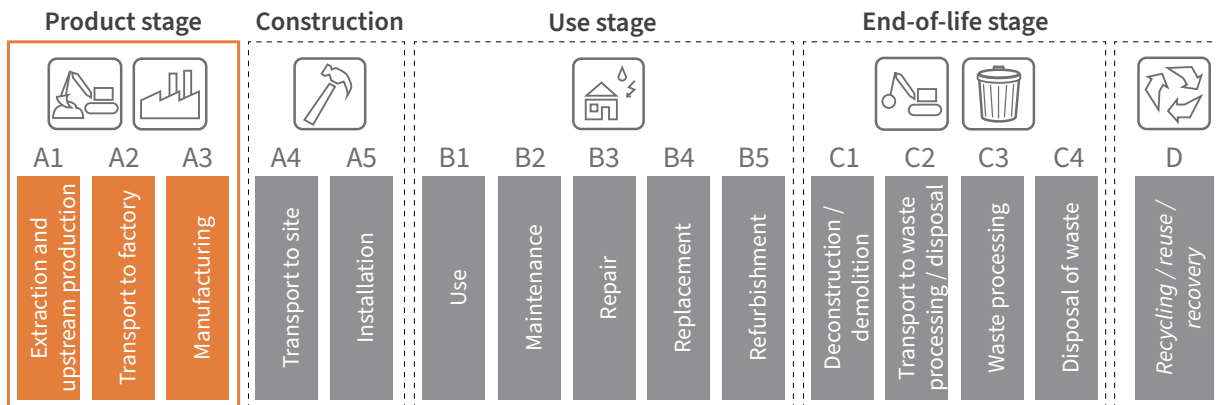
With limited time to act to avoid the worst consequences of climate change and increasing federal headwinds, focusing efforts on the highest potential strategies and associated policies is critical. CLF, RMI, and the UW Life Cycle Lab collaborated to advance research to address the following three questions to support industrial and building sector decarbonization in the United States:

- 1. What is the projected cradle-to-gate embodied carbon trajectory of the United States between now and 2050?** Using material intensity and historic material consumption data, we established a business-as-usual (BAU) emissions trajectory for cradle-to-gate embodied carbon for 30 key construction materials used in the United States between 2020 and 2050. This is described in section 2, “Projecting Business-as-Usual Material Consumption and Embodied Carbon in the US”.
- 2. What cradle-to-gate embodied carbon trajectory would be required over the next 30 years for the United States to meet global climate targets to keep below 1.5°C of warming?** We used global emissions trajectories set by the Intergovernmental Panel on Climate Change (IPCC) to allocate emissions reductions to the US construction sector using three primary attribution principles. This is described in section 3, “Embodied carbon targets toward 1.5°C”.
- 3. Which strategies and policies are most likely to help close the gap between BAU and 1.5°C- aligned targets?** We leveraged existing research on industrial and building decarbonization and demand reduction strategies and policies to evaluate the relative potential of different levers for closing the gap between BAU and target emissions trajectories. This is described in section 4, “Pathways to 2050: Reduction strategies and policies”.

## 1.1 Scope

The analysis in this report focuses on the emissions from the raw material supply and extraction, transportation, and manufacturing of products (A1-A3) used in the construction of buildings and infrastructure in the United States (see Figure 1), including the following scope:

- **Life Cycle Stages:** A1-A3 (referred to as “cradle-to-gate” or “product stage”)
- **Production Region:** The United States and countries with construction material exports to the United States.
- **Physical Scope:**
  - New buildings: Structure, foundations, enclosure, and some interiors (SEI). Interiors were reported in varying degrees of completeness and are generally limited to the primary materials used for interior partition framing, and wall, floor, and ceiling finishes (Benke et al, 2025).
  - Non-building infrastructure: Asphalt, concrete, sand and gravel, and steel.
  - Renovations: Quantities of steel and concrete used to renovate existing buildings are included in the non-building infrastructure estimates. Otherwise, renovations are excluded.
- **Indicator:** Global Warming Potential (GWP) using GWP 100
- **Biogenic Carbon:** Excluded. All included GWP values are based on reported GWP without biogenic carbon.



**Figure 1. Life cycle stages included in the analysis.** Extraction and manufacturing (A1), transport to factory (A2), and manufacturing (A3) are included.

The analysis excludes emissions from transportation to the construction site (A4), construction and installation (A5), use-phase (B stages), and end-of-life activities (C stages) due to data availability constraints for non-building infrastructure, which comprises approximately half of the emissions in the study. As a result, the magnitude of embodied carbon reported in this study underestimates the US construction footprint. See section 2.3 for further discussion of estimated remaining emissions outside the scope of this study.

## 2. Projecting Business-as-Usual Material Consumption and Embodied Carbon in the US

A critical component in evaluating decarbonization pathways for the US building and construction sectors is establishing a baseline or “business as usual” (BAU) scenario for building floor area projections, material consumption, and embodied carbon emissions.

We used three primary steps to establish BAU: (1) collecting data on the projected floor area of different building types in the United States, (2) using historic material consumption data and material use intensity data for the same building types to project the total consumption of key construction materials per year, and (3) establishing BAU cradle-to-gate embodied carbon intensity values for each material.

The result is a BAU projection of embodied carbon from 2025 to 2050. This BAU projection represents cradle-to-gate embodied carbon from construction materials if current practices continue, both in terms of the rate of consumption and in the production of the materials being consumed.

### 2.1 Projecting US building floor area additions

Projecting new US floor area by building typology is the first step needed to establish a BAU embodied carbon scenario projection from 2025 to 2050 for new buildings. The projections described in this section are used only for new buildings.

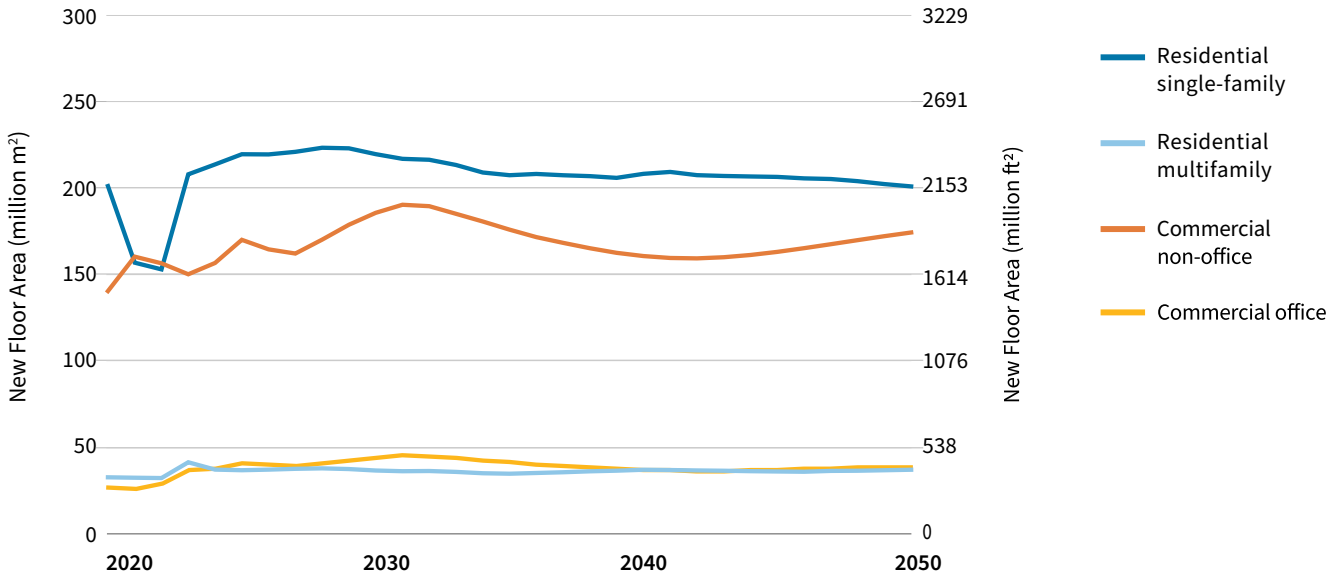
We first reviewed available floor area and economic data from the US Energy Information Administration (EIA) (US Energy Information Administration, n.d.), the US Census Bureau (US Census Bureau, n.d.), and other sources.

To characterize projected floor area growth from 2025-2050, data was primarily sourced from the EIA Annual Energy Outlook 2023 (AEO 2023) (US Energy Information Administration, 2023a). Historic data for years 2020-2024 was sourced from a combination of datasets from the EIA (US Energy Information Administration, 2020a) and the US Census Bureau (US Census Bureau, n.d.). More specifically, the projections for each building typology were derived as follows:

- **Commercial floor area projections:** Commercial building floor area projections were extracted directly from EIA AEO 2023 for 9 different building typologies: office, warehouse and storage, mercantile/service, public assembly, education, food service, lodging, food sales, health care, and other. EIA data characterizes all commercial building floor area as ‘new additions’ and ‘surviving’ floor area in each year projected. For this study, the ‘new additions’ for each year were assumed to represent all new construction activity for each typology. The ‘new additions’ floor area was allocated to each commercial sub-typology based on the total proportion of floor area added for each building typology in the given year.
- **Residential building projections:** Floor area projections for residential buildings followed a different method, leveraging data from the EIA AEO 2023 (US Energy Information Administration, 2023a), the Residential Energy Consumption Survey (RECS) 2020 (US Energy Information Administration, 2020b, 2023a), the National Energy Modeling System (NEMS) produced by the EIA (US Energy Information Administration, 2023b), and the US Census Bureau (US Census Bureau, n.d.). Because the AEO 2023 does not separate surviving building stock from new additions, additional data from RECS, NEMS, and the US Census Bureau were needed to approximate the quantity of existing residential buildings that are demolished each year by building sub-typology (i.e., single-family residential, multifamily residential, and mobile homes).

Further information about historical floor area data and floor area projections is included in Appendix A.

**Figure 2** shows annual floor area projections in the United States across four building use categories: single-family residential, multifamily residential, commercial (office), and commercial (non-office). The historic data from 2020-2022 shows significant shifts in the rate of construction for new single-family residential buildings, dropping approximately 25% from 2020 to 2021, likely due to the effects of the global COVID-19 pandemic on housing construction. The effects on multifamily residential, commercial office, and commercial non-office buildings were less pronounced, with almost <1% change in construction rates for multifamily housing units from 2020-2022, and a 12% increase in new floor area construction per year for both commercial categories.



**Figure 2. Floor area for newly constructed buildings in the US between 2020-2050.** Analysis based on data from the EIA Annual Energy Outlook 2023

## 2.2 Projecting BAU material consumption for buildings and infrastructure

In order to project the BAU consumption of key construction materials from 2020-2050, we used two complementary approaches:

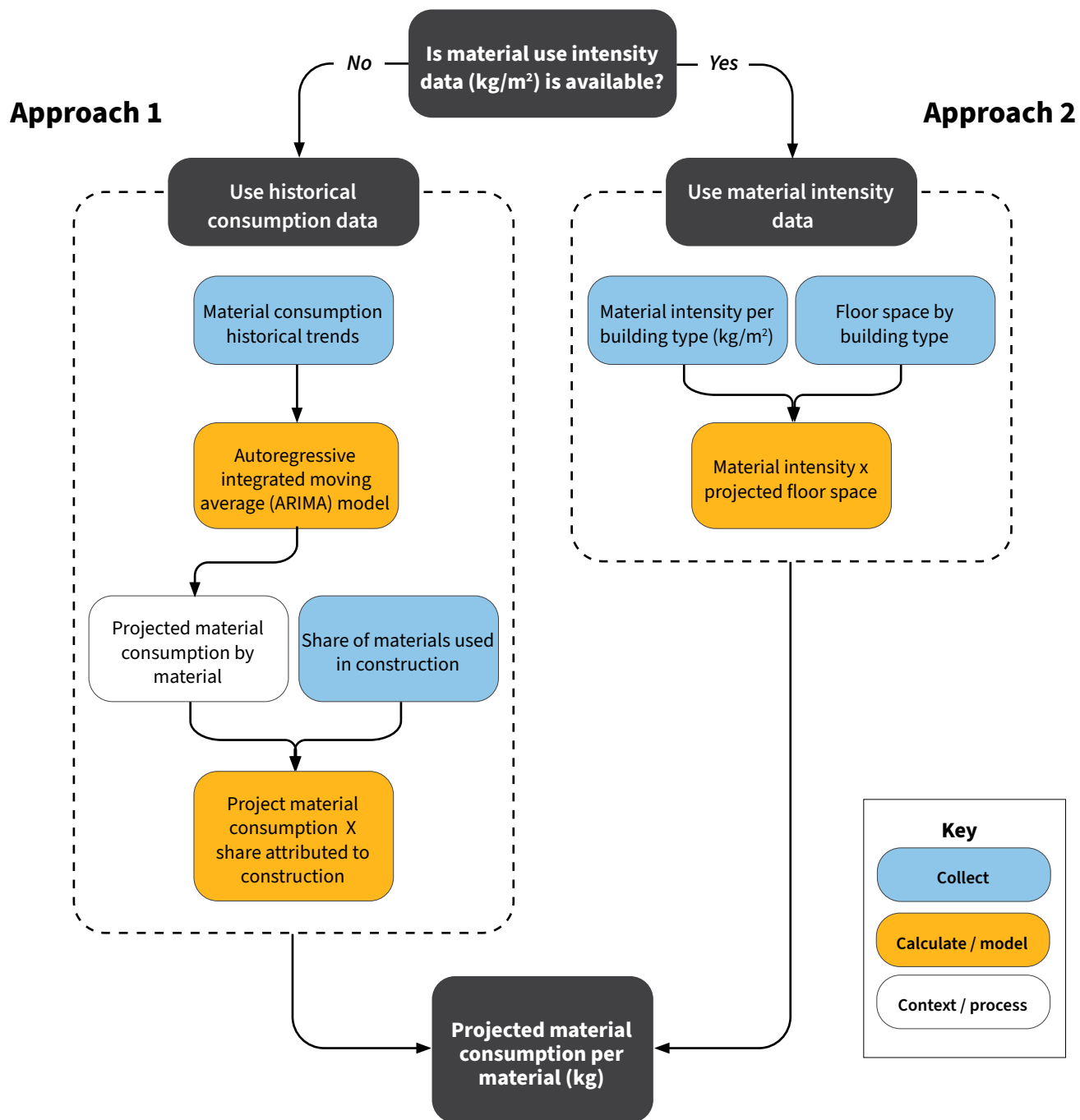
- **Approach 1 (Non-Building Infrastructure) – Historical Consumption and Time Series Modeling:** Utilizing historical raw material consumption data primarily sourced from the US Geological Survey (USGS) and the National Asphalt Pavement Association (NAPA), we applied statistical time series regression models (ARIMA/SARIMA) to forecast future material demand for a range of materials. Because USGS data is typically reported at a broad, sector-wide level, assumptions were necessary to isolate the portion directly attributable to the building and construction sector. Ultimately, this approach was used to project the consumption of asphalt, sand and gravel, concrete and steel.
- **Approach 2 (New Buildings) – Material Use Data:** Approach 2 leverages average (i.e. mean) **material use intensity (MUI, kg/m<sup>2</sup>)** for 117 distinct material types across various new construction building typologies in North America from *A Harmonized Dataset of High-Resolution Whole Building Life Cycle Assessment Results in North America* (Benke et al, 2025). We multiplied MUI with building floor area growth projections (see section 2.1) to generate future material stock estimates.

In total, these approaches allowed us to project material consumption of 30 material categories: four categories representing key materials used for civil infrastructure systems and other construction (using approach 1), and 26 representing materials commonly found in new construction buildings (using approach 2). For new buildings, the 26 material categories adapted from the classification used in Benke et al (2025) and Ashtiani et al (2025) include nearly all materials used in the structure, foundations, enclosure and interiors of new buildings, only excluding materials that made up less than 1% of the quantity of materials. For non-building infrastructure, concrete, steel, and asphalt together account for more than 90% of Scope 3 emissions in roadway infrastructure (Ashtiani et al., 2024).

The results from Approaches 1 and 2 were integrated to create a more comprehensive BAU material projection capturing building, infrastructure, and other construction. This required subtracting the concrete and steel projections for new buildings calculated using Approach 2 from sector-wide projections from Approach 1 to prevent double counting. The resulting projection serves as the basis for assessing decarbonization scenarios and the potential impacts of various policy interventions (see section 4).

**Figure 3** provides an overview of the modeling framework used to develop the BAU material stock projections.

Detailed descriptions of each methodological approach, including specific assumptions, data manipulations, calculations, and a literature review of similar material stock modeling studies, are provided in Appendix B. Additionally, all Python code scripts and methods employed in these projections are publicly accessible and documented in a Life Cycle Lab's GitHub repository (<https://github.com/Life-Cycle-Lab/wedge-material-stock-projection>). Although these methods were developed for the building and construction sector in the United States, the underlying logic and code could be expanded to any geographic scope with appropriate adjustments to input datasets and assumptions.



**Figure 3. Overview of modeling framework used to create material stock projection.** For additional details, see Appendix B.

## 2.3 Projecting BAU embodied carbon from 2020-2050

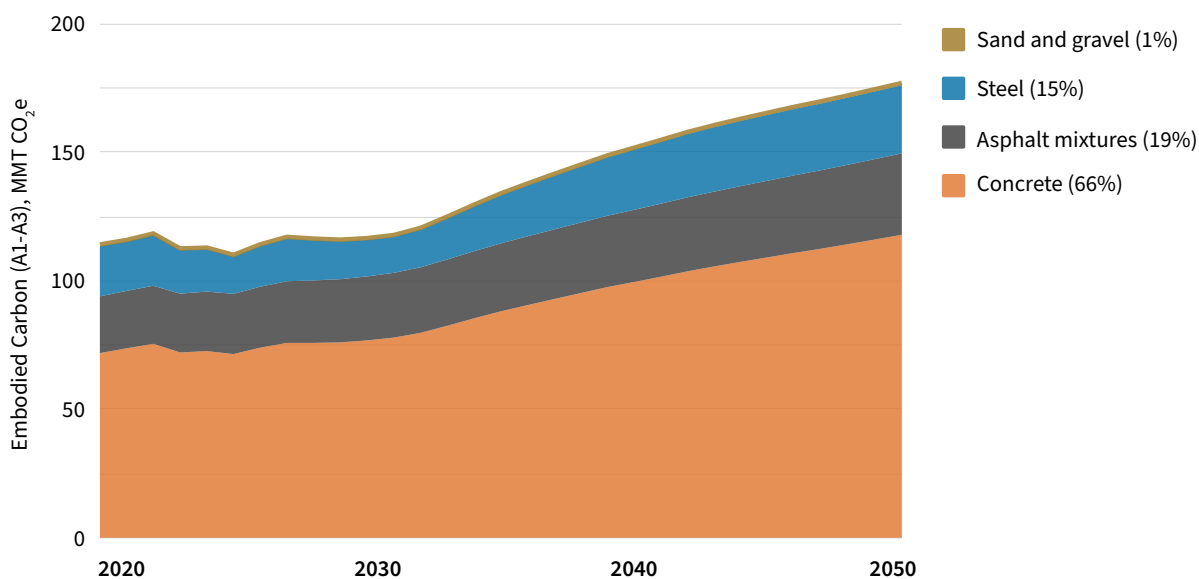
To project the embodied carbon for the BAU trajectory, we estimated baseline global warming potential factors for each material to multiply the baseline emissions intensity per unit of material by each stock projection to establish an emissions estimate.

Baseline emission intensity factors were calculated differently for Approach 1 (non-building) and Approach 2 (new building construction) as follows:

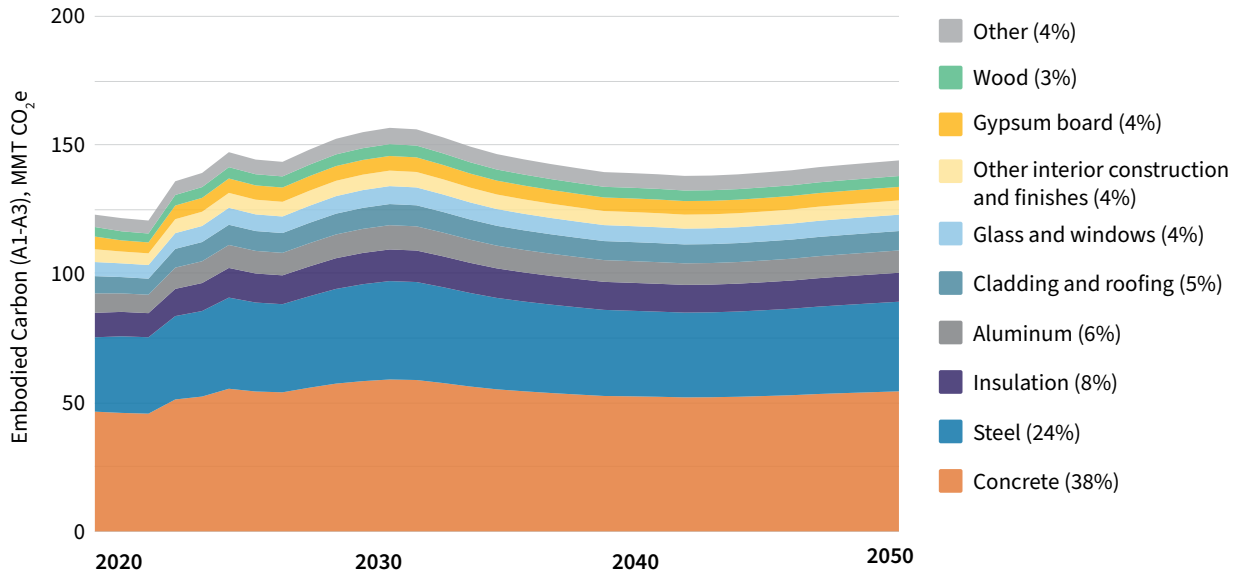
- **Approach 1 (Infrastructure and other):** Industry-average GWP values from environmental product declarations (EPDs) and other life cycle inventory data (where EPDs were not available) were used to establish baseline A1-A3 emissions intensity factors for concrete, steel, sand and gravel, and asphalt mixtures. The resulting projections are shown in Figure 4.
- **Approach 2 (New buildings):** Simplified A1-A3 emissions intensity factors were calculated by dividing the average ECI (kgCO<sub>2</sub>e/m<sup>2</sup>) by average MUI per material type (kg/m<sup>2</sup>), derived from the WBLCA benchmark material-level data. The resulting projections are shown in Figure 5.

While the projected growth in embodied carbon from new buildings is relatively flat, there is a more notable increase in embodied carbon for non-building infrastructure. This is influenced by the difference in methods for approaches 1 and 2. The US EIA projects relatively flat growth of new building construction, so new building materials have only modest growth. Historical consumption pattern data (used for infrastructure and other uses beyond new buildings) predict more growth.

For non-building infrastructure, Figure 4 shows that embodied carbon due to concrete production contributes 66% of projected emissions in 2050. The second largest contributor is asphalt mixtures at 19%, followed by steel at 15%. While the proportion of infrastructure project emissions associated with asphalt mixtures remains relatively unchanged from 2020 to 2050, Figure 4 shows an overall embodied carbon increase of 44% in the same time period.



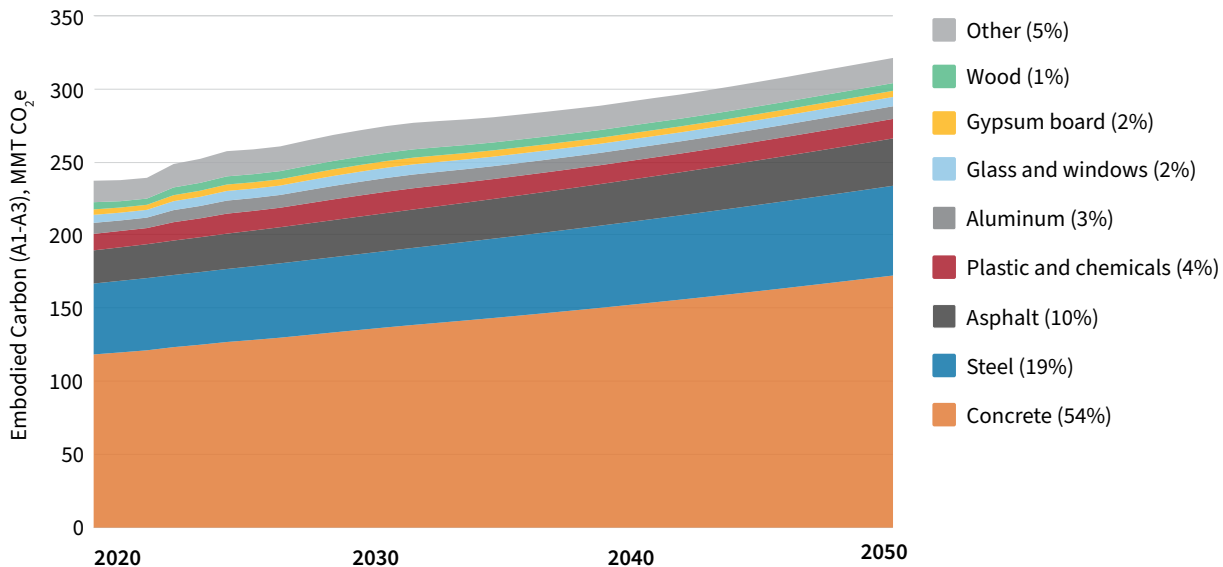
**Figure 4. Projected embodied carbon from extraction and manufacturing for concrete, steel, asphalt, and sand and gravel used in the United States, 2020-2050, excluding newly constructed buildings.**



**Figure 5. Projected embodied carbon from extraction and manufacturing for construction materials used in new building construction in the US, 2020-2050.** SEI = structure, enclosure, and interiors.

For new buildings, Figure 5 shows embodied carbon from concrete production as the largest contributor at approximately 38% of projected A1-A3 emissions in 2050. Steel is the second largest contributor at 24% of emissions, with 15% from structural steel (e.g. Wide-flanges, HSS, channels) and 9% from reinforcement (e.g. rebar). Other high embodied carbon materials for building construction include insulation, aluminum, gypsum board, cladding, glass and windows, interior finishes, and wood.

Figure 6 provides a holistic picture of projected US embodied carbon from construction products, combining approaches 1 and 2. Projected cradle-to-gate embodied carbon of key construction materials increases an



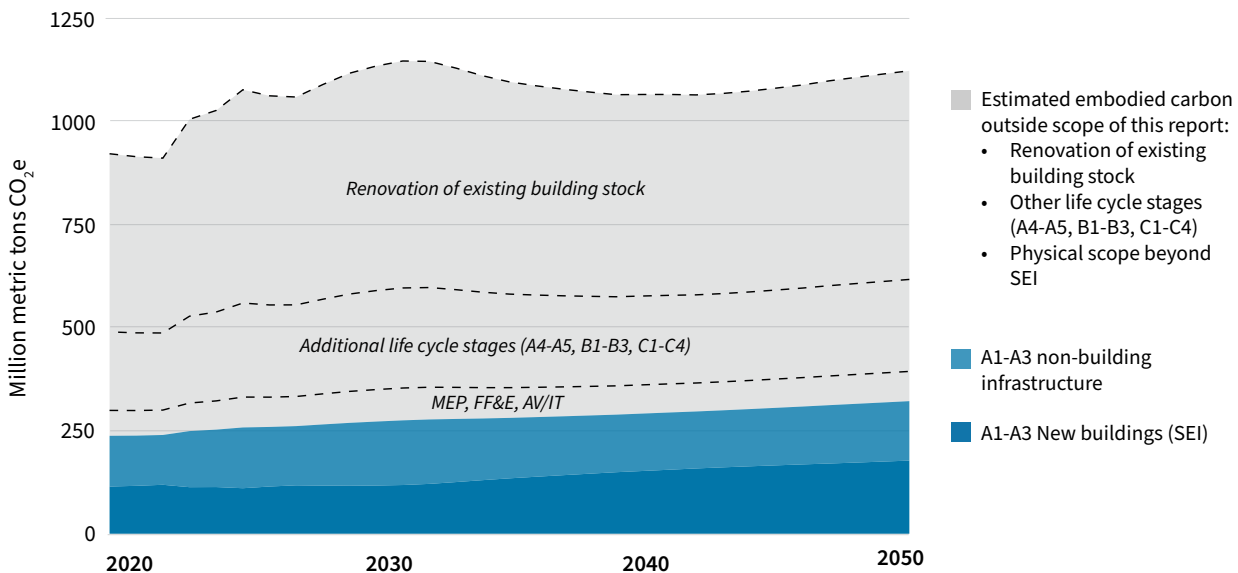
**Figure 6. Projected embodied carbon from extraction and manufacturing for key construction materials for buildings and infrastructure in the United States, 2020-2050.**

estimated 35% from 2020 to 2050, assuming the industry continues to produce buildings and infrastructure following the BAU trend. The largest total contributors to projected embodied carbon are concrete (54%), steel, (19%), asphalt, (10%), and plastic and chemicals (4%).

As discussed in section 1.1, the project emissions shown in Figure 6 are an underestimate of total US embodied carbon for buildings and infrastructure. Emissions from raw material supply and extraction, transportation, and manufacturing of products for the structure, foundations, and enclosure of new buildings is a major contributor the total life cycle embodied carbon for new buildings, but excludes key emissions from mechanical, electrical, and plumbing (MEP) systems, furniture and equipment, and other excluded scope that lacks robust material use intensity data required for inclusion in this analysis. Additionally, construction stage (A4 and A5) emissions for buildings and infrastructure are excluded, which can be particularly significant for infrastructure when materials must be trucked long distances to be installed. Refrigerants (typically captured in B1) and end-of-life emissions (C stage) are also excluded. Last, the renovation of existing building stock contributes significantly to embodied carbon - particularly in a developed economy like the US - but is excluded from available floor area projections and therefore not included in this analysis. Only concrete and steel used in renovations is included.

To understand the scale of excluded scope, we used the analysis in *Washington State Carbon Emissions Estimation: 2025 - 2050: Operational and embodied carbon of the built environment* to establish scaling factors to create an order of magnitude estimate for excluded scopes. This report aims to address a gap in knowledge by estimating often excluded scopes of embodied carbon to create a more comprehensive estimate of Washington State embodied carbon projections between 2025 and 2050 (Jensen et al, 2025).

**Figure 7** shows the resulting analysis, which demonstrates that the inclusion of scope beyond A1-A3 – particularly renovation of existing building stock (B4) – is critical in understanding the total US embodied carbon to 2050 and pathways for decarbonization. Future research could be integrated into the modeling analysis summarized in this report to provide a more holistic US embodied carbon reduction roadmap.



**Figure 7. Order of magnitude estimate of embodied carbon from renovation of existing building stock, life cycle stages beyond A1-A3, and additional physical scope for new buildings.** Analysis created through scaling factors based on the results of Jensen et al. (2025). SEI = structure, enclosure, interiors, MEP = mechanical, plumbing, and electrical, FF&E = furniture, fixtures, and equipment, and AV/IT = audio-visual and information technology.

## 3. Embodied carbon targets toward 1.5°C

The global carbon budget must be broken down and allocated to embodied carbon in US buildings to establish policy pathways for embodied carbon in the United States that comply with a 1.5°C warming limit (in line with IPCC). Allocating global emissions to the US building stock involves three major steps: (1) allocating a fair share of the global carbon budget to the United States, (2) allocating a portion of the US carbon budget to new building construction activity, disaggregated by building typology, and (3) deriving an embodied carbon intensity per square meter of constructed floorspace based on projected annually constructed floorspace. This allocation process is referred to as downscaling.

The result is a set of emissions intensity targets for each building typology over time that can guide public policy, investment strategies, and climate-aligned design and construction practices.

### 3.1 Downscaling the Global Carbon Budget to Buildings in the US

The global 1.5°C-aligned carbon budget is based on IPCC AR6 mitigation scenarios (Edward Byers et al., 2022). These scenarios were developed by the IPCC as part of the Sixth Assessment Report (AR6) of Working Group III. The quantitative, model-based scenarios represent a variety of social, economic, and other conditions that could lead to achieving a 1.5°C warming limit globally, and they report socio-economic development, greenhouse gas emissions, energy, and other data. Rather than analyzing each AR6 scenario, this analysis considers the median scenario, which is often used in analysis to represent a central tendency or a more ‘typical’ outcome.

The US share of the global carbon budget is derived by applying an attribution principle to the median AR6 scenario. Attribution principles use different metrics such as GDP, population, and historic emissions to allocate global emissions to different countries. Our analysis applied three widely recognized attribution principles: grandfathering, ability to pay, and equal per capita which follow the same definitions employed by the Science Based Targets initiative (SBTi) (Science Based Targets initiative, 2024). There is no consensus in the scientific community around using specific attribution principles, as they are intended to demonstrate a diversity of potential allocation scenarios that have different equity implications. The three attribution principles in this report were chosen as they are commonly used principles that demonstrate a wide range of potential emissions allocations.

The effort-sharing approaches that we used to downscale global emissions to the United States are described as follows:

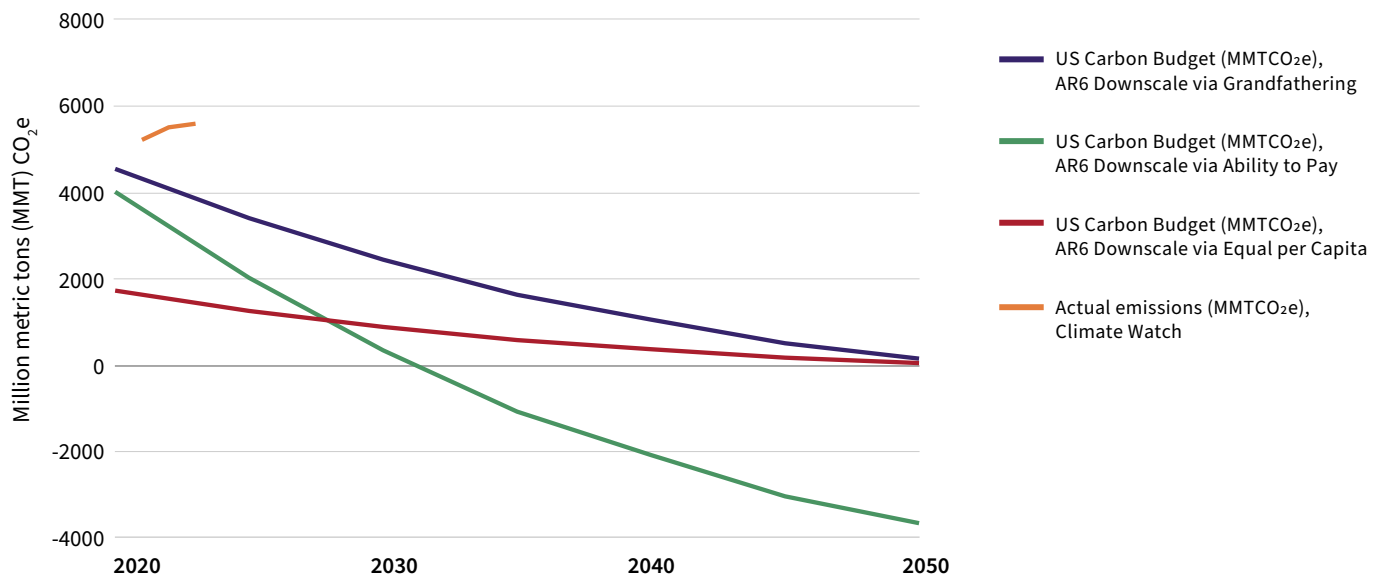
- **Grandfathering:** The grandfathering principle allocates future emissions allowances based on each country’s historical share of emissions. In this analysis, the US carbon budget for each year from 2020 to 2050 was calculated by allocating each future year’s global carbon budget based on the United States’ percentage share of global greenhouse gas emissions in the base year 2020 (Climate Watch & World Resources Institute, 2024). This approach assumes continued proportional responsibility aligned with past emissions contributions.
- **Ability to Pay:** The ability to pay approach adjusts carbon budget allocations based on a nation’s economic capacity. This method incorporates a reduction factor and a correction factor derived from the GHG emissions data in the base year 2020 (Climate Watch & World Resources Institute, 2024) and GDP per capita (World Bank Group, 2025) across all countries. The resulting adjusted US budget reflects the expectation that wealthier nations should contribute more to mitigation efforts. The analytical framework and formulas for the ability to pay approach were published by (Berg et al., 2020).
- **Equal per Capita:** This equal per capita principle allocates the global carbon budget based on each nation’s population, reflecting a rights-based approach, in which resources or burdens are equally

distributed across a population. For each year between 2020 and 2050, the US share of the global carbon budget was determined by dividing that year's global carbon budget by the projected US proportion of global population for that year. United States and global population projections were sourced from the United Nations World Population Prospects (United Nations Department of Economic and Social Affairs: Population Division, 2025).

Each principle yields a unique emissions pathway for the United States from 2020 to 2050, as shown in **Figure 8**. The grandfathering carbon budget indicates the highest carbon budget for the United States across all years. This is expected, as the United States has historically had the greatest or second greatest emissions globally, which would yield it a higher proportion of the carbon budget. In this approach, the 2020 budget is 4557 MMT CO<sub>2</sub>e, while the 2050 budget is 157 MMT CO<sub>2</sub>e, indicating a 97% reduction from 2020 to 2050. The 2022 carbon emissions from the United States were reported to be 5604 MMT CO<sub>2</sub>e (Climate Watch & World Resources Institute, 2024), which is 23% higher than the 2020 target established using the grandfathering approach.

The Equal per Capita principle yields a lower budget each year than the grandfathering principle. The Equal per Capita target is 1734 MMT CO<sub>2</sub>e for 2020 and 54 MMT CO<sub>2</sub>e for 2050, a 97% reduction. It is expected that the Equal per Capita principle would necessitate a lower carbon emissions target for the United States than the grandfathering principle, as the United States has historically had an outsized carbon emissions footprint per capita when compared with other countries (IEA, 2024).

The Ability to Pay scenario affords the United States a relatively high carbon budget in the year 2020 when compared with the Equal per Capita scenario, but it is the only principle to allocate a negative carbon budget in years 2032-2050, which is in line with the approach outlined by van den Berg et al (Berg et al., 2020). The negative budget used in this approach indicates that the United States would need to reduce carbon emissions and in some way offset its emissions via carbon storage or other means.



**Figure 8. US embodied carbon budget downscaled from global emissions based on three attribution principles: grandfathering, ability to pay, and equal per capita.**

### 3.2 Allocating the US Carbon Budget to Buildings by Typology

After downscaling the global carbon budget to emissions in the United States using the three attribution principles discussed above, we performed a secondary analysis to downscale the US carbon budget to new construction activities for each building typology. This secondary analysis uses the grandfathering approach to allocate all US carbon emissions to four building typologies based on the historical emissions from new construction by typology.

Though other downscaling approaches were considered for this step (i.e. equal per capita, ability to pay), only the grandfathering principle was analyzed in this section for two reasons. First, allocating future emissions to new construction by building typology based on the historical emissions of each building typology is much more logical and direct than allocating emissions based on other factors such as population and GDP which can't be easily allocated to building types. Second, high quality floor area projection data is available through 2050, while the data needed to apply other attribution principles (e.g., economic data) is not. As a result, grandfathering is the only approach that was used to downscale emissions from the United States to new construction activity by building typology.

Under the grandfathering approach, the share of emissions for new construction of each building typology in the base year (2020) was used to allocate the US carbon budget to each typology over time. For the three national emissions pathways developed in Section 3.1, building-sector emissions were distributed by typology using the estimated share of emissions per typology in year 2020. This was assessed by multiplying an embodied carbon intensity (ECI, kgCO<sub>2</sub>e/m<sup>2</sup>) benchmark value for each building typology by the total floor area of that typology. The floor area for each building typology was derived in section 2.1.

For single-family residential buildings, a baseline ECI for all detached single-family homes in the United States was derived from the 2025 report “Building with Biomass: A New American Harvest,” (Magwood et al., 2025) which established a baseline for embodied carbon across single-family residential homes in the United States. For all other building typologies, we used average values data extracted from the published dataset from *A Harmonized Dataset of High-Resolution Whole Building Life Cycle Assessment Results in North America* (Benke et al., 2025) and *Material Use and Embodied Carbon Intensity of New Construction Buildings in North America* (Ashtiani et al., 2025). Those ECI values are summarized in **Table 1**.

The scope of the LCAs to derive these ECIs is limited to LCA stages A1-A3. The system boundary includes structure, foundations, enclosure and interiors, but the inclusion of physical scope varies slightly based on differences in user input for certain materials. In particular, the interiors scope for buildings types other than single family is very limited compared to the full interior construction and finishes used on a typical project.

LCA data for single-family residential buildings were derived from the BEAM Estimator (v1.1), while LCA data for all other building typologies came from a combination of Tally and One Click LCA. More detail about the LCA goals and scopes used can be found in *Building with Biomass: A New American Harvest* (Magwood et al., 2025) and the *The Embodied Carbon Benchmark Report: Embodied Carbon Budgets and Analysis of 292 Buildings in the US and Canada* (Benke et al., 2025).

**Table 1. Average embodied carbon intensity and material use intensity by building typology, including data source.**

Embodied carbon intensities are normalized by constructed floor area to match the floor area definition used by EIA.

Building Typology	Embodied Carbon Intensity (kg CO <sub>2</sub> e/m <sup>2</sup> )	Source
Residential single-family*	153	Magwood et al., 2025
Residential multifamily	308	Ashtiani et al., 2025
Warehouse and storage	246	Ashtiani et al., 2025
Commercial office	386	Ashtiani et al., 2025
Mercantile/service**	420	Ashtiani et al., 2025
Public assembly	436	Ashtiani et al., 2025
Education	433	Ashtiani et al., 2025
Food service**	420	Ashtiani et al., 2025
Lodging**	420	Ashtiani et al., 2025
Food sales**	420	Ashtiani et al., 2025
Health care	388	Ashtiani et al., 2025
Other**	413	Ashtiani et al., 2025

\*Single-family also used to represent mobile homes due to a lack of data for mobile home ECI.

\*\*Average ECI for all non-office commercial buildings in the CLF V2 dataset used for Mercantile/Service, Food service, Lodging, and Food sales commercial buildings.

\*\*\*Average ECI for all commercial buildings (including office buildings) in the CLF V2 dataset used to represent buildings in the Other category. These are buildings that could not be categorized into any of the other typologies listed above.

The embodied carbon of all newly added floor area in the United States by year (shown in Figure 2) was calculated by multiplying the floor area for each building typology (m<sup>2</sup>) by its corresponding ECI (kgCO<sub>2</sub>e/m<sup>2</sup>) as identified in Table 1, resulting in an estimate of total global warming potential by building typology (kg CO<sub>2</sub>e). This total was divided by the average annual US carbon emissions from 2016 to 2021 (5650 MMT CO<sub>2</sub>e) to yield the percentage of carbon emissions allocated to each building typology. For the grandfathering approach, the percentage of US emissions allocated to each building typology for A1-A3 is 0.65%, 0.21%, 0.22%, and 1.13% for single-family residential, multifamily residential, commercial office, and commercial non-office buildings, respectively.

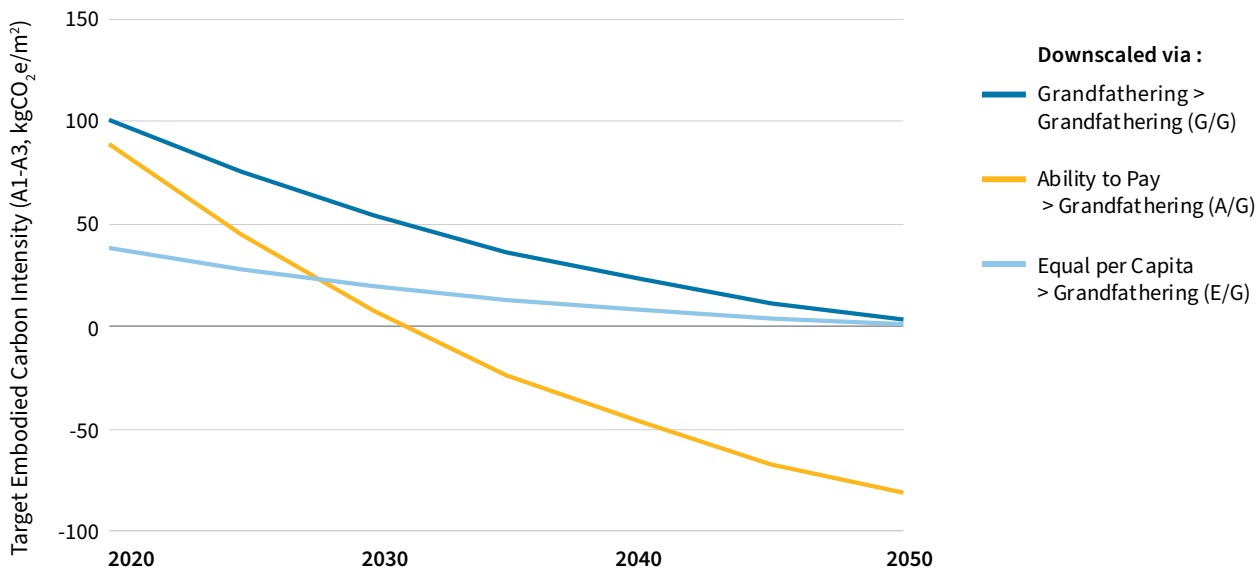
There are several reasons to believe this projection is a conservative estimate of US cradle-to-gate embodied carbon. The values used to represent industry average in Table 1 are based on collected data from two studies that likely skew toward project teams that perform whole building life cycle assessments on their projects, which likely means that these project teams are already implementing some best practices for reducing embodied carbon emissions. These studies are the best available data sources for their respective building typologies, but they likely skew toward lower ECI values. Additionally, there are limitations in included LCA scope, which excludes some interior finish materials, MEP, FF&E, and sitework. Some of the available data sources do not account for emissions outside of LCA stages A1-A3, so use-phase, renovation, and end-of-life emissions are also excluded. These shortcomings mean that approximately 70% of the total embodied carbon for buildings and infrastructure may be excluded from this study. This analysis must therefore be expanded as data is available to create relevant targets for policies and programs with a more holistic scope.

### 3.3 Pathways to 1.5°C in the US Building Sector

#### 3.3.1 Emissions Pathway to 1.5°C for all US Buildings

The CO<sub>2</sub> emissions for buildings in the United States for each combination of attribution principles is shown in Figure 9. The trends in Figure 9 for the building sector are similar to those shown in Figure 8 for total US emissions, as they represent a fixed proportion of the total US budget.

The emissions budget for US Buildings — using the grandfathering approach to downscale global emissions to the United States and the grandfathering approach to downscale emissions to each typology (G/G) — falls from 101 MMT CO<sub>2</sub>e in 2020 to 3.5 MMT CO<sub>2</sub>e in 2050, indicating a 97% reduction in building sector emissions. For the equal per capita and grandfathering approach (E/G), the budget falls from 38.4 MMT CO<sub>2</sub>e in 2020 to 1.2 MMT CO<sub>2</sub>e in 2050. For the ability to pay and grandfathering scenario (A/G), the budget drops from 89 MMT CO<sub>2</sub>e in 2020 to 0 MMT CO<sub>2</sub>e in 2032 and -81 MMT CO<sub>2</sub>e in 2050.



**Figure 9. The US Carbon budget for all buildings in the US toward 1.5°C based on three combinations of attribution principles.** Each budget has been downscaled to the US, using either a grandfathering, ability to pay, or equal per capita approach, and then further to the building sector in the US using a grandfathering approach.

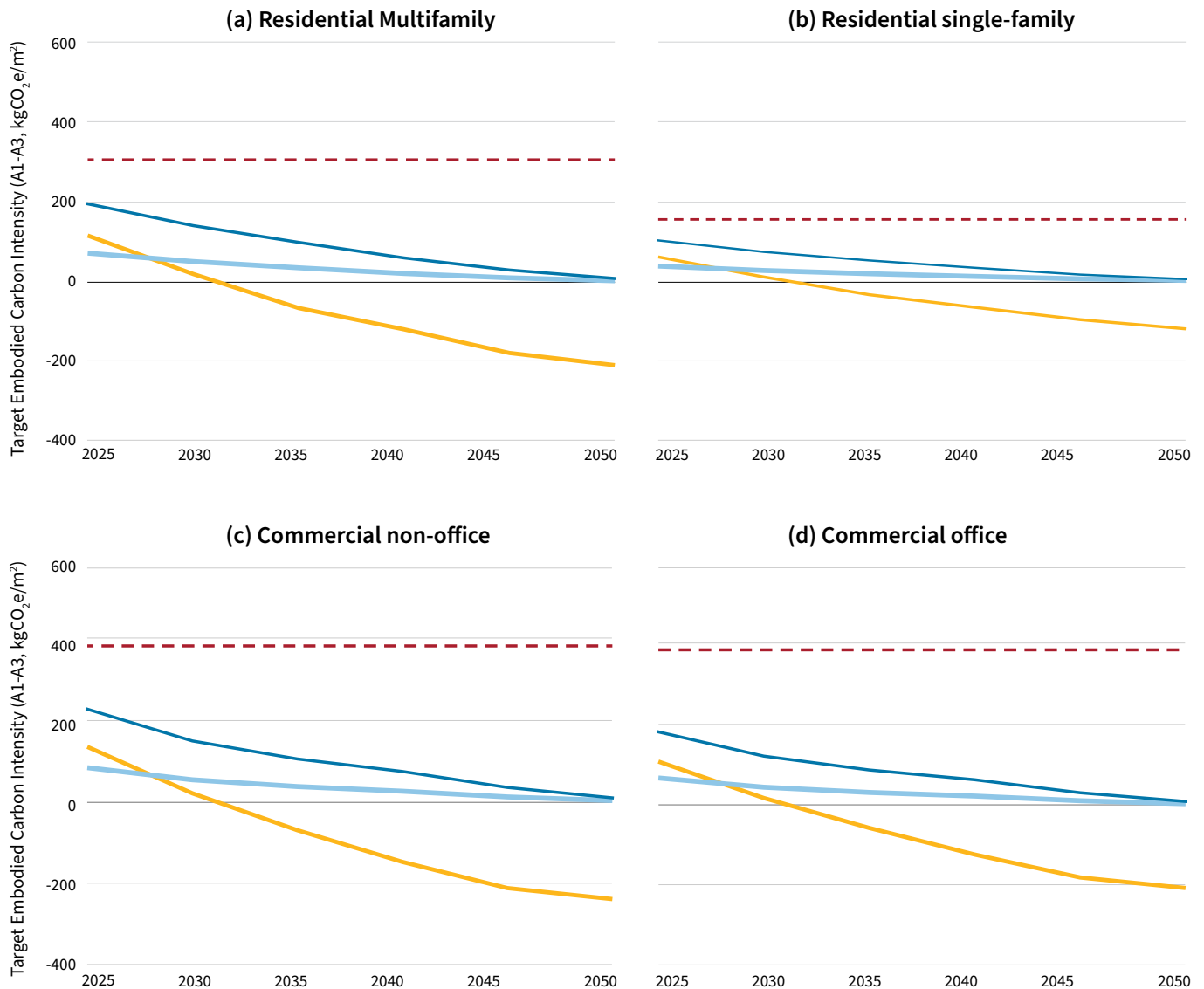
#### 3.3.2 Establishing 1.5°C-aligned ECI targets by building typology

The 1.5°C-aligned carbon budgets for each building typology were converted into ECI targets to serve as a reference point at the building scale. The downscaled emissions targets for each typology between 2020 and 2050 were divided by the projected floor area to be constructed over the same period, yielding ECI targets for each year in units of kilograms of CO<sub>2</sub>-equivalent emissions per square meter (kgCO<sub>2</sub>e/m<sup>2</sup>), shown in Figure 9.

Figure 9 also compares the calculated 1.5°C-aligned ECI targets to a static benchmark ECI for each building typology (see Table 1). These benchmark values represent average US embodied carbon intensity based on current practices, whereas the 1.5°C-aligned targets identify what that embodied carbon intensity would need to be for each building typology to be on a path to achieving 1.5°C. In other words, if a building typology, on aggregate, were to achieve this target in each year, it would indicate that a given segment of the new construction sector is in line with achieving 1.5°C based on the applicable attribution principles.

**Figure 10** shows that, for all building typologies, the benchmark ECI is notably higher than the 2025 1.5°C-aligned ECI target. **Figure 10a** shows the ECI targets for single-family residential buildings, with the G/G, A/G, and E/G scenarios showing a similar trajectory to the national targets presented in Figure 9. For each scenario, the 2025 target is lower than the benchmark ECI. For the G/G and E/G scenarios, the targets trend toward zero, while the targets for the A/G scenario approach zero in 2032 and are negative from 2033-2050. Achieving low or negative ECI targets will require the use of carbon-storing materials, carbon capture and sequestration (CCS) technologies, or other approaches that store more carbon than is emitted during material manufacturing and building construction.

**Legend** — Benchmark ECI — Downscaled via Grandfathering > Grandfathering (G/G) — Downscaled via Ability to Pay > Grandfathering (A/G) — Downscaled via Equal per Capita > Grandfathering (E/G)

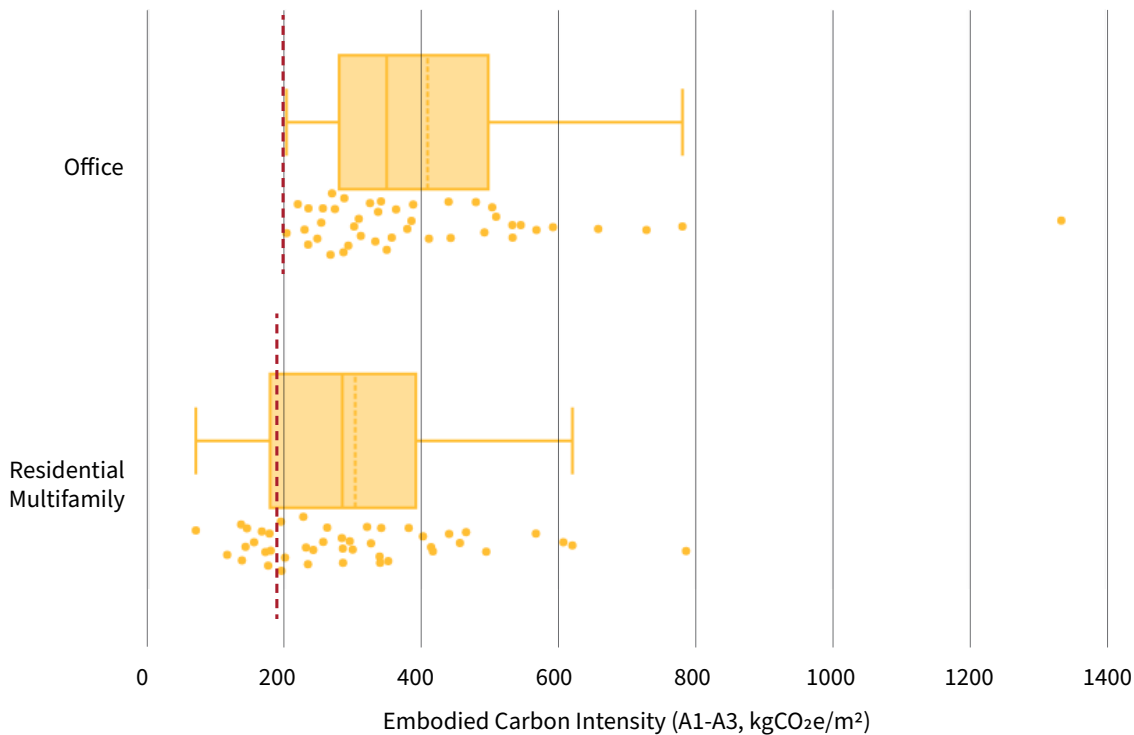


**Figure 10. Target ECIs (kgCO<sub>2</sub>e/m<sup>2</sup>) for each building typology from 2020-2050 based on downscaled 1.5°C-aligned scenarios.** 10a = residential single family, 10b = residential multifamily, 10c = commercial office, and 10d commercial non-office.

Although the 2050 targets show a need to significantly reduce the ECI of different building typologies when compared with the respective benchmarks, the 2025 targets are achievable today using current techniques.

For example, with multifamily residential buildings, the median ECI benchmark is 308 kgCO<sub>2</sub>e/m<sup>2</sup> and the 2025 targets are between 73-197 kgCO<sub>2</sub>e/m<sup>2</sup>. The CLF WBLCA Benchmark Study V2 includes data from multifamily residential buildings that meet each of these targets (Benke et al., 2025). Although a minority of buildings included in the dataset achieve these 2025 targets, those buildings are proof that the 2025 targets are achievable based on today's technologies and practices. The low- and negative-ECI targets required in later years will need to be addressed using more aggressive strategies and policies.

None of the commercial office building ECIs from the CLF benchmark study are below the 1.5°C-aligned targets for 2025. The median ECI benchmark is 386 kgCO<sub>2</sub>e/m<sup>2</sup>, while the 1.5°C-aligned targets are between 67-182 kgCO<sub>2</sub>e/m<sup>2</sup>. This indicates that today's "typical" commercial office building (as defined by the CLF benchmark) would require substantial embodied carbon emissions reductions in order to be aligned with current 1.5°C-aligned targets, and even greater reductions in future years.



**Figure 11. Comparison of 1.5°C- aligned targets (G/G) for multifamily residential and commercial office against data from the CLF WBLCA Benchmark Study v2 for each primary building use type.** Data generated using the CLF Benchmark Explorer (<https://wblca-benchmark-explorer.carbonleadershipforum.org/>).

## 4. Pathways to 2050: Reduction Strategies and Policies

This section describes our research to identify and quantify potential impact from strategies and policies that can close the gap between BAU and 1.5°C-aligned emissions reduction targets.

### 4.1 Assessing available emissions reduction strategies

The first step in assessing pathways for reaching 1.5°C-aligned reduction targets was to collect data on the range of available industrial and building sector decarbonization strategies. We focused on two factors:

- 1. Unconstrained emissions reduction potential:** This factor captures the technical potential of each reduction strategy, expressed as a percentage reduction from BAU. These percentages express the potential unconstrained by considerations of cost, technological readiness level (TRL), market-readiness, and other feasibility challenges.
- 2. Adoption rate curves:** This value (which increases over the period of 2020-2050) expresses the percentage of the market that has deployed each strategy in a given year, compared to 2020 levels. This factor takes into account the cost, TRL, and other challenges absent from the unconstrained potential.

#### 4.1.1 Unconstrained emissions reduction potential

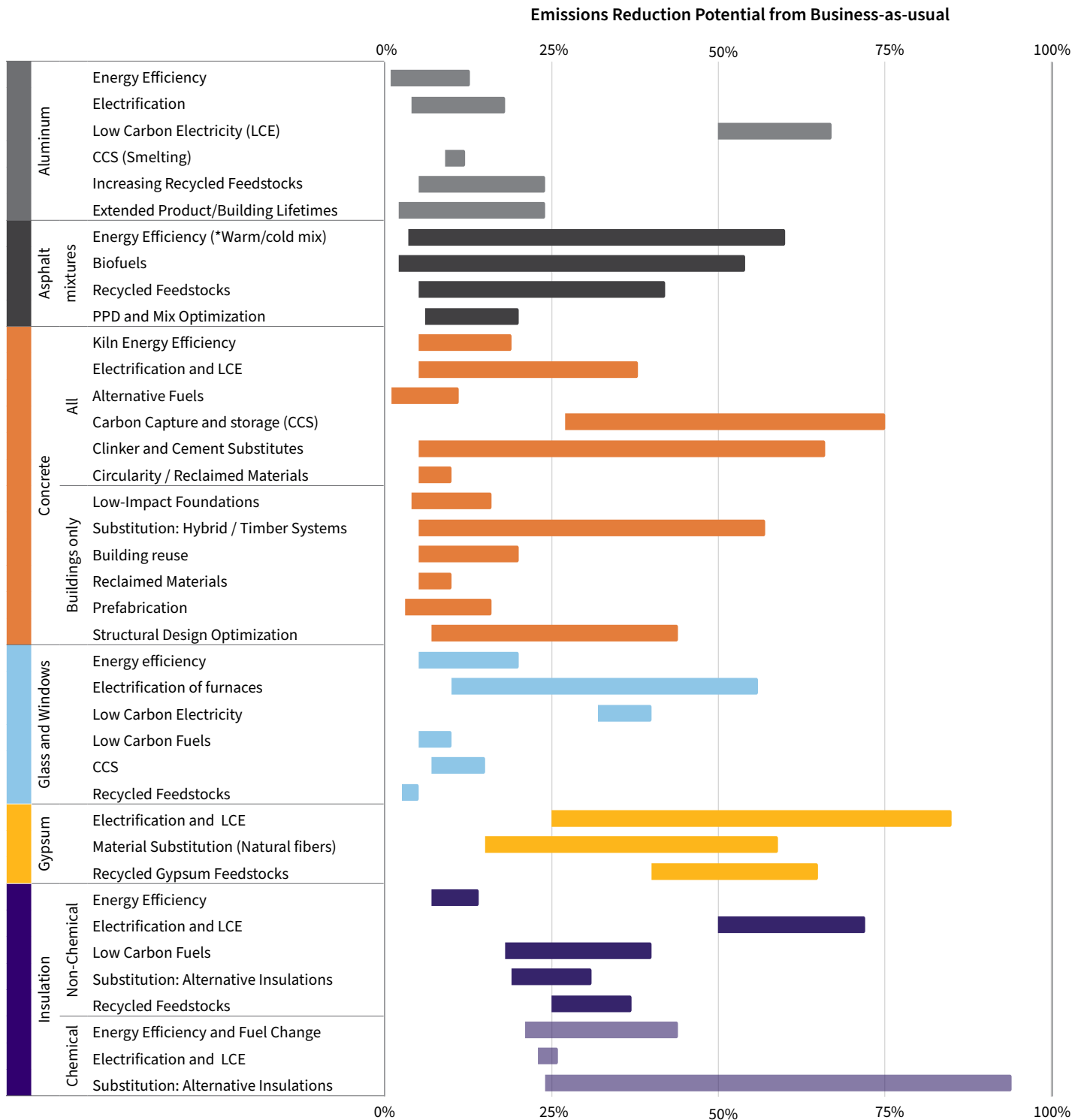
We collected data from peer-reviewed papers, government research, and industry roadmaps on the potential of different strategies to reduce emissions. Our literature review and analysis included:

- Industrial decarbonization strategies that focus on reducing the emissions intensity of production through energy efficiency, electrification, low carbon fuels, and carbon capture
- Demand reduction strategies like material substitution, circularity, and material efficient design

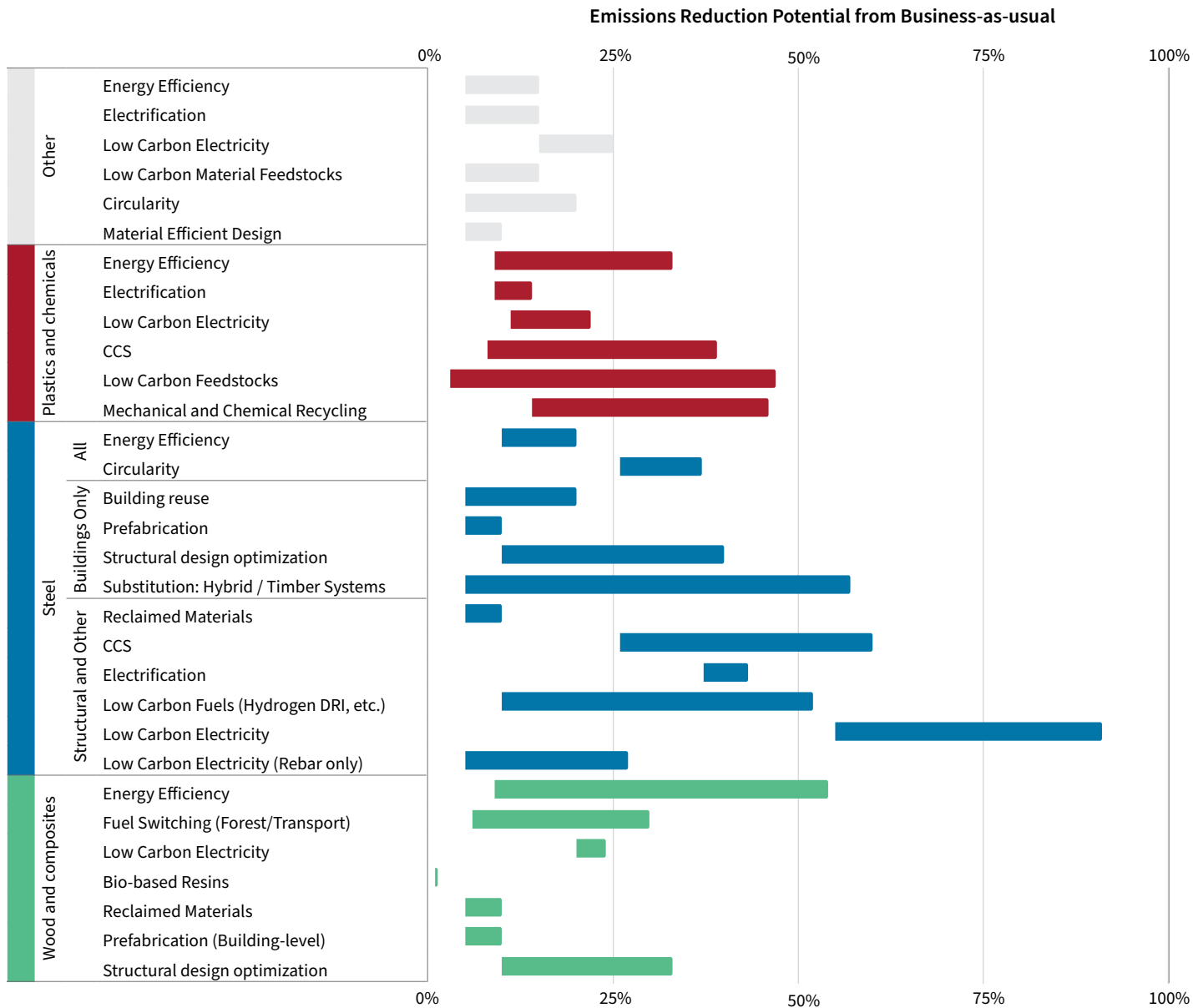
**Figure 12** summarizes the emissions reduction potential for each strategy identified in the reviewed research, organized by material category. The range of reductions cited here represent differences expressed in the literature regarding the range of emissions reductions that are possible for different strategies (e.g. if one source states a 5% reduction potential and another source cites a 50% reduction potential, the range would be 5-50%). Strategies with smaller ranges therefore may have greater agreement on the reduction potential of the strategy, or less relevant research available.

The reviewed research reveals very broad ranges of emissions reduction potentials. This reflects both the range of potential dependent on the facility and project as well as disagreement within reviewed research. Additionally, materials beyond concrete and steel had extremely limited research available on decarbonization strategies. The results from individual practitioner LCA studies were not a focus of the reviewed research, which may have changed the percentage reduction on strategies such as building reuse that show larger percentage reductions on a building-by-building case than found in academic research and industry roadmaps. Overall, there is a need for additional research on the specific emissions reductions of using different material substitution, manufacturing R&D, and design innovation strategies (among others).

**Table 2** describes the categories we used to group these strategies. To learn more about our methodology related to reduction strategies, see Appendix C.



**Figure 12a. List of the strategies and associated GHG emissions reduction potential from benchmark levels for the Aluminum, Asphalt mixtures, Concrete, Glass and windows, Gypsum, and Insulation material groups.** Reduction potentials are based on reviewed academic and industry literature, organized by material category.



**Figure 12b. List of the strategies and associated GHG emissions reduction potential from benchmark levels for the Other, Plastics and chemicals, Steel, and Wood and composites material groups.** Reduction potentials are based on reviewed academic and industry literature, organized by material category. “Other” category is conservative assumptions used for materials that individually comprise less than 1% of total emissions.

**Table 2. Eight categories of emissions intensity reduction (decarbonization) and demand reduction strategies.**

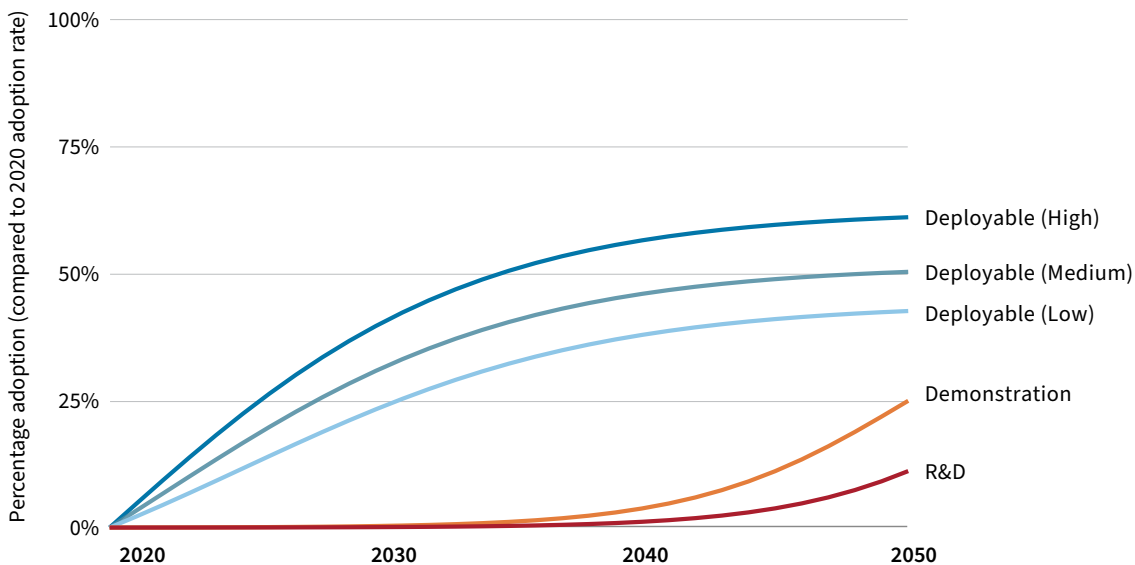
Category	General description	Example(s)
<b>Emissions intensity reduction (decarbonization) strategies</b>		
<b>Energy (E)</b>		
Energy efficiency (EE)	Measures related to reducing the required energy inputs for a process, machine, or facility along the value chain	Implementing waste heat recovery to improve blast furnace efficiency in steel production Using warm mix asphalt technology to reduce the temperature (and therefore fuel) required to produce and place asphalt
Electrification (EL)	Electrification of a manufacturing facility or process along the value chain	Electrification of steam crackers (a key stage of chemical processing)
Low carbon electricity (RE)	Use of electricity downstream from a completely decarbonized grid.	Decarbonizing the power used for aluminum production through the use of nuclear small modular reactors, hydro power plants and/or low-carbon electricity grids
Low carbon fuels (LCF)	Replacing traditional fossil fuels with alternative fuels such as waste, biomass, or newer technologies like hydrogen	Replacing natural gas with alternative fuels like liquid biofuels and synthetic methane Displacing coal and gas in steel making through Hydrogen Based Direct Reduction
<b>Carbon Capture</b>		
Carbon capture (CC)	Integrating technology to capture, store and/or utilize CO <sub>2</sub> emissions from production processes	Capturing and storing CO <sub>2</sub> emissions associated with clinker productions and heat in cement facilities
<b>Demand reduction strategies</b>		
<b>Material Substitution (MS)</b>		
Low Carbon Feedstocks (LCFS)	Replacing traditional ingredients with lower carbon alternatives	Using cement/clinker substitutes, alternative cements, and/or alternative chemistries to replace Portland Cement.
Recycled Feedstocks (LCFS-C)	Using secondary (recycled) feedstocks as ingredients in new products	Use of Reclaimed Asphalt Pavement (RAP) in asphalt mixtures
Material Substitution (MS)	Substituting higher carbon products or systems with lower carbon alternatives	Replacing plastics-based insulations (e.g. XPS, EPS) with conventional (e.g. mineral wool) or alternative (e.g. cellulose, cork, hemp) insulations
<b>Material Circularity</b>		
Circularity (MC)	Improving the collection, sorting and recycling of different material types. Includes reuse and refurbishment to extend the life of existing elements.	Mechanical recycling and chemical recycling of plastics
<b>Material Efficiency</b>		
Material efficient design (ME)	Optimizing the design of a building or process to reduce the need for new material, such as through structural design optimization or prefabrication	Improved design practices to optimize concrete structural systems, such as voided slab systems, post-tensioned slabs, optimizing thickness, or topology optimization (e.g. beam/column layout)

### 4.1.2 Adoption rate

We allocated one of five adoption rates to each strategy shown in Figure 12 based on technology readiness level, cost, and implementation timelines cited in the reviewed literature and reports:

- 1. Research and Development (R&D):** Strategies that are currently still in the early stages of R&D
- 2. Demonstration:** Strategies that have graduated from research and development but are still not commercially viable
- 3. Deployable (low):** Deployable technologies that are cost prohibitive or have other commercial viability constraints (e.g. supply constraints) limiting full adoption.
- 4. Deployable (medium):** Deployable technologies that still have lower market demand due to their lack of longevity in the market, higher cost, and/or perceived challenges by the construction sector
- 5. Deployable (high):** Widely deployable strategies that are proven to reduce emissions, have low cost impacts and are ready to scale quickly.

Each of these adoption rates is represented by a curve in **Figure 13** that demonstrates the anticipated uptake over time. Learn more in Appendix C.



**Figure 13. Example adoption rate curves used to model the R&D, Demonstration, and Deployable categories.** The adoption rate describes the growth in deployment of the strategy in the US market based on technology readiness level, cited cost, and implementation timelines cited in the reviewed literature and reports. Curves follow a logistic function formula using different growth rates ( $k$ ) and timelines for adoption.

## 4.2 Assessing embodied carbon reduction policies

Additionally, we assessed embodied carbon reduction policies from peer-reviewed papers and industry reports. We mapped these policies to emissions reductions strategies to help identify which policies may result in greater embodied carbon reductions.

The relative potential of each policy in achieving emissions reductions was assessed through which strategies each policy can encourage. This is primarily based on the scope of the policy and relative reach (i.e. voluntary vs. private or public sector projects or all). Learn more in Appendix C.

**Table 3** provides an overview of the 32 industrial, building, private sector, urban planning, and waste policies included in this analysis. Each policy is further grouped under the following five categories:

- **Standards** that specify technology- or performance-based levels that a facility, product, or building must achieve. Examples include building codes and facility emissions standards.
- **Financing and incentives**, such as direct fiscal incentives (e.g., tax credits, tax exemptions, subsidies), competitive financing (e.g., low-interest loans, loan guarantees, low-cost insurance), competitive grants, or urban planning incentives (e.g. density bonuses, expedited permitting).
- **Research, Development, and Demonstration (RD&D)**, including government pilot projects or incentives and support for developing emerging industrial decarbonization solutions (e.g. hydrogen-based DRI, chemical recycling).
- **Carbon pricing**, including carbon taxes, cap-and-trade programs and carbon taxes, or carbon border adjustment mechanisms (CBAM policies) that establish a direct or indirect price on units of GHG emissions (e.g., dollars per ton) in a defined market.
- **Clean procurement** policies like Buy Clean that set standards for public building and infrastructure projects, establishing a market for low-carbon products.

Many supporting policies and programs — such as workforce training, education, and policies that drive grid decarbonization — are relevant but out of the scope of this analysis.

**Table 3. Overview of the 32 industrial, building, private sector, urban planning, and waste policies analyzed.** Each policy is grouped into standards, financing and incentives, research development and demonstration (RD&D), carbon pricing, or clean procurement for the purpose of summarizing findings.

Category	Included policies
<b>Industrial policies</b>	
Standards	<ul style="list-style-type: none"> <li>• Facility emissions/pollution standards, targets, and reporting</li> <li>• Facility energy efficiency standards, targets, and mandatory audits</li> <li>• Product emissions standards, targets, and reporting</li> <li>• Near zero emission material mandate for cement, concrete, and steel</li> </ul>
RD&D	<ul style="list-style-type: none"> <li>• Government pilot and demonstration projects</li> <li>• Government-funded R&amp;D Grants (state or federal)</li> </ul>
Financing and incentives	<ul style="list-style-type: none"> <li>• Financing (loans, bonds, green banks)</li> <li>• Tax credits and incentives (facility-level or product-level)</li> </ul>
Clean procurement	<ul style="list-style-type: none"> <li>• Advance Market Commitments</li> <li>• Government carbon limits for building materials (Buy Clean)</li> <li>• Public sector procurement incentives</li> </ul>
Carbon pricing	<ul style="list-style-type: none"> <li>• Cap and trade systems</li> <li>• Carbon Border Adjustment Mechanism (CBAM) or Border Carbon Adjustments</li> <li>• Carbon taxes</li> </ul>
<b>Building policies</b>	
Standards	<ul style="list-style-type: none"> <li>• Building-level (kgCO<sub>2</sub>/m<sup>2</sup>) embodied carbon requirements in codes (or similar)</li> <li>• Product-level (kgCO<sub>2</sub>/unit) embodied carbon requirements in codes (or similar)</li> <li>• Prohibition of extremely high emitting materials (e.g. hydrofluorocarbons)</li> </ul>
Clean procurement	<ul style="list-style-type: none"> <li>• Space use and occupancy efficiency</li> </ul>
<b>Urban planning</b>	
Standards	<ul style="list-style-type: none"> <li>• Zoning and land use policies that encourage density and avoid sensitive soils</li> <li>• Design efficiency policies (e.g. space efficiency guidelines; parking requirement removals or reductions)</li> <li>• Zoning requirements for bio-based materials</li> </ul>
Financing and incentives	<ul style="list-style-type: none"> <li>• Density bonus, expedited permitting, and other incentives for embodied carbon</li> <li>• Incentives for building reuse (e.g. zoning incentives, demolition fees)</li> </ul>
<b>Waste &amp; circularity</b>	
Standards	<ul style="list-style-type: none"> <li>• Circularity and recycling standards for industrial facilities</li> <li>• Deconstruction and/or construction and demolition (C&amp;D) diversion ordinances</li> </ul>
Clean procurement	<ul style="list-style-type: none"> <li>• Salvaged, reused, or recycled material minimums for government projects</li> </ul>
<b>Private sector</b>	
Standards/ Clean procurement	<ul style="list-style-type: none"> <li>• Product-level owner design and procurement requirements/incentives</li> <li>• Building-level owner design and construction requirements/incentives</li> <li>• Material efficient structural design requirements or targets</li> </ul>
RD&D	<ul style="list-style-type: none"> <li>• Private sector pilot projects</li> </ul>
Financing and incentives	<ul style="list-style-type: none"> <li>• Private sector advance market commitments (AMCs)</li> <li>• Book and claim systems for steel, cement, and concrete</li> </ul>

## 4.3 Scenario Development

We used a matrix method (described in Appendix C) to model the relative potential of each strategy and policy to reduce emissions using six different scenarios. The goal of the scenario analysis was to reveal which strategies hold the greatest emissions reduction potential, what level of strategy adoption will be required to achieve the targets described in section 3, and which policies could drive that level of adoption.

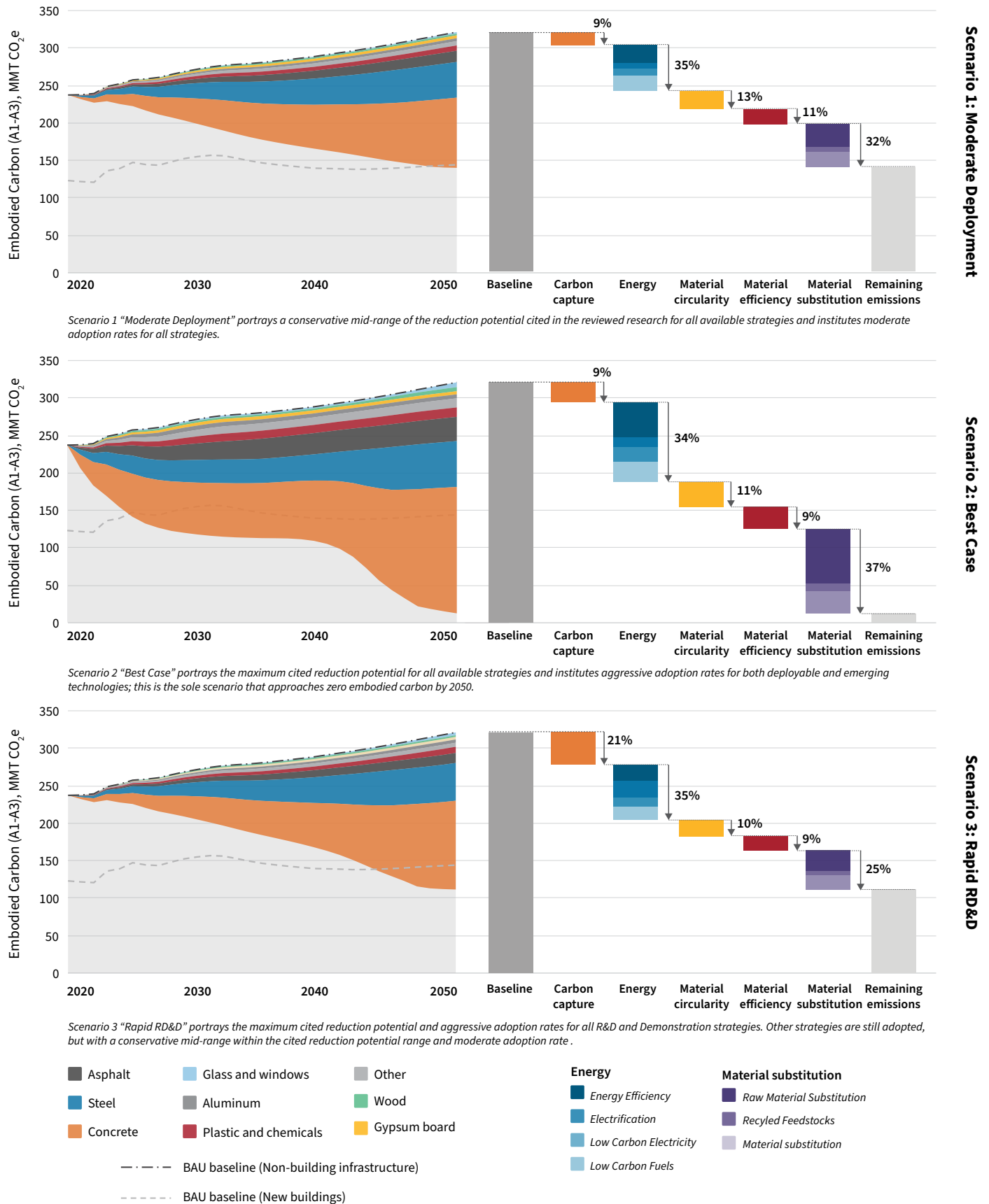
Each scenario explores a different emissions reduction pathway for the building and industrial sectors over the next 25 years. All six scenarios rely on the full suite of strategies included in our study, even in scenarios where a portion of strategies are a larger focus. Appendix D includes a summary of the assumptions and results for each scenario. Up to three aspects of the model are changed in each scenario:

- 1. Reduction potential:** A range of emissions reduction potential within range defined in Figure 12.
- 2. Level of Adoption:** The percentage of manufacturers and projects deploying each strategy on real projects. Some scenarios use more aggressive curves than those described in Figure 13.
- 3. Deployability assumptions:** An adjusted adoption rate for a specific subset of strategies that simulates the potential impact of increased support and/or private sector attention.

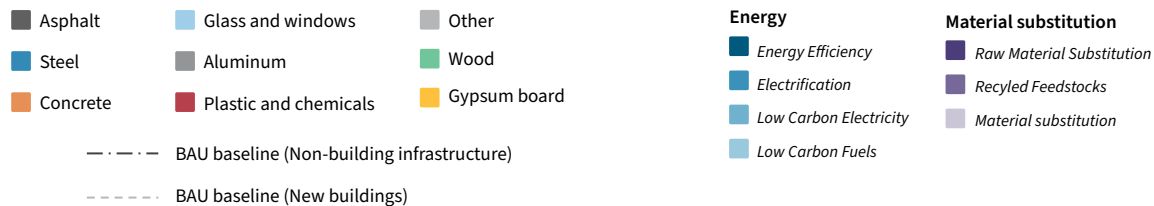
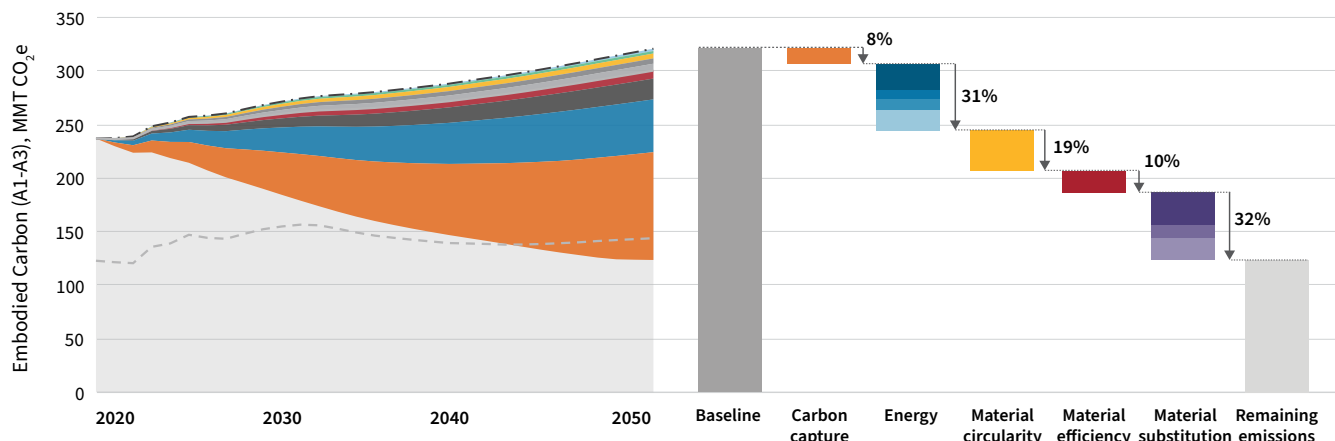
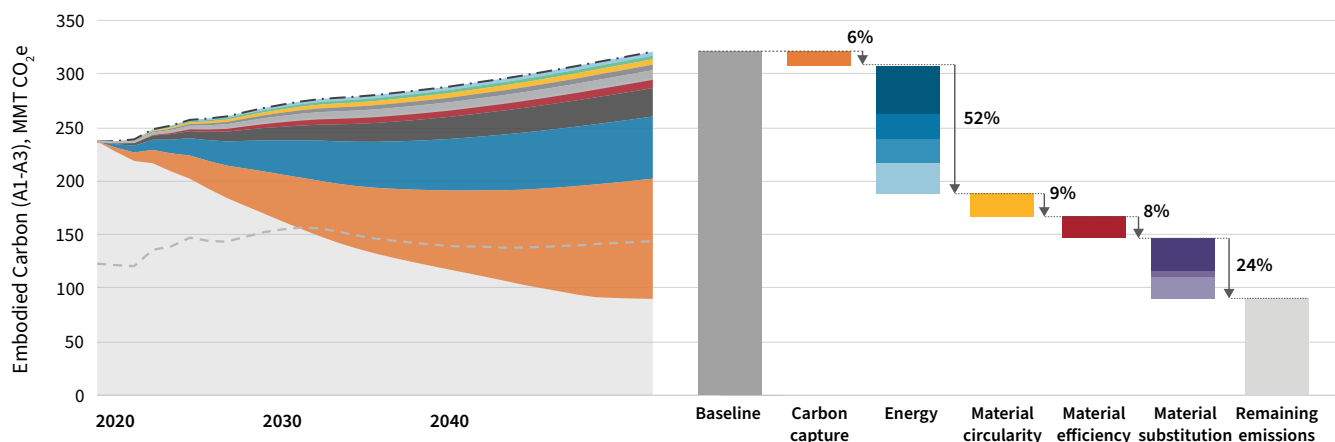
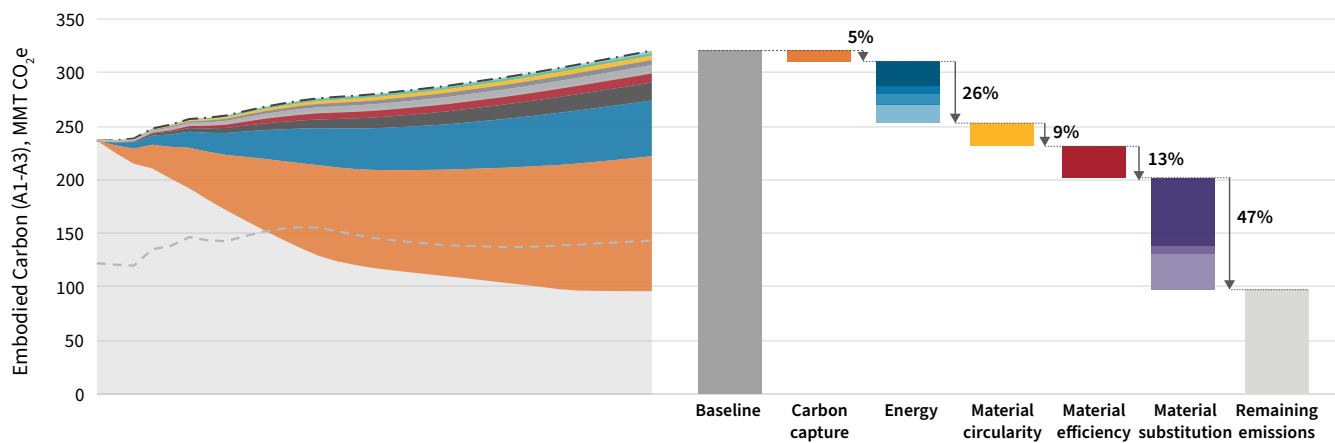
The six scenarios are defined as follows:

- **Scenario 1 “Moderate Deployment”** portrays a conservative mid-range of the reduction potential cited in the reviewed research for all available strategies and institutes moderate adoption rates for all strategies.
- **Scenario 2 “Best Case”** portrays the maximum cited reduction potential for all available strategies and institutes aggressive adoption rates for both deployable and emerging technologies; this is the sole scenario that approaches zero embodied carbon by 2050.
- **Scenario 3 “Rapid RD&D”** portrays the maximum cited reduction potential and aggressive adoption rates for all R&D and Demonstration strategies. Other strategies are still adopted, but with a conservative mid-range within the cited reduction potential range and moderate adoption rate .
- **Scenario 4 “Focus on Design Innovation”** portrays the maximum cited reduction potential and aggressive adoption rates for all material efficient design, building/system-level material substitution (MS), and low carbon feedstocks (LCFS) strategies. Other strategies are still adopted, but using the conservative mid-range of cited reduction potentials and moderate adoption rates.
- **Scenario 5 “Focus on Energy”** portrays the maximum cited reduction potential and aggressive adoption rates for all Energy strategies, including energy efficiency (EE), electrification (EL), renewable energy (RE), and low carbon fuels (LCF). Other strategies are still adopted, but using the conservative mid-range of cited reduction potentials and moderate adoption rates.
- **Scenario 6 “Focus on Circularity”** portrays the maximum cited reduction potential and aggressive adoption rates for all material circularity (MC) and recycled feedstocks (LCFS-C) strategies. Other strategies are still adopted, but using the conservative mid-range of cited reduction potentials and moderate adoption rates.

**Figure 14** shows the trajectory of emissions between 2020 and 2050 for all materials and the strategies utilized to achieve reductions in 2050 for each scenario.



**Figure 14a. Reductions from business-as-usual (BAU) projected emissions (million metric tons CO<sub>2</sub>e) for Scenarios 1 “Moderate Deployment, 2 “Best Case”, and 3 “Rapid Research, Development, and Demonstration (RD&D).”** Each shows projected emissions (by material) from 2020-2050 for new buildings and non-building infrastructure (left) and the contribution of each decarbonization pillar (right) to the total 2050 reductions in each scenario.



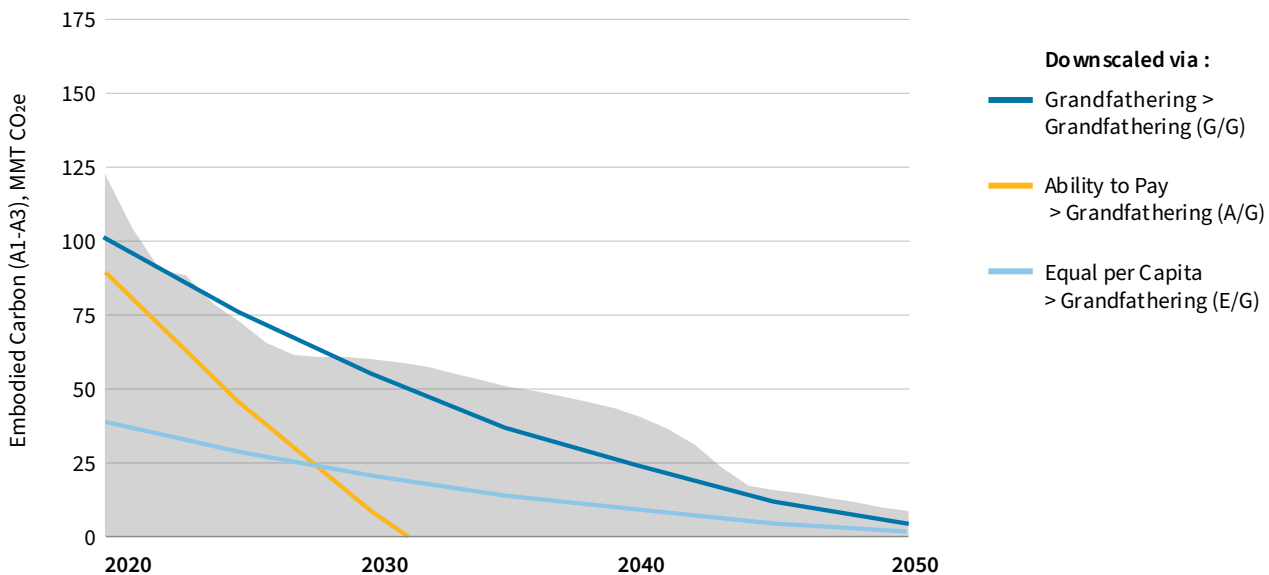
**Figure 14b. Reductions from business-as-usual (BAU) projected emissions (million metric tons CO<sub>2</sub>e) for Scenarios 4 “Focus on Design Innovation”, 5 “Focus on Energy”, and 6 “Focus on Circularity.”** Each shows projected emissions (by material) from 2020-2050 for new buildings and non-building infrastructure (left) and the contribution of each decarbonization pillar (right) to the total 2050 reductions in each scenario.

### 4.3.1 Comparing scenarios against 1.5°C-aligned targets

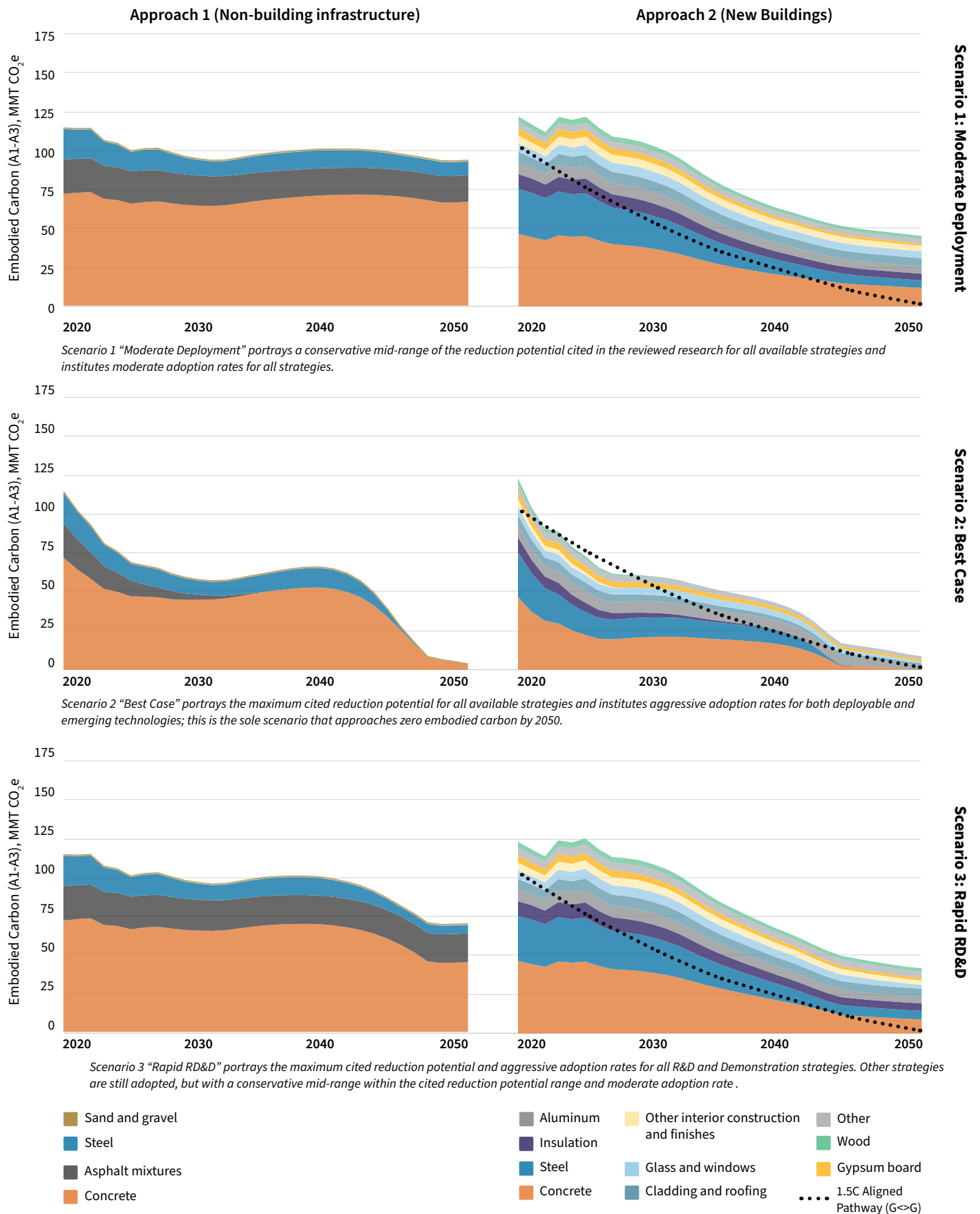
In this section, we separate the reduction pathways for new buildings from other uses of steel, concrete, and sand and gravel to compare the results of the scenario analysis against the 1.5°C-aligned CO<sub>2</sub> emissions targets for buildings in the United States described in Section 3.

**Figure 15** explores how each of the 1.5°C-aligned trajectories (see Section 3) compares against the “Best Case” Scenario. This figure demonstrates that even in the best case scenario, achieving 1.5°C goals will be a challenge, requiring aggressive adoption of current best practices starting immediately and through the year 2050. The reported 2020 emissions targets for the three 1.5°C-aligned scenarios vary due to the difference in attribution principles described in Section 3.

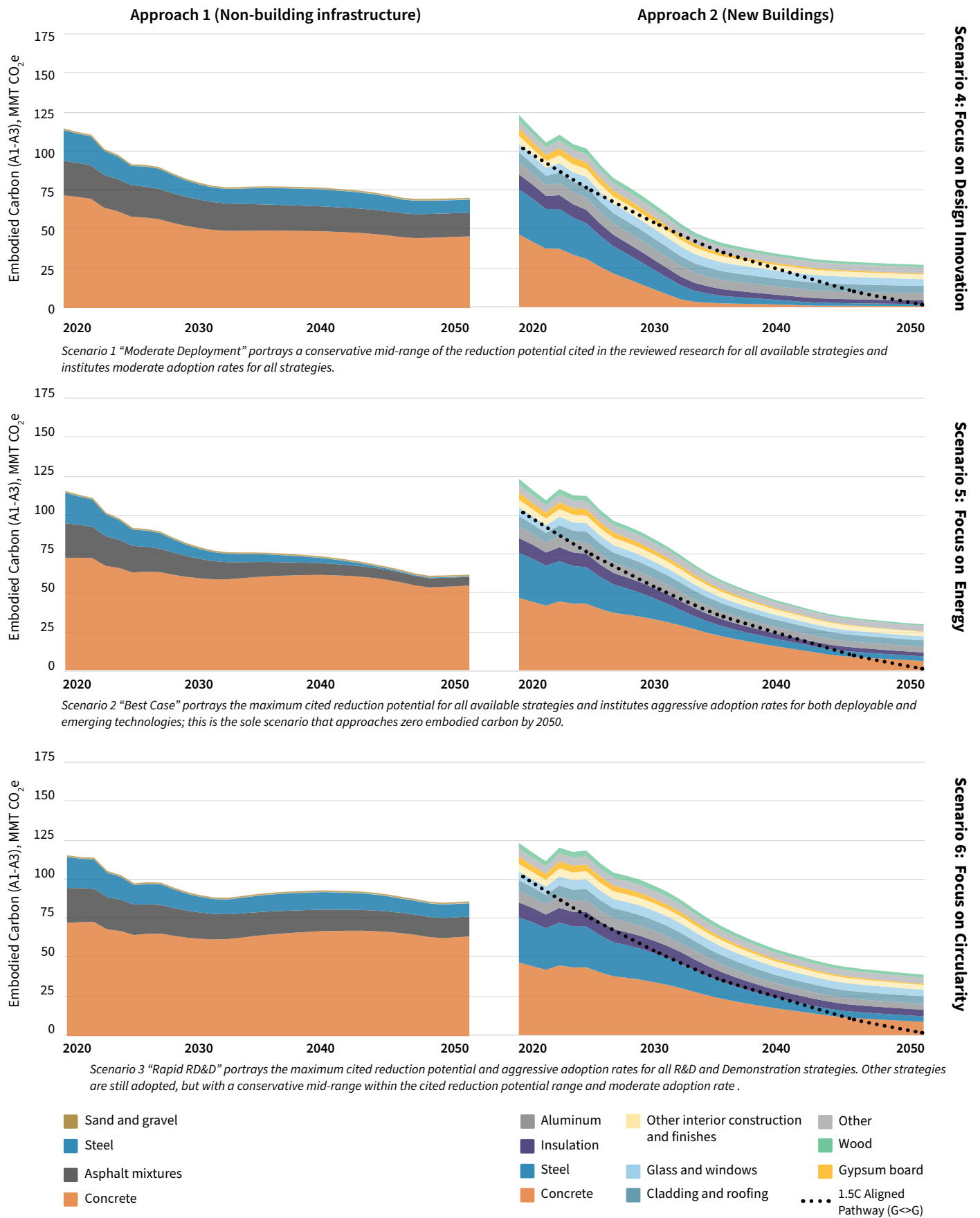
**Figure 16** shows the trajectory of cradle-to-gate embodied carbon emissions by material from 2020 to 2050 for each scenario. The figure compares that trajectory to the 1.5°C-aligned targets using the G/G approach described in Section 3. The G/G approach is shown as a reference to highlight the differences across scenarios and indicates how close or far each scenario is from realizing the most conservative 1.5°C-aligned pathway. The 2020 embodied carbon emissions for the 1.5°C-aligned G/G approach differ from the projected BAU 2020 emissions because the 1.5°C-aligned targets are calculated using a top-down approach derived from global emissions, while the scenario analysis relies on bottom-up projections based on material use intensity benchmarks. Each approach has benefits and limitations, which are explored more in Section 5.



**Figure 15. 2020-2050 Reduction Scenario 2 “Best Case” compared with the 1.5°C-aligned targets for the G/G, E/G, and A/G downscaling approaches analyzed in Section 3.** The G/G targets are achievable for some years in the Best Case Scenario.



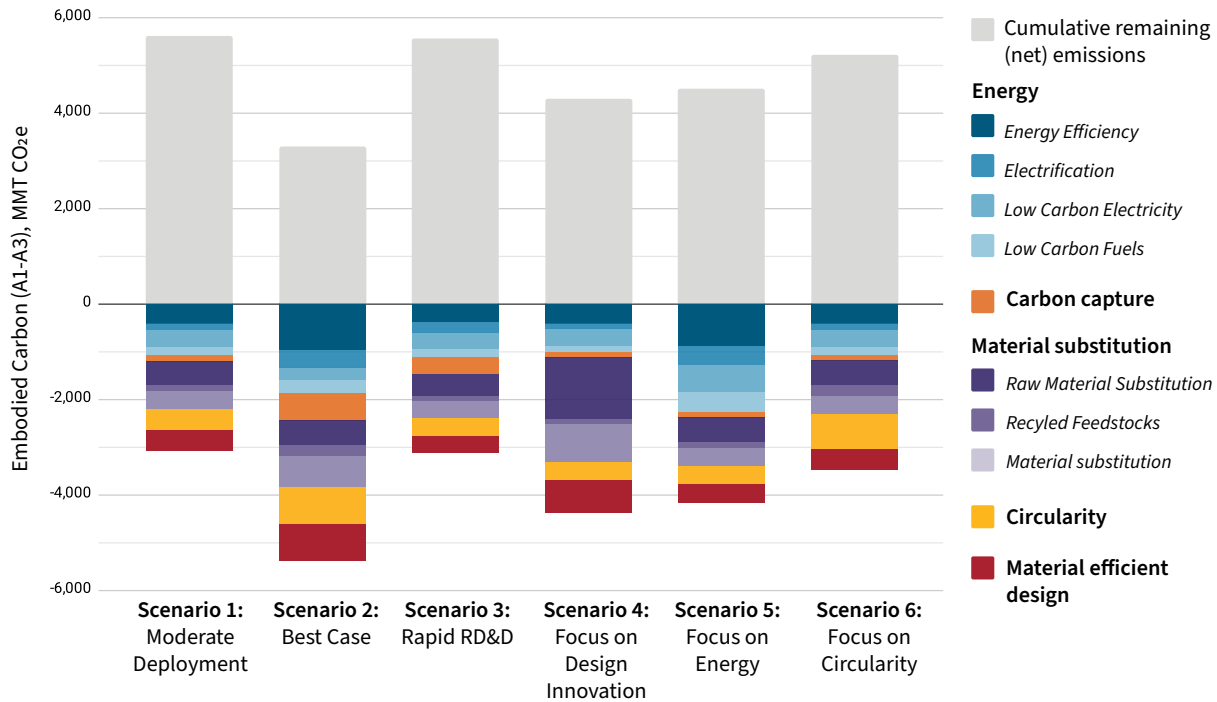
**Figure 16a. 2020-2050 reduction from business-as-usual by construction material group, calculated using approach 1 (left) and approach 2 (right).** The dotted line represents the 1.5°C-aligned target generated using the grandfathering > grandfathering (G/G) approach.



**Figure 16b. 2020-2050 reduction from business-as-usual by construction material group, calculated using approach 1 (left) and approach 2 (right).** The dotted line represents the 1.5°C-aligned target generated using the grandfathering > grandfathering (G/G) approach.

## 4.4 Takeaways: Priority Actions

The scenarios that achieved the largest reductions were scenarios #2 Best Case, #4 Focus on Design Innovation, and #5 Focus on Energy. **Figure 17** shows the cumulative reductions and cumulative net emissions (BAU minus reductions) between 2020 and 2050 resulting from each scenario, highlighting which scenarios are able to achieve the greatest total reductions.



**Figure 17. Comparison of cumulative reductions and net remaining embodied carbon (2020-2050) across scenarios 1-6.** The scenarios with the greatest progress toward 2050 goals (in order) were: #2 Best Case, #4 Focus on Design Innovation, and #5 Focus on Energy, all of which resulted in less than 5,000 million metric tons of cumulative remaining embodied carbon across 2020-2050. #6 Focus on Circularity, #3 Rapid RD&D, and #1 Moderate Deployment resulted in less than 6,000 million metric tons of cumulative remaining embodied carbon.

The scenarios that made the most significant emissions reductions and progress toward zero A1-A3 emissions by 2050 had three commonalities. They each: (1) deployed a wide range of strategies, (2) balanced a focus on currently deployable best practices with focus on emerging technologies, and (3) had high adoption of concrete emissions reductions strategies for buildings and infrastructure. Those keys to success are detailed as follows:

- Deploying a wide range of strategies:** All scenarios relied on the full suite of potential strategies, with the more successful strategies either (1) increasing focus on a subset of strategies (e.g. energy, design innovation) or (2) ramping up adoption rate, likely driven by broad policy adoption. Given that only one scenario was close to zero emissions in 2050 despite this long list of strategies, it is clear that there is no silver bullet for limiting embodied carbon by 2050. The construction sector must deploy a wide range of strategies to make progress.

- **Balancing focus on current best practices and emerging technologies:** The speed of technology and strategy deployment is central to reducing emissions, which is why scaling current best practices as quickly as possible will be critical to achieving substantial emissions reductions. Directing too much funding and attention to emerging technologies risks de-emphasizing impactful strategies that are currently deployable. These strategies could be responsible for the majority of reductions for the next twenty years while new technologies develop and scale. However, a near-zero emissions scenario is not possible without the adoption of emerging technologies. Emissions reductions from emerging technologies like carbon capture are significant and could drive large emissions reductions.

These findings are evidenced by the results of design innovation, rapid RD&D and best case scenarios. The design innovation scenario focused on currently deployable material efficiency and material substitution strategies, and achieved 29% greater cumulative emissions reductions than the rapid RD&D scenario. However, the best case scenario (closest to zero in 2050) required nearly full adoption of design innovation strategies by 2030 *and* significant adoption of emerging technologies beginning in 2040.

- **High Adoption of Concrete Strategies:** Concrete decarbonization and demand reduction strategies are essential to achieving significant emissions reductions. This is obvious given that concrete comprised over half of projected cradle-to-gate embodied carbon in 2050.

This is demonstrated in the Focus on Circularity scenario, which focuses on strategies to increase material circularity and maximize the use of recycled feedstocks. While this scenario achieves large emissions reductions, the total reductions are restricted, in large part due to the lower number and reduction potential of circularity strategies for concrete.<sup>1</sup>

All of the strategies reveal significant differences in the pathways for new buildings as compared with infrastructure and other construction, as shown in Figure 15. This is due in part to the larger range and market-readiness of available strategies affecting the buildings sector. The reviewed research did not include analysis of the reduction potential of project-level material substitution (e.g. timber bridges over steel bridges), design material efficiency strategies (e.g. structural optimization for material efficiency), or project-level circularity strategies (e.g. adaptive reuse) for infrastructure.

As a result, infrastructure strategies were more limited to facility-focused improvements and product-level material substitution, significantly limiting reduction potential. Infrastructure materials were also more sensitive to the adoption rate of emerging technologies, due to the absence of design innovation strategies.

---

<sup>1</sup> Scenario 6 may have shown greater emissions reductions if at least a portion of the clinker/cement replacement strategies were categorized as LCFS-C, e.g. use of waste products (slag, fly ash) as SCMs. This was not the case in our analysis because additional strategies grouped under this category (LC3, PLC, alternative chemistries) do not use waste products.

#### 4.4.1 Key Strategies

The strategies with the largest potential apply to materials with large emissions projections and have either a very high potential for emissions reductions and/or a medium potential for reductions but can be adopted immediately. **Table 4** highlights the top twelve individual reduction strategies across our analysis.

By far, raw material substitution in concrete was the highest impact strategy, contributing an average of 16% of cumulative emissions reductions between 2020-2050 across scenarios. This strategy captures reductions from cement and clinker substitution and use of alternative cements and/or alternative chemistries. Currently, this is primarily achieved through low-cost supplementary cementitious materials (SCMs) like fly ash and slag that can reduce the required quantity of clinker. The use of alternative cements (e.g. Portland limestone cement (PLC) and limestone calcined clay cement (LC3)) are also beginning to play a larger role as they become more broadly available. Alternative chemistries (such as decarbonated raw materials and alternative binders) may contribute to these reductions but are not expected to contribute until after 2040 or 2045 due to their low TRL.

**Table 4. Top reduction strategies across scenarios, in order of average percent contribution to cumulative reductions between 2020 and 2050.** Created by averaging the percentage contribution to reductions from the top 10 strategies across the six scenarios. Total reductions ranged from approximately 3000 to 5400 million metric tons (MMT). Strategies are color-coded by their contribution to economy-wide emissions reductions. Greater than 15% (dark blue), 5-10% (medium blue), and less than 5% (light blue)

Reduction Strategy	Cumulative reductions by strategy (MMT), 2020-2050	Impacted material
Raw Material (Cement) Substitution in Concrete	600	Concrete
Use of low-carbon electricity in steel production	220	Steel
Structural design optimization in new buildings	200	Concrete and steel
Cement kiln energy efficiency	200	Cement
Structural system material substitution	170	Concrete and steel
Cement Plant CCS	130	Cement
Reuse / refurbishment of existing concrete buildings and infrastructure	125	Concrete
Warm and cold mix asphalt	90	Asphalt
Increased use of recycled feedstocks in asphalt mixtures	60	Asphalt
Use of biofuels in asphalt production	50	Asphalt
Substituting plastic-based insulation for alternative insulations	40	Insulation
Use of alternative fuels in cement kilns	20	Cement

**Table 5** shows the top contributing strategies separately for 2030 and 2050 to reveal how key strategies shift over time. The findings indicate that structural design innovation strategies, including design optimization and material substitution for concrete and steel structures, are the second and third most effective strategies for reducing emissions in 2030. They still play a large role in 2050, but with a lower contribution to overall reductions due to the increased importance of CCS and the use of low-carbon electricity in steel production. The use of low-carbon electricity in steel production is key to eliminating emissions from the energy usage and processes of steel making (Delasalle et. al., 2022). This includes the use of low-carbon electricity in steel production facilities, including both those with electrified processes (i.e. electric arc furnace plants) as well as plants that must first be upgraded.

**Table 5. Top reduction strategies in 2030 and in 2050, in order of percent contribution to cumulative economy-wide reductions.** The percent contribution was calculated as the average contribution from the top 10 strategies across all scenarios in each year.

Top reduction strategies by % contribution to economy-wide reductions in year 2030 and 2050			
2030 Reductions (Average across scenarios)		2050 Reductions (Average across scenarios)	
Raw Material (Cement) Substitution in Concrete	16%	Raw Material (Cement) Substitution in Concrete	18%
Structural design optimization in new buildings (concrete and steel)	8%	Cement Plant CCS	7%
Use of low-carbon electricity in steel production	6%	Use of low-carbon electricity in steel production	7%
Structural system material substitution (concrete)	5%	Cement kiln energy efficiency	4%
Cement kiln energy efficiency	4%	Structural design optimization in new buildings (concrete)	4%
Reuse and refurbishment of existing concrete buildings and infrastructure	3%	Structural system material substitution (concrete)	3%
Warm and cold mix asphalt	3%	Reuse and refurbishment of existing concrete buildings and infrastructure	3%
Cement Plant CCS	2%	Warm and cold mix asphalt	2%
Increased use of recycled feedstocks in asphalt mixtures	1%	Increased use of recycled feedstocks in asphalt mixtures	1%
Use of biofuels in asphalt production	1%	Cement kiln electrification (with low-carbon electricity)	<1%
Substituting plastic-based insulation for alternative insulations	1%	Use of biofuels in asphalt production	<1%
Structural system material substitution (steel)	<1%	Use of alternative fuels in cement kilns	<1%

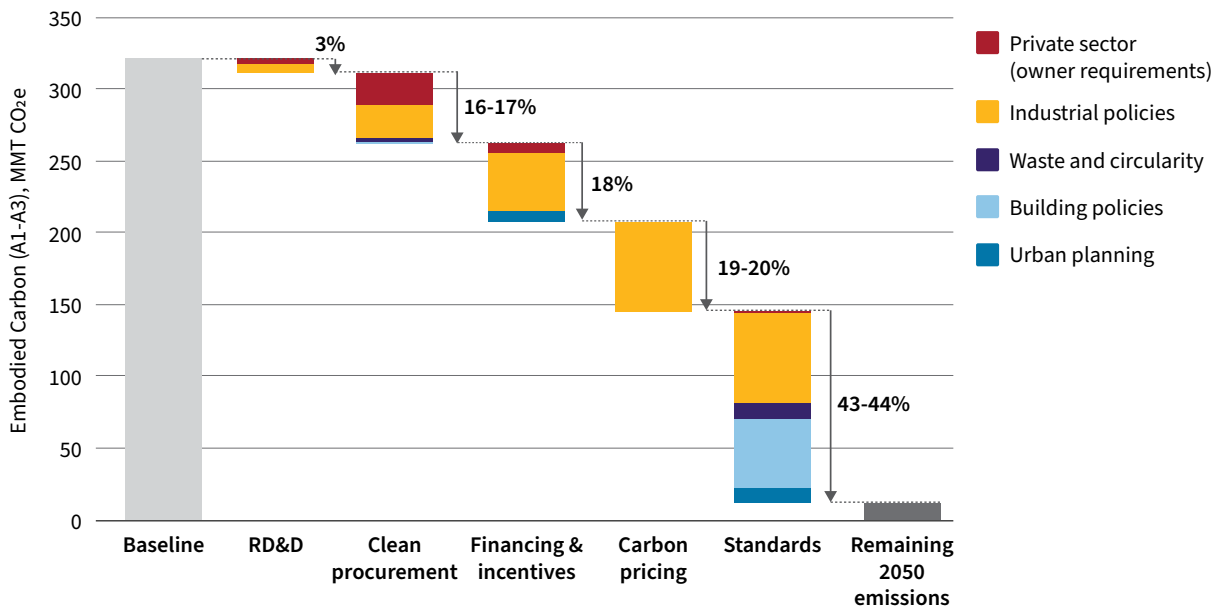
### 4.5.2 Key Policies to Support Reduction Pathways

The total emissions reductions associated with each policy are dependent on three main factors: the total emissions reduction potential of the strategies associated with that policy, whether it is voluntary or required, and its relative reach (i.e. whether it impacts private sector projects, public sector, or both). The policies with the largest emissions reduction potential therefore are those that incentivize the strategies with the largest projected reductions and/or are required across the broadest range of projects.

This study was intended to provide an order of magnitude analysis of emissions reduction potentials stemming from each policy. This helps to reveal which policies would be most effective or most likely to enable the strategies described above. Key findings include:

- Building-level standards are a key complement to industrial regulations:** Establishing mandatory embodied carbon budgets (e.g. kgCO<sub>2</sub>e/m<sup>2</sup>) for new construction on public and private sector projects was the first or second policy (in terms of associated emissions reductions) across all scenarios. This is likely due to the fact these policies can incentivize the largest range of strategies of any included policy, including deployable material substitution and design optimization strategies in addition to reductions driven by facility upgrades.
- Carbon Pricing:** Cap-and-trade systems and carbon border adjustment mechanisms provide flexible pathways for incentivizing facility changes, if policies are designed correctly.
- Product vs. facility standards:** Industrial policies to regulate the emissions of facilities and products are both effective tools for emissions reductions. However, product emissions standards had a higher impact due to their ability to incentivize raw material substitution. For example, regulations on cement facilities (rather than regulation of the emissions from concrete products) cannot directly incentivize clinker and cement substitution, the highest impact strategy across all scenarios.

**Figure 18** highlights the policy sectors and categories with the greatest potential to reduce emissions via the strategies analyzed above. Standards had the greatest impact reduction potential, followed by carbon pricing, and financing and incentives. As expected, clean procurement and RD&D policies had lower reduction



**Figure 18. Contribution of different policy levers to 2050 reductions.** This figure shows the results from Scenario 2 “Best Case”, but the relative contribution is similar across scenarios.

potentials as these policies impact a smaller number of projects (and therefore result in less direct emissions reductions). However, procurement and R&D policies are still foundational in unlocking broader action across the private sector by creating a market for new low carbon construction materials and accelerating initial research and deployment of emerging technologies.

Surprisingly, the same policies were dominant in all six scenarios, with only small variations in the percent contribution to cumulative reductions from 2020-2050. The top 10 policies across all six scenarios, in order of percentage contribution to cumulative reductions between 2020 and 2050, were:

1. Building-level embodied carbon requirements in zoning and building codes (e.g. kgCO<sub>2</sub>e/m<sup>2</sup> reductions) for all building types
2. Financing (loans, bonds, green banks) for facility upgrades (i.e. energy efficiency, electrification, low carbon fuels, carbon capture) and raw material substitution
3. Product emissions standards, targets, and reporting
4. Carbon taxes (\*Assumes funding is put back into grid decarbonization efforts)
5. Product-level GWP limits (e.g. kgCO<sub>2</sub>e/unit of material) in zoning and building codes
6. Cap and trade systems (applied at the facility level)
7. Carbon Border Adjustment Mechanism (CBAM) – applied at the facility level
8. Facility emissions standards, targets, and reporting
9. Building-level owner requirements and performance incentives (e.g. kgCO<sub>2</sub>e/m<sup>2</sup> reductions)
10. Product-level owner requirements and performance incentives (e.g. private sector Buy Clean)

## 5. Opportunities and limitations

This analysis is limited by the underlying floor area, material intensity, and emissions data, as well as the modeling assumptions that allow us to approximate cradle-to-gate embodied carbon across the United States. While the limitations of this analysis do constrain the results, they also represent several opportunities for further analysis, data availability, and innovation in the building and infrastructure sectors.

- **Life cycle scope is limited to A1-A3:** The total emissions in this analysis are an underestimate, as they are limited to A1-A3 and exclude stages that would likely include significant emissions, such as B1 (due to refrigerants) and B4 (due to renovations) (Jensen et al, 2025).

Future research can identify further reductions available, particularly in the use phase and end of life phases. For example, inclusion of the use phase would allow for analysis of the benefits of investing in longer life materials. End of life phase analysis would be able to explore additional emissions reductions from circularity strategies beyond the existing scope.

- **Gaps in renovation analysis:** Renovations are largely excluded from this analysis, under counting the projected quantities as well as emissions reduction potential of insulation, gypsum board, and other interior construction finishes significantly. The non-building infrastructure projections include uses of concrete and steel in renovations, as these projections capture all uses of cement and steel for construction in the United States (based on raw material data from USGS), excluding new building construction.

A more detailed analysis of renovation material quantities including materials beyond concrete and steel could reveal additional opportunities for circularity and design innovation

- **Building element scope is limited:** The new building construction scope includes the structure, enclosure, and some interiors. The interior scope is an underestimate, as interior scope was reported in varying degrees of completeness and generally limited to the primary materials used for interior partition framing, and wall, floor, and ceiling finishes (Benke et al, 2025). This means that MEP (including key steel, copper, and aluminum impacts), furniture, equipment, and other building scope is excluded.
- **Gaps in infrastructure design innovation strategies:** This report focuses primarily on product and material emissions reduction strategies for non-building infrastructure, with a very limited set of project-level strategies.

Building design optimization for material efficiency and material substitution unlock large emissions reduction opportunities in new buildings: similar strategies for infrastructure would be significant in reducing additional emissions between now and 2050. New research and design innovation could help fill this gap and explore these important strategies.

- **Available data on EC reduction strategies is very limited:** The reviewed research reveals very broad ranges of emissions reduction potentials with disagreement on the technical potential of some strategies. Additionally, materials beyond concrete and steel had extremely limited research available on decarbonization strategies.

There is an opportunity for researchers to develop more science-based models that can quantify specific emissions reductions using different material substitution, manufacturing R&D, and design innovation strategies (among others).

- **Detailed policy analysis:** This report provides a rough order of magnitude analysis for policies with the intent to help prioritize between different policy levers.

There is an opportunity for researchers to develop more policy-specific analysis that can quantify the emissions reductions for individual policy types at different levels of government (e.g. state, city), allowing for more nuanced investigation of policy design assumptions. For example, this analysis does not test the impact of different GWP limits in performance-based standards.

- **Biogenic carbon is excluded:** Biogenic emissions and removals (i.e. storage) are excluded from this analysis. The use of carbon-storing materials may help address the gap in remaining emissions for the scenarios evaluated in section 4.
- **Top-down and bottom-up approaches based on limited data:** The top-down approach utilized to calculate 1.5°C-aligned targets in Section 3 and the bottom-up approach (utilized to project embodied carbon in Section 2) each have benefits and drawbacks due to the quality of available data. The top-down approach relies on the accuracy of projected global GHG emissions, GDP, and population data, and an allocation of building sector emissions based on historic square footage and the ECI benchmarks from Benke et al (2025). The bottom-up approach utilized in Section 4 relies on the accuracy of area projections and representativeness of the material use intensity factors derived from Ashtiani et al (2025). The combination of these two approaches allow for a more robust analysis of results. However, the accuracy of results will increase over time as more comprehensive benchmarking data is available based on greater adoption of whole-building LCA in the United States to increase the sample size, and thus, representativeness of the data.

## 6. Conclusion

This report serves as a call to action, urging the industrial and construction sectors to continue progress towards global targets. The embodied carbon of key construction materials used in buildings and infrastructure in the United States is significant and requires deployment of a large range of strategies. Scaling best practices while advancing emerging technologies will be critical to reducing embodied carbon to reach global climate targets.

Our analysis reveals that a combination of strategies — from material substitution and design optimization to electrification and carbon capture — is essential to achieving the necessary emissions reductions. Long-term success will demand a transformative shift, including the adoption of emerging technologies and uptake of best practices across the value chain. In the short-term, there is potential for significant reductions by 2030 through current best practices, such as clinker and cement substitution in concrete, structural design optimization and material substitution in new buildings, and increasing the use of clean power in the US steel sector, which is already heavily electrified.

The deployment of aggressive policy frameworks — such as building-level embodied carbon budgets and product-level GWP limits in zoning and building codes; financing and incentives for industrial facility upgrades; and product emissions standards — will be indispensable to bridging the gap between business-as-usual trajectories and 1.5°C-aligned embodied carbon targets.

In the short-term, US states and cities can continue to lead by developing effective policy models. They can build on the strong foundation of Buy Clean policies already in place in the United States by expanding into building code requirements and standards that target high emissions industrial facilities and products. The private sector also has a significant role to play in driving reductions by setting building and product requirements. Governments and real estate firms with building and infrastructure requirements can further accelerate reductions by using performance incentives to drive larger reductions and supporting leaders who are taking steps toward the longer term decarbonization pathways outlined in this report. Ultimately, leadership in the manufacturing sector — particularly for cement, concrete, and steel suppliers — will be critical in pursuing these pathways.

# References

## Report Reference Publications

- Ashtiani, M., Benke, B., Shen, Y., & Simonen, K. (2025). Material Use and Embodied Carbon Intensity of New Construction Buildings in North America. *PREPRINT Available at Research Square*. <https://doi.org/10.21203/rs.3.rs-6315460/v1>
- Ashtiani, M. (2025). *Embodied Carbon and Material Use Intensity Visualizer*. <https://wblca-benchmark-v2-mui-eci.lifecyclelab.org/>
- Ashtiani, M. Z., Huang, M., Lewis, M. C., Palmeri, J., & Simonen, K. (2024). Greenhouse Gas Emissions Inventory from Roadway Construction: Case Study for the Washington State Department of Transportation. *Transportation Research Record*, 1–13. <https://doi.org/10.1177/03611981241233278>
- Benke, B., Chafart, M., Shen, Y. et al. A Harmonized Dataset of High-Resolution Embodied Life Cycle Assessment Results for Buildings in North America. *Sci Data* 12, 1085 (2025). <https://doi.org/10.1038/s41597-025-05216-0>
- Berg, N. J. van den, Soest, H. L. van, Hof, A. F., Elzen, M. G. J. den, Vuuren, D. P. van, Chen, W., Drouet, L., Emmerling, J., Fujimori, S., Höhne, N., Köberle, A. C., McCollum, D., Schaeffer, R., Shekhar, S., Vishwanathan, S. S., Vrontisi, Z., & Blok, K. (2020). Implications of various effort-sharing approaches for national carbon budgets and emission pathways. *Climatic Change*, 162(4), 1805–1822. <https://doi.org/10.1007/s10584-019-02368-y>
- Carbon Leadership Forum (CLF). (2020). *CLF Policy Toolkit 1: Embodied Carbon 101* (CLF Policy Toolkit). <https://carbonleadershipforum.org/embodied-carbon-101/>
- Climate Watch, & World Resources Institute. (2024). *Climate Watch data: Climate Watch Historical GHG Emissions*. [https://www.climatewatchdata.org/ghg-emissions?end\\_year=2022&start\\_year=1990](https://www.climatewatchdata.org/ghg-emissions?end_year=2022&start_year=1990)
- Delasalle, F., Speelman, E. (2022). *Making net-zero steel possible: An industry-backed, 1.5°C-aligned transition strategy*. Mission Possible Partnership. <https://missionpossiblepartnership.org/wp-content/uploads/2022/09/Making-Net-Zero-Steel-possible.pdf>
- Edward Byers, Volker Krey, Elmar Kriegler, Keywan Riahi, Roberto Schaeffer, Jarmo Kikstra, Robin Lamboll, Zebedee Nicholls, Marit Sanstad, Chris Smith, Kaj-Ivar van der Wijst, Alaa Al Khourdajie, Franck Lecocq, Joana Portugal-Pereira, Yamina Saheb, Anders Strømman, Harald Winkler, Cornelia Auer, Elina Brutschin, ... Detlef van Vuuren. (2022). *AR6 Scenarios Database hosted by IIASA*. International Institute for Applied Systems Analysis. <https://data.ece.iiasa.ac.at/ar6>
- Intergovernmental Panel on Climate Change (IPCC). (2018). *Global warming of 1.5°C: An IPCC special report on the impacts of global warming of 1.5°C above pre-industrial levels*. <https://www.ipcc.ch/sr15/>
- IPCC. (2023). *AR6 synthesis report: Climate change 2023*. <https://www.ipcc.ch/report/ar6/syr/>
- International Energy Agency (IEA). (2024) *The changing landscape of global emissions – CO2 Emissions in 2023 – Analysis*. IEA, Paris. Retrieved June 8, 2025, from <https://www.iea.org/reports/co2-emissions-in-2023/the-changing-landscape-of-global-emissions>
- Jensen, A., Chafart, M., Raju, S., and Lewis, M. (2025). *Washington State Embodied Carbon Estimation: 2025-2050*. Carbon Leadership Forum.

- Magwood, C., Bukauskas, A., Huynh, T., & Olgyay, V. (2025). *Building with Biomass: A New American Harvest*. Rocky Mountain Institute. <https://rmi.org/insight/building-with-biomass-a-new-american-harvest>
- Rhodium Group. (2023). *Pathways to Paris: A policy assessment of the U.S. 2030 emissions target*. <https://rhg.com/research/pathways-to-paris-2023/>
- Science Based Targets initiative. (2024). *1.5C PATHWAYS FOR THE GLOBAL BUILDINGS SECTOR'S EMBODIED EMISSIONS: DEVELOPMENT DESCRIPTION*. <https://files.sciencebasedtargets.org/production/files/Buildings-Embodied-Emissions-Pathway-Development-Description.pdf>
- United Nations Department of Economic and Social Affairs: Population Division. (2025, June 8). *World Population Prospects 2024 [Dataset]*. <https://population.un.org/dataportal/>
- United States (US) Environmental Protection Agency (EPA). (2025, March 31). Industry Sector Emissions. <https://www.epa.gov/ghgemissions/industry-sector-emissions>
- US Census Bureau. (n.d.). *American Housing Survey (AHS)*. Retrieved June 13, 2025, from <https://www.census.gov/programs-surveys/ahs.html>
- US Department of Energy (DOE). (2024). *Decarbonizing the U.S. Economy by 2050: A National Blueprint for the Buildings Sector*.
- US Energy Information Administration. (2020a). *Annual Energy Outlook 2020 with projections to 2050*. <https://www.eia.gov/outlooks/aeo/pdf/aeo2020%20full%20report.pdf>
- US Energy Information Administration. (2020b). *Residential Energy Consumption Survey (RECS)*. <https://www.eia.gov/consumption/residential/>
- US Energy Information Administration. (2023a). *Annual Energy Outlook 2023*. [https://www.eia.gov/outlooks/aeo/pdf/aeo2023\\_narrative.pdf](https://www.eia.gov/outlooks/aeo/pdf/aeo2023_narrative.pdf)
- US Energy Information Administration. (2023b). *The National Energy Modeling System: An Overview*. [https://www.eia.gov/outlooks/aeo/nems/overview/pdf/0581\(2023\).pdf](https://www.eia.gov/outlooks/aeo/nems/overview/pdf/0581(2023).pdf)
- US Energy Information Administration. (n.d.). *Today in Energy*. Retrieved June 13, 2025, from <https://www.eia.gov/>
- Waldman, B., Palmeri, J., and Lewis, M. (2024). *Buy Clean Policies: Overview and Implementation*. Carbon Leadership Forum. Seattle, WA. <https://carbonleadershipforum.org/buy-clean-policies-overview/>
- World Bank Group. (2025). *World Bank national accounts data, and OECD National Accounts data files [Dataset]*. <https://data.worldbank.org/>

## **Data References**

- Arehart, J. H., Pomponi, F., D'Amico, B., & Srubar, W. V. (2022). Structural material demand and associated embodied carbon emissions of the United States building stock: 2020–2100. *Resources, Conservation and Recycling*, 186, 106583. <https://doi.org/10.1016/j.resconrec.2022.106583>
- Brennan, M., Murdoch, H., Fitzgerald, J., Majsztrik, P. (2023). *Pathways to Commercial Liftoff: Decarbonizing*

*Chemicals and Refining*. U.S. Department of Energy.

British Glass. (2021). *Net Zero by 2050 - A Roadmap for the Global Energy Sector*. International Energy Agency (IEA). [https://iea.blob.core.windows.net/assets/deebef5d-0c34-4539-9d0c-10b13d840027/NetZeroBy2050-ARoadmapfortheGlobalEnergySector\\_CORR.pdf](https://iea.blob.core.windows.net/assets/deebef5d-0c34-4539-9d0c-10b13d840027/NetZeroBy2050-ARoadmapfortheGlobalEnergySector_CORR.pdf)

Chen, S., Huang, Q., Muttarak, R., Fang, J., Liu, T., He, C., Liu, Z., & Zhu, L. (2022). Updating global urbanization projections under the Shared Socioeconomic Pathways. *Scientific Data*, 9(1), 137. <https://doi.org/10.1038/s41597-022-01209-5>

Cheng, D., Reiner, D. M., Yang, F., Cui, C., Meng, J., Shan, Y., Liu, Y., Tao, S., & Guan, D. (2023). Projecting future carbon emissions from cement production in developing countries. *Nature Communications*, 14(1), 8213. <https://doi.org/10.1038/s41467-023-43660-x>

Clean Energy Buyers Association (CEBA). (2024). *Powering United States Primary Steel Decarbonization*.

Deetman, S., Marinova, S., Voet, E. van der, Vuuren, D. P. van, Edelenbosch, O., & Heijungs, R. (2020). Modelling global material stocks and flows for residential and service sector buildings towards 2050. *Journal of Cleaner Production*, 245, 118658. <https://doi.org/10.1016/j.jclepro.2019.118658>

Den, X. L., Steinmann, J., Röck, M., H. Birgisdottir, Horup, L. H., Tozan, B., & Sørensen, A. (2022). *Towards embodied carbon benchmarks for buildings in Europe - Summary Report* (Ramboll). Ramboll. <https://fs.hubspotusercontent00.net/hubfs/7520151/RMC/Content/EU-ECB-Summary-Report.pdf>

Dollinger, C., Cresko, J., Gage, S., Kamath, D., Ray, B., Zuberi, J., Hanabeigi, A. (2024). *Pathways Analysis Summary: Decarbonization Potential for Industrial Subsectors - Preliminary Modeling Results*. U.S. Department of Energy.

Energy Transitions. (2018). *Mission Possible: Reaching net-zero carbon emissions from harder-to-abate sectors by mid-century*. Energy Transitions Commission.

European Cement Research Academy. (2022). *The ECRA Technology Papers 2022: State of the Art Cement Manufacturing*. Mission Possible Partnership.

European Committee for Standardization (CEN). (2011). *EN 15978:2011: Sustainability of construction works - Assessment of environmental performance of buildings*. European Committee for Standardization (CEN). <https://standards.iteh.ai/catalog/standards/cen/62c22cef-5666-4719-91f9-c21cb6aa0ab3/en-15978-2011?srsItd=AfmBOorflu8DNkZqKF9U03-x17i8bdfueXR4Xt1ytV6GuJ4jZKIs1X7S>

Fishman, T., Mastrucci, A., Peled, Y., Saxe, S., & Ruijven, B. van. (2024). *RASMI: Global ranges of building material intensities differentiated by region, structure, and function*. *Scientific Data*, 11(1), 418. <https://doi.org/10.1038/s41597-024-03190-7>

Fishman, T., Schandl, H., Tanikawa, H., Walker, P., & Krausmann, F. (2014). Accounting for the Material Stock of Nations. *Journal of Industrial Ecology*, 18(3), 407–420. <https://doi.org/10.1111/jiec.12114>

Fransen, T., Lebling, K., Weyl, D., Kennedy, K. (2021). *Toward a Tradable Low-Carbon Cement Standard: Policy Design Considerations for the United States*. World Resources Institute.

Gailani, A., Cooper, S., Allen, S., Pimm, A., Taylor, P., Gross, R. (2024). *Assessing the potential of decarbonization options for industrial sectors*. Joule Perspective.

Global Cement and Concrete Association. (2021). *Concrete Future: The GCCA 2050 Cement and Concrete Industry*

Roadmap for Net Zero Concrete. <https://gccassociation.org/concretefuture/wp-content/uploads/2022/10/GCCA-Concrete-Future-Roadmap-Document-AW-2022.pdf>

Goldman, S., Majsztik, P., Sgro Rojas, I., Gavvalpalli, M., Gaikwad, R., Feric, T., Visconti, K., McMurtry, B. (2023). *Pathways to Commercial Liftoff: Low-Carbon Cement*. U.S. Department of Energy.

Gregory, J. (2019). *Solving the Climate Crisis: Reducing Industrial Emissions Through U.S. Innovation*. Testimony for the Congress of the United States House of Representatives. <https://docs.house.gov/meetings/CN/CN00/20190926/110026/HHRG-116-CN00-Wstate-GregoryJ-20190926.pdf>

Güneralp, B., Zhou, Y., Ürge-Vorsatz, D., Gupta, M., Yu, S., Patel, P. L., Fragkias, M., Li, X., & Seto, K. C. (2017). Global scenarios of urban density and its impacts on building energy use through 2050. *Proceedings of the National Academy of Sciences*, 114(34), 8945–8950. <https://doi.org/10.1073/pnas.1606035114>

Habert, G., Rock, M., Steininger, K., Lupisek, A., Birgisdottir, H., Design, H., Chandrakumar, C., Pittau, F., Passer, A. Rovers, R., Slavkovic, K. Hollberg, A., Hoxha, E., Jusselme, T., Nault, E., Allacker, K., Lützkendorf, T. (2020). *Carbon Budgets for Buildings: Harmonising Temporal, Spatial and Sectoral Dimensions*. Buildings and Cities.

Hart, J., D’Amico, B., Pomponi, F. (2021). *Whole-life embodied carbon in multistory buildings: Steel, concrete and timber structures*. *Journal of Industrial Ecology*, 25, 2, 403-318.

Hasanbeigi, A., Sibal, A. (2023). *What is Green Steel? Definitions and Scopes from Standards, Initiatives, and Policies around the World*. <https://www.globalefficiencyintel.com/what-is-green-steel>

Hasanbeigi, A., Sibal, A. (2024). *The Scale And Impact Of Green Public Procurement of Steel and Cement in Canada, Germany, the UK, And the US*. <https://www.globalefficiencyintel.com/scale-and-impact-of-green-public-procurement-of-steel-and-cement-in-canada-germany-uk-us>

Heeren, N., & Fishman, T. (2019). A database seed for a community-driven material intensity research platform. *Scientific Data*, 6(1), 23. <https://doi.org/10.1038/s41597-019-0021-x>

Hong, L., Zhou, N., Feng, W., Khanna, N., Fridley, D., Zhao, Y., & Sandholt, K. (2016). Building stock dynamics and its impacts on materials and energy demand in China. *Energy Policy*, 94, 47–55. <https://doi.org/10.1016/j.enpol.2016.03.024>

Huang, B, Xing, K., Rameezdeen, R. (2023). *Exploring Embodied Carbon Comparison in Lightweight Building Structure Frames: A Case Study*. *Sustainability*, 15, 20, 15167.

Hurmekoski, E. (2016). *Long-term outlook for wood construction in Europe*. [https://www.researchgate.net/publication/291358292\\_Long-term\\_outlook\\_for\\_wood\\_construction\\_in\\_Europe](https://www.researchgate.net/publication/291358292_Long-term_outlook_for_wood_construction_in_Europe)

International Finance Corporate. (2023). *Net Zero Roadmap for Copper and Nickel: Technical Report*. <https://ccsi.columbia.edu/sites/default/files/content/docs/publications/ccsi-net-zero-roadmap-copper-nickel.pdf>

ISO. (2020). *ISO 21678 Sustainability in buildings and civil engineering works — Indicators and benchmarks — Principles, requirements and guidelines*. <https://www.iso.org/standard/71344.html>

ISO. (2022). *ISO 21931-1:2022 Sustainability in buildings and civil engineering works — Framework for methods of assessment of the environmental, social and economic performance of construction works as a basis for sustainability assessment — Part 1: Buildings*. ISO.

Jiang, L., & O’Neill, B. C. (2017). Global urbanization projections for the Shared Socioeconomic Pathways. *Global Environmental Change*, 42, 193–199. <https://doi.org/10.1016/j.gloenvcha.2015.03.008>

- Karlsson, I., Rootzén, J., Johnsson, F., Erlandsson, M. (2021). *Achieving net-zero carbon emissions in construction supply chains – A multidimensional analysis of residential building systems*. *Developments in the Built Environment*, 8, 100059.
- Karlsson, I., Rootzén, J., Johnsson, F. (2020). *Reaching net-zero carbon emissions in construction supply chains – Analysis of a Swedish road construction project*. *Renewable and Sustainable Energy Reviews*, 120, 109651.
- Lettner, M., Solt, P., Rößiger, B., Pufky-Heinrich, D., Jääskeläinen, A., Schwarzbauer, P., Hesser, F. (2018). *From Wood to Resin—Identifying Sustainability Levers through Hotspotting Lignin Valorisation Pathways*. *Sustainability*, 10, 8, 2745.
- Lewis, M., Waldman, B., Carlisle, S., Benke, B., & Simonen, K. (2023). *Advancing the LCA Ecosystem A Policy-Focused Roadmap for Reducing Embodied Carbon* (Carbon Leadership Forum (CLF)). Carbon Leadership Forum (CLF). <https://carbonleadershipforum.org/advancing-lca-ecosystem/>
- Li, X., Song, L., Liu, Q., Ouyang, X., Mao, T., Lu, H., Liu, L., Liu, X., Chen, W., & Liu, G. (2023). Product, building, and infrastructure material stocks dataset for 337 Chinese cities between 1978 and 2020. *Scientific Data*, 10(1), 228. <https://doi.org/10.1038/s41597-023-02143-w>
- Lushnikova, N., Dvorkin, L. (2016). *25 Sustainability of gypsum products as a construction material*. *Sustainability of Construction Materials (Second Edition)*, 643-681.
- Marinova, S., Deetman, S., Voet, E. van der, & Daioglou, V. (2020). Global construction materials database and stock analysis of residential buildings between 1970-2050. *Journal of Cleaner Production*, 247, 119146. <https://doi.org/10.1016/j.jclepro.2019.119146>
- McKinsey Consulting. (2018). *Decarbonization of Industrial Sectors: The Next Frontier*. <https://www.mckinsey.com/~media/mckinsey/business%20functions/sustainability/our%20insights/how%20industry%20can%20move%20toward%20a%20low%20carbon%20future/decarbonization-of-industrial-sectors-the-next-frontier.pdf>
- Miatto, A., Schandl, H., Wiedenhofer, D., Krausmann, F., & Tanikawa, H. (2017). Modeling material flows and stocks of the road network in the United States 1905–2015. *Resources, Conservation and Recycling*, 127, 168–178. <https://doi.org/10.1016/j.resconrec.2017.08.024>
- Mission Possible Partnership. (2022). *Making Net-Zero Aluminum Possible: An industry-backed, 1.5°C-aligned transition strategy*.
- Mission Possible Partnership. (2023). *Making Net-Zero Concrete and Cement Possible: An industry-backed, 1.5°C-aligned transition strategy*.
- Moynihan, M., Allwood, J. (2014). *Utilization of structural steel in buildings*. *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences*.
- Pedreño-Rojas, Fořt J., Černý R., Rubio-de-Hita, P. (2020). *Life cycle assessment of natural and recycled gypsum production in the Spanish context*. *Journal of Cleaner Production*.
- Pittau, F., Lumia, G., Heeran, n., Innaccone, G., Haabert, G. (2019). *Retrofit as a carbon sink: the carbon storage potentials of the EUhousing stock*. *Journal of Cleaner Production*.
- Plank, B., Streeck, J., Virág, D., Krausmann, F., Haberl, H., & Wiedenhofer, D. (2022). From resource extraction to manufacturing and construction: flows of stock-building materials in 177 countries from 1900 to 2016. *Resources, Conservation and Recycling*, 179, 106122. <https://doi.org/10.1016/j.resconrec.2021.106122>

Portland Cement Association. (2021). *PCA Roadmap to Carbon Neutrality*. Portland Cement Association (PCA). [https://www.cement.org/docs/default-source/roadmap/pca-roadmap-to-carbon-neutrality\\_10\\_10\\_21\\_final.pdf](https://www.cement.org/docs/default-source/roadmap/pca-roadmap-to-carbon-neutrality_10_10_21_final.pdf)

Quintana, A. Alba, J., Del Rey, R., Guillén-Guillamón, I. (2018). *Comparative Life Cycle Assessment of gypsum plasterboard and a new kind of bio-based epoxy composite containing different natural fibers*. *Journal of Cleaner Production*, 185, 408-420.

Ramage, M., Burrige, H., Busse-Wicher, M., Fereday, G., Reynolds, T., Shah, D., Wu., Yu, L., Fleming, P., Densely-Tingley, D., Allwood, J., Dupree, P., Linden, P.F., Scherman, O. (2017). *The wood from the trees: The use of timber in construction*. *Renewable and Sustainable Energy Reviews*. <https://www.sciencedirect.com/science/article/pii/S1364032116306050>

Reyna, J., Wilson, E., Parker, A., Satre-Meloy, A., Egerter, A., Bianchi, C., Praprost, M., Speake, A., Liu, L., Horsey, R., Dahlhausen, M., CaraDonna, C., & Rothgeb, S. (2022). *U.S. Building Stock Characterization Study: A National Typology for Decarbonizing U.S. Buildings* (NREL). National Renewable Energy Laboratory (NREL).

Röck, M., Sørensen, A., Balouktsi, M., Saade, M. R. M., Nygaard, F., Birgisdottir, H., Frischknecht, R., Lützkendorf, T., Endrit, H., Habert, G., Satola, D., Truger, B., Tozan, B., Kuittinen, M., Nicolas, A., Allacker, K., & Passer, A. (2023). *Global Buildings Database Seed on Whole Life Carbon Emissions, Energy Performance, and Material Intensity (CarbEnMats-Buildings) (v0.2.0)*. *Zenodo*. <https://doi.org/10.21203/rs.3.rs-3373442/v1>

Royan, J. (2020). *Embodied Carbon: Structural Sensitivity Study*. Buro Happold Engineering.

Sarkisian, M., Long, E., Beghini, A., Garai, R., Shook, D., Diaz, A., Henoach, R. (2019). *Efficient Post-Tensioned Slab Design Informed Through Topology Optimization*. IABSE Congress, New York, New York 2019: The Evolving Metropolis. 10.2749/newyork.2019.1043.

Sathre, R., O'Connor, J. (2010). *Meta-analysis of greenhouse gas displacement factors of wood product substitution*. *Environmental Science & Policy*. <https://www.sciencedirect.com/science/article/pii/S1462901109001804>

Scott, K., Gilbert, A., Freeman, J., Brennan, M., Goldman, S., Gertler, C., Shepard, J., Green, T., Jacobson, R. (2023). *Pathways to Commercial Liftoff: Industrial Decarbonization*. U.S. Department of Energy.

Shacat, J., Willis, R., Ciavola, B. (2024). *The Carbon Footprint of Asphalt Pavements: A Reference Document for Decarbonization*. National Asphalt Pavement Association.

Shacat, J., Willis, R., Ciavola, B. (2022). *TGHG emissions inventory for asphalt mix production in the United States: Current industry practices and opportunities to reduce future emissions*. National Asphalt Pavement Association. [https://www.asphalt pavement.org/uploads/documents/Sustainability/SIP-106\\_GHG\\_Emissions\\_Inventory\\_for\\_Aspalt\\_Mix\\_Production\\_in\\_the\\_US\\_%E2%80%93\\_NAPA\\_June\\_2022.pdf](https://www.asphalt pavement.org/uploads/documents/Sustainability/SIP-106_GHG_Emissions_Inventory_for_Aspalt_Mix_Production_in_the_US_%E2%80%93_NAPA_June_2022.pdf)

Shanks, W., Dunant, C., Drewniok, M., Lupton, R., Serrenho, A., Allwood, J. (2019). *How much cement can we do without? Lessons from cement material flows in the UK*. *Resources, Conservation and Recycling*. 10.1016/j.resconrec.2018.11.002.

Skullestad, J., Bohne, R., Lohne, J. (2016). *High-rise Timber Buildings as a Climate Change Mitigation Measure – A Comparative LCA of Structural System Alternatives*. *Energy Procedia*. <https://www.sciencedirect.com/science/article/pii/S1876610216307512>

Sprecher, B., Verhagen, T. J., Sauer, M. L., Baars, M., Heintz, J., & Fishman, T. (2022). *Material intensity database for the Dutch building stock: Towards Big Data in material stock analysis*. *Journal of Industrial Ecology*, 26(1),

272–280. <https://doi.org/10.1111/jieec.13143>

Steel Construction Institute. (2017). *Embodied Carbon Assessment of a Light Steel Framed Residential Building*. Steel Knowledge.

Stephan, A., & Athanassiadis, A. (2018). Towards a more circular construction sector: Estimating and spatialising current and future non-structural material replacement flows to maintain urban building stocks. *Resources, Conservation and Recycling*, 129, 248–262. <https://doi.org/10.1016/j.resconrec.2017.09.022>

The Copper Mark. (2024). *The Copper Mark: Sector Decarbonization Approach*. [https://coppermark.org/wp-content/uploads/2024/05/CopperMark\\_SDA\\_InfoSession\\_2024-may-06.pdf](https://coppermark.org/wp-content/uploads/2024/05/CopperMark_SDA_InfoSession_2024-may-06.pdf)

Upton, B., Miner, R., Spinney, M., Heath, L. (2008). *The greenhouse gas and energy impacts of using wood instead of alternatives in residential construction in the United States*. *Biomass and Bioenergy*, 32, 1, 1-10.

U.S. Department of Energy. (2022). *Industrial Decarbonization Roadmap*. <https://www.energy.gov/sites/default/files/2022-09/Industrial%20Decarbonization%20Roadmap.pdf>

Watari, T., Northey, S., Giurco, D., Hata, S., Yokoi, R., Nansai, K., Nakajima, K. (2022). *Global copper cycles and greenhouse gas emissions in a 1.5 °C world*. *Resources, Conservation and Recycling*.

Watari, T., Serrenho, A. C., Gast, L., Cullen, J., & Allwood, J. (2023). Feasible supply of steel and cement within a carbon budget is likely to fall short of expected global demand. *Nature Communications*, 14(1), 7895. <https://doi.org/10.1038/s41467-023-43684-3>

Webster, M., Arehart, J., Chepuri, R., D'Aloisio, J., Gregorian, K., Gryniuk, M., Hogroian, J., Jeseritz, C., Johnson, L., Kestner, D., Lombardi, L. McSweeney, B., Stringer, M., VanGeem, M., Downey, E. (2020). *Achieving Net Zero Embodied Carbon in Structural Materials by 2050*. Structural Engineering Institute.

Whittaker, C., Mortimer, N. (2010). *Understanding the carbon footprint of timber transport in the United Kingdom*.

Wyns, T., Axelson, M. (2016). *Decarbonising Europe's energy intensive industries The Final Frontier*. <https://carbonmarketwatch.org/wp-content/uploads/2016/05/Final-Frontier-Innovation-Report-Web-Version.pdf>

Yoffe, H., Rankin, K. H., Bachmann, C., Posen, I. D., & Saxe, S. (2024). Mapping construction sector greenhouse gas emissions: a crucial step in sustainably meeting increasing housing demands. *Environmental Research: Infrastructure and Sustainability*, 4(2), 025006. <https://doi.org/10.1088/2634-4505/ad546a>

Younis, A., Dodoo, A. (2022). *Cross-laminated timber for building construction: A life-cycle-assessment overview*. *Journal of Building Engineering*. 52.

Zier, M., Stenzel, P., Kotzur, L., Stolten, D. (2021). *A review of decarbonization options for the glass industry*. *Energy Conversion and Management*, 10, 100083.

# Appendix A: Floor Area Projection Methodology

The first key element of the bottom-up approach is to establish floor area projections for each building typology studied. In this study, floor area projections between 2023-2050 were extracted from the EIA Energy Outlook 2023, while 2020-2022 floor areas were based on historical data.<sup>1</sup>

## Commercial Building Floor Area

Commercial building floor area data for 2023 and projections from 2024-2050 were extracted directly from the EIA Energy Outlook 2023. Projections began in year 2023, because at the time of this analysis, the EIA Annual Energy Outlook 2023 included the most up-to-date floor area data for this report. Data in the EIA Outlook was based on 9 different building typologies: warehouse and storage, office, mercantile/service, public assembly, education, food service, lodging, food sales, health care, and other. EIA data characterizes all commercial building floor area as ‘new additions’ and ‘surviving’ floor area. For this study, the ‘new additions’ for each year were allocated to each commercial sub-typology based on the total proportion of floor area added for each building typology in the given year.

For some graphics in the report, commercial buildings were split into ‘office’ and ‘non-office’ commercial buildings. The ‘commercial non-office’ category includes warehouse and storage, mercantile/service, public assembly, education, food service, lodging, food sales, health care, and other building categories.

Historical commercial building floor area data for years 2020, 2021, and 2022 were extracted from the respective ‘current year’ floor areas reported in the US EIA Annual Energy Outlook reports from 2020, 2021, and 2022.<sup>2</sup>

## Residential Building Floor Area

Floor area projections for residential buildings from 2023-2050 followed a different method from the commercial building method, leveraging data from the EIA Energy Outlook 2023, the Residential Energy Consumption Survey 2020, and the US Census Bureau were used to approximate the square footage of newly added single-family residential floor area by residential sub-typology. While most of the relevant projection data came from the EIA Energy Outlook 2023, this source only provided a projected ‘number of housing units’ by residential sub-typology (single family, multifamily, and mobile homes) and an average square footage for all housing units regardless of typology. To robustly determine the exact square footage of added residential buildings by sub-typology, a more detailed approach needed to be taken:

- First, the annual number of housing units by residential sub-typology (single family, multifamily, and mobile homes) and average size of housing unit were extracted from the EIA Outlook 2023.
- For a given year and building sub-typology, the number of newly added housing units (HUs) were calculated as follows, where building sub-typology is represented by typology ‘A’ and the current year is represented by Year X:

$$New\ HU_{A,X} = Existing\ HU_{A,X} - (Existing\ HU_{A,X-1}) \times HDDR$$

- The housing demolition and decay rate (HDDR) value was extracted from HDDRs in the EIA National Energy Modeling System<sup>3</sup>
- Next, the average square footage of each housing unit in a given year by building typology was calculated by using the average size of housing unit across all typologies, provided by the EIA, and additional data to parse the average size by sub-typology, as follows:

<sup>1</sup> Residential floor area data from 2020-2022 based on data from the US Census Bureau Characteristics of New Housing reports. Commercial data based on EIA Energy Outlook reports from 2020-2022.

<sup>2</sup> US Energy Information Administration (EIA). (2020). *Annual Energy Outlook 2020*. <https://www.eia.gov/outlooks/aeo/pdf/aeo2020%20full%20report.pdf>  
US EIA. (2021). *Annual Energy Outlook 2021*. [https://www.eia.gov/outlooks/aeo/pdf/AEO\\_Narrative\\_2021.pdf](https://www.eia.gov/outlooks/aeo/pdf/AEO_Narrative_2021.pdf)  
US EIA (2022). *Annual Energy Outlook 2022*. [https://www.eia.gov/outlooks/aeo/pdf/AEO2022\\_Narrative.pdf](https://www.eia.gov/outlooks/aeo/pdf/AEO2022_Narrative.pdf)

<sup>3</sup> See <https://github.com/EIAgov/NEMS/blob/main/input/rdm/rsmisc.txt#L21>

$$Avg. Area_{A,X} = New HU_{A,X} \times Avg. HU_{AreaAll,EIA2023} \times HU Proportion_{A,RECS2020} \times CF$$

- $Avg. Area_{A,X}$  indicates the average area of building typology A in year X
  - $New HU_{A,X}$  indicates the number of new housing units of typology A in year X from the EIA Annual Energy Outlook 2023, as calculated in the previous step
  - $Avg. HU_{AreaAll,EIA2023}$  is the average size of all residential housing units from the EIA Annual Energy Outlook 2023
  - $HU Proportion_{A,RECS2020}$  is a proportion of the average size of a specific residential sub-typology to the average size across all typologies taken from the Residential Energy Consumption Survey (RECS), 2020<sup>4</sup>.
  - $CF$  is a correction factor developed by us to ensure that the average floor area derived in this calculation are consistent with the average floor area derived via the EIA Energy Outlook 2023. Essentially, it normalizes the floor areas between RECS 2020 and the EIA Outlook.<sup>5</sup>
- Finally, the new floor area for each typology (New Area) per year was calculated as follows, where A represents a given residential sub-typology and X represents the given year:

$$New Area_{A,X} = New HU_{A,X} \times Avg. Area_{A,X}$$

Historical residential floor area data was extracted from several sources. The number of single family, multifamily, and mobile home units completed in each year from 2020-2022 were extracted from the US Census Bureau. The number of completed housing units for single-family and multifamily buildings are reported in the US Census Bureau New Residential Construction reports.<sup>6</sup> The number of mobile home units constructed for each year between 2020-2022 were taken from the US Census Bureau Manufactured Housing Survey.<sup>7</sup> Once the number of historical housing units were recorded, the average area for each building typology was calculated using the methods listed above for residential floor area projections.

<sup>4</sup> US EIA. (2020b). *Residential Energy Consumption Survey (RECS)*. <https://www.eia.gov/consumption/residential/>

<sup>5</sup> US EIA. (2023). *Annual Energy Outlook 2023*. [https://www.eia.gov/outlooks/aeo/pdf/aeo2023\\_narrative.pdf](https://www.eia.gov/outlooks/aeo/pdf/aeo2023_narrative.pdf)

<sup>6</sup> US Census Bureau. (n.d.). *New Residential Construction*. Retrieved July 16, 2025, from <https://www.census.gov/construction/nrc/index.html>

<sup>7</sup> Bureau, U. C. (n.d.). *Manufactured Housing Survey (MHS) Data*. Census.Gov. Retrieved July 16, 2025, from <https://www.census.gov/programs-surveys/mhs/data.html>

# Appendix B: Material Stock Projection Methodology Details

## B.1 Material Stock Projection Using Historical Consumption and Time Series Modeling (Approach 1)

### *Data Acquisition and Preparation*

Approach 1 projects future construction material stocks using historical apparent consumption data sourced primarily from the US Geological Survey (USGS). The projection follows **Seasonal Auto-Regressive Integrated Moving Average (SARIMA)** models due to their capability to effectively capture both short-term seasonality and long-term trends. Three primary datasets underpin this approach:

1. **Historic Consumption Data:** Annual apparent consumption data for major construction materials in metric tons (1900–2020), sourced from the USGS.
2. **Construction Share Data:** Percentages representing the fraction of total material consumption specifically used by the construction sector (buildings and infrastructure), derived from USGS and supported by assumptions and other resources from the literature for incomplete data.
3. **Embodied Carbon Inventory:** Materials' GWP factors (in kgCO<sub>2</sub>e per kg of a given material) obtained from various sources (CLF's Material Baselines, in particular), critical for estimating bottom-up sectoral embodied carbon impacts.

### *Data Import and Verification*

The following datasets were imported and verified:

- `historic_data` (Historic consumption)
- `construction_share` (Construction sector share)
- `ghg_inventory` (Embodied carbon intensities)

Initial data reviews were performed to ensure accuracy and completeness.

### *Data Imputation*

Missing data in historical consumption records were systematically imputed using raw material consumption trends for the entire US (included in USGS database). Cells containing imputed values were explicitly marked within the `historic_data` dataset to transparently indicate areas of uncertainty. Trend-based imputation was assumed to maintain continuity without significantly compromising data quality.

### *SARIMA Modeling*

SARIMA models are an extension of ARIMA models that account for repeating seasonal patterns in time series data. These models are especially suitable when historical observations exhibit both cyclical behavior and underlying trends—common in construction-related material flows. SARIMA includes components for auto regression (AR), differencing to achieve stationarity (I), and moving averages (MA), alongside explicit seasonal terms. This makes SARIMA particularly powerful for generating reliable, interpretable forecasts based on historical data with annual or multi-year seasonality. For further methodological background, refer to Hyndman & Athanasopoulos (2018), Box et al. (2015), and Taylor & Letham (2018).

The following additional steps were taken to implement and validate the SARIMA model:

- **Stationarity Testing:** Augmented Dickey-Fuller (ADF) tests were performed to confirm non-stationarity (p-values > 0.05) in the historic consumption time series, supporting the necessity of differencing methods inherent in SARIMA models. It was assumed that non-stationarity observed is due primarily to sustained long-term growth or shifts in material usage.

- **Model Selection and Optimization:** Optimal SARIMA model parameters for each material category were determined using Python's `auto_arma` function (from the `pmdarima` package). Multiple seasonal periods were initially tested, but a consistent seasonal period of 24 months was selected across all materials to balance model complexity and accuracy. Minimum root mean square error (RMSE) was used as the metric for evaluating model performance. In these models, it was assumed that historical seasonal consumption patterns remain stable into the future.
- **SARIMA Model Implementation:** Optimized SARIMA models projected annual material consumption from 2021 to 2050. The forecasts were then integrated with historical data, providing coherent and continuous projections. It was assumed that future material consumption continues historical trends without major disruptions.
- **Model Validation:** SARIMA forecasts were validated against recent historical data (2010–2020), demonstrating high accuracy. Comparative scatter plots on a logarithmic scale highlighted strong predictive reliability. Historical and projected material consumption data were further visualized per material category, explicitly marking imputed data points within historic data.

### *Construction Sector Allocation*

Material consumption projections were proportionally allocated to the construction sector using historical shares. When available from USGS, historic construction share data were averaged across years with reported values. A key assumption in this allocation step is that the share of construction sector in total raw material consumption per material group remain consistent post-2020.

### *Recategorization of Materials*

Materials were recategorized into industry-standard groupings for practical interpretation:

- Concrete: Calculated from residual crushed stone not used in asphalt, cement (12%), water (7%), and aggregates (81%).
- Asphalt: Based on average binder content (3.5%), Recycled Asphalt Pavement (RAP) content (20%, 100% asphalt binder contribution at 5.5% effective asphalt binder content).
- Aggregates: Split into concrete (27%), asphalt (9%), road base (23%), and other uses (41%).
- Steel: Assumed 35% allocation to construction.

For the baseline scenario, it was assumed that these ratios remain constant through 2050.

### *Embodied Carbon Calculation*

Projected construction material quantities were multiplied by respective GWP factors per material category to quantify embodied carbon stocks. This analysis is crucial for evaluating the environmental impacts of future construction activities and as a point of comparison to top-down approaches in establishing carbon budgets. For the baseline scenario, GWP factors are assumed to remain stable unless explicitly altered by a carbon reduction strategy due to technological or policy interventions.

### *Fitting Best Lines to Projections*

Alternative regression models (polynomial, exponential, logarithmic, power) were fitted into SARIMA projections from 2020 to 2050 to enhance predictive accuracy and consistency with other projections. Models with the highest  $R^2$  values were selected to refine long-term forecasts. As a result, trend lines that best represent projection trends per material categories were generated and used.

## B.2 Material Stock Projection Using Building and Material Level Data (Approach 2)

Approach 2 projects future building material demand using a combination of floor area growth projections and material use intensities. This method specifically relies on two datasets: floor area growth projections (see section 2.1) and detailed MUI values from the Carbon Leadership Forum's (CLF) Whole Building Life Cycle Assessment benchmarking study. By linking the floor area projections – which represent expected annual growth in building stock across different building types – with CLF's empirical material intensity data (kg of material per square meter), the approach provides direct estimates of annual material consumption. The process described below is scripted in Python and is available in a GitHub repository created for this study.

### Data Import and Initial Cleaning

The method begins by importing essential Python libraries required for data handling and visualization, including `pandas` and `numpy` for data manipulation and `matplotlib` for plotting. Two primary datasets from CLF Benchmarking Study were then imported:

1. Building Metadata (`wblca_meta_data`), containing descriptive project details such as building use type, construction floor area (`bldg_cfa`), building project type (`bldg_proj_type`), and a unique project identifier (`project_index`).
2. Full Life Cycle Assessment (LCA) Results (`wblca_results_full`), which include detailed environmental impact metrics, specifically the mass inventory (`inv_mass`) and global warming potential (`gwp`) for various materials and life cycle stages across building projects.

Immediately after importing, data cleaning involved removing rows from the LCA results dataset with either zero or missing (NaN) values in the `inv_mass` or `gwp` columns. This cleaning step ensures that subsequent analysis is performed on valid and meaningful data points.

### Data Pre-Processing

#### Calculation of Building-Level MUI and ECI

The analysis focuses specifically on the “A1-A3” life cycle stages, representing material extraction and manufacturing processes. The LCA dataset was filtered to include only data corresponding to these stages. Aggregation was performed at the project level (`project_index`), summing the total mass (`inv_mass`) and total global warming potential (`gwp`) for each project.

These aggregated values were then merged with corresponding building metadata based on the `project_index`. Following this merge, two critical metrics were computed for each building:

- Material Use Intensity (MUI): the total mass of materials per unit of building construction floor area ( $\text{kg}/\text{m}^2$ ).
- Embodied Carbon Intensity (ECI): the total global warming potential per unit of building construction floor area ( $\text{kgCO}_2\text{e}/\text{m}^2$ ).

#### Calculation of Material-Level MUI and ECI

Three metrics were computed at the material level for each project:

- Material-level MUI: calculated as the individual material mass divided by the building's construction floor area.
- Material-level ECI: calculated as the individual material GWP divided by the building's construction floor area.
- Global Warming Potential Factor (GWP Factor): calculated as the ratio of material GWP to material mass, quantifying the embodied carbon per unit of material mass.

### Outlier Detection and Removal

To maintain the integrity and robustness of the analysis, potential outlier projects were identified and excluded. Due to the significant variability observed in MUI and ECI values, the method applied a log-transformation before calculating z-scores

for both metrics. Projects exhibiting an absolute z-score greater than 3 in either log-transformed MUI or ECI were classified as outliers and subsequently removed from the dataset.

## Data Merging and Filtering

Following outlier removal, the cleaned metadata was merged back with the full LCA results dataset (`wblca_results_full`) using a left join based on the `project_index`. This merged dataset was further filtered to include only new construction projects (`bldg_proj_type = "New Construction"`) and exclusively the life cycle stage "A1-A3." For streamlined analysis, the dataset was reduced to retain only relevant columns, including project identifiers, material and element classifications (`mat_group`, `mat_type`), physical parameters (`inv_mass`, `gwp`, `bldg_cfa`), building usage information (`bldg_prim_use`), and metadata about LCA software and physical scope (`lca_software`, `lca_phys_scope`).

## Data Restructuring and Building Use Type Categorization

To facilitate detailed analysis by building use, a new categorical variable, `wedge_bldg_prim_use`, was created by recategorizing the original primary building use types (`bldg_prim_use`). The rationale behind this categorization was to consolidate less frequent building use types into an "Other" category to ensure sufficient representation for statistical analyses:

- **Project Count Evaluation:** The number of unique projects (`project_index`) within each original building use category was computed. Categories with fewer than five projects were identified as insufficiently represented.
- **Category Consolidation:** Original building use categories with fewer than five unique projects were combined into a broader "Other" category, while categories with adequate representation remained unchanged.
- **Final Categorization:** The new categorical variable, `wedge_bldg_prim_use`, thus represents a simplified and statistically robust grouping of building uses for subsequent analyses.

## Data Summaries

### *Data Summaries for All Buildings*

MUI was analyzed at the material group (`mat_group`) level without segmenting by building use type. The analysis included the following steps:

- **Summation per Project:** The total MUI for each `mat_group` was calculated for every individual project (`project_index`).
- **Summary Statistics Calculation:** Key summary statistics were computed across all projects, including mean, median, first quartile (Q1), third quartile (Q3), and project count for each `mat_group`.
- **Aggregate Metrics:** The sum of average MUIs across all material groups provided a comprehensive intensity measure, and the average total MUI across all projects was calculated to indicate typical project intensity.
- **Material Type Contributions:** MUIs were computed at the more detailed material type (`mat_type`) level. Each material type's mean contributions to its corresponding material group were quantified and normalized to reflect proportional contributions accurately within each material group. These normalized contributions were visualized using stacked horizontal bar charts.

Similar analytical procedures were employed for the case of ECI. Since these MUI and ECI values consider all building use types in the dataset, they are sometimes referred to as "weighted average" values.

### *Data Summaries by Building Use Type*

The analysis was extended to investigate MUI specifically segmented by primary building use type (`wedge_bldg_prim_use`). The following steps were undertaken for each distinct building use category:

- **Data Segmentation:** The dataset was filtered based on individual building use types, creating subsets of data specific to each building function.
- **Project-Level Aggregation:** Within each filtered subset, MUI values were summed for each material group (`mat_group`) at the individual project (`project_index`) level.
- **Statistical Analysis:** Comprehensive summary statistics, including mean, median, first quartile (Q1), third quartile (Q3), and project count, were calculated across all projects within each building use category and material group.
- **Visualization:** Horizontal bar charts illustrated these summary statistics clearly, showing mean and median intensities per material group with interquartile range (IQR) error bars. These charts utilized a logarithmic scale to effectively manage the wide variability and range of the data.
- **Material Type Breakdown:** Further analysis detailed each material type's (`mat_type`) proportional contributions within their corresponding material groups. Mean and median contributions for each material type were normalized against total material group intensities. Stacked horizontal bar charts visually represented these normalized contributions, providing insights into the relative importance of individual material types in different building use contexts.

Similarly, the analysis was performed for the case of ECI. Resulted analysis data were exported and maintained for future reference or use by the other steps of the methodology.

## Estimating MUI and ECI for Single-Family Residential Buildings

Because the CLF WBLCA Benchmark Study V2 dataset lacked sufficient direct representation of new construction, single-family buildings, a proxy-based method was employed to estimate their material and embodied carbon intensities. This estimation process involved filtering and transforming relevant subsets of the dataset, calculating summary statistics, and generating visualizations.

To approximate Single-Family Residential MUI and ECI:

- Building use types categorized as “Residential: Multifamily (5 or more units)” and constructed with “Wood: Light-frame” structural systems were selected.
- These projects were relabeled as “Residential: Single-family” to serve as a reasonable proxy for detached low-rise construction, aligning with dominant practices in the single-family sector.

A similar process was then followed to create MUI and ECI summaries per material categories and for the newly defined single-family residential buildings. The single-family estimates were further merged with the broader dataset of other building use types to create a comprehensive dataset that includes all building use types.

These estimates are limited in that they do not account for alternative single family structural systems (e.g., concrete block) and it assumes that single-family MUIs are similar to multifamily MUIs for stick-framed buildings. However, given that concrete single family residences make up a negligible percentage of overall single family building stock, this was not seen as a major limitation.

Note: Due to normalization by material group, total intensities may not align exactly with project-level averages. However, this approach prioritizes material-level insight, which is critical for targeted carbon-reduction strategies.

## Bottom-Up Integration of Floor Area Growth and MUI

The final phase of Approach 2 focused on generating forward-looking material and embodied carbon projections by integrating floor area growth estimates with material use intensity data. This bottom-up process linked projected new construction floor area across multiple building typologies to the resultant MUI data as explained earlier. The goal was to produce high-resolution forecasts of both material stock (in metric tons) and associated embodied carbon (in metric tons CO<sub>2</sub>e) from 2020 through 2050 by material type.

### *Data Import and Preprocessing*

Annual floor area growth data (in million m<sup>2</sup>/year) across a range of US building typologies were imported from the analysis conducted (see Section 2.1). These projections spanned from 2020 to 2050 and included the following building typologies:

- Single-family residential
- Multifamily residential
- Office
- Education
- Healthcare
- Warehouse and storage
- Mercantile and service
- Food sales and service
- Lodging
- Public assembly
- Other

Initial processing involved removing extraneous characters and harmonizing column names. A new total floor area growth column (`RMI_total_growth_million_m2`) was created by summing across all typologies, providing a baseline check for completeness.

### *Harmonization of Building Use Categories*

The typologies provided in the RMI projections did not fully align with the CLF WBLCA categories, particularly in categories where detailed MUI or ECI data were sparse or missing (e.g., Lodging, Food Sales, and Mercantile). To address this mismatch and ensure complete coverage of all floor area categories, several RMI categories were consolidated into a composite category called “Other CLF category.” To calculate material and carbon projections for this catch-all group, the weighted average MUI and ECI values will be used as the best representation.

### *Merging Floor Area and MUI/ECI data*

After harmonizing typologies, the floor area dataset was transposed to make each building use category a row and each year a column. This format was joined with a cleaned `material_intensity_building_use_list`, which contains average (mean) material MUI and ECI by material type and building use. Using the merged datasets, the following formulas were applied:

- Material Stock (tons):  
 $\text{Floor Area} \times \text{Mean MUI (kg/m}^2) \times 1000$
- Embodied Carbon Stock (tons CO<sub>2</sub>e):  
 $\text{Floor Area} \times \text{Mean GWP Intensity (kgCO}_2\text{e/m}^2) \times 1000$

Two new data frames were created from this process:

- `mui_df`: Projected material quantities by year, material type, and building use.
- `eci_df`: Projected embodied carbon by year, material type, and building use.

To support external analysis, validation, and policy modeling, projection data were exported to structured CSV files:

- `material_stock_projection_by_wedge_categories.csv`
- `carbon_stock_projection_by_wedge_categories.csv`

These tables summarize total stock and emissions by material type for every year from 2020 through 2050.

### *Estimating Global Warming Potential (GWP) Factors for the Year 2020*

To harmonize Approach 2 with the time-series projections in Approach 1, the script calculated a simplified GWP factor for each material type using 2020 projection data:

- Formula:  
GWP Factor = CO<sub>2</sub>e Stock / Material Stock (for 2020 only)

These values represent the average GWP factor of each material within the material type categories (in kgCO<sub>2</sub>e/kg) as modeled in the baseline scenario, incorporating both empirical material intensity values and projected floor area. The resulting dataset (`gwp_factor_by_material_type_2020.csv`) was saved for use in downstream modeling tasks, including emissions back casting and comparative assessments. The following assumptions are also implicitly or explicitly made:

- Stability of Intensity Values: All MUI and ECI values were assumed to remain constant over time in the absence of decarbonization interventions.
- Full Floor Area Coverage: The weighted average category was developed to ensure that all RMI floor area projections were accounted for, even when direct benchmarking data were limited.
- Proportional Scaling: Material and carbon stock estimates were linearly scaled based on floor area, assuming no changes in construction practices or material substitution in the baseline scenario.

Estimating GWP factors is inherently challenging to calculate for materials at this scale, as each of the 26 categories includes a large range and difference within materials. The GWP factors for the year 2020 used for new construction use data from the CLF Benchmarking Study v2 and therefore pull from at least two background datasets (from two WBLCA tools).

## **B.3 Integration of Material Stock Projections from Approaches 1 and 2**

To establish a unified and comprehensive baseline of material stock projections, results from both methodological approaches (i.e., Approach 1 and Approach 2) were systematically merged. This integration ensures that projections account for both historical macro-scale material trends and building-level construction practices, enabling a more nuanced understanding of future material demand across the US built environment.

### *Data Harmonization and Preparation*

Projections from Approach 1, which rely on historical apparent consumption data and SARIMA time series models, were first transposed and reformatted to match the structure of Approach 2 data, which was derived from floor area growth projections and measured material use intensities. Each dataset was tagged with an identifying label (`approach_1` or `approach_2`) and concatenated into a single combined dataset.

Because raw materials in Approach 1 are sometimes reported at a finer level of disaggregation (e.g., cement, aggregates, and concrete products), key material categories were restructured to align with the more aggregated “wedge material categories” used in Approach 2. For example, four distinct material entries related to cement and aggregates were summed and relabeled as “cement\_concrete” to ensure consistency with corresponding categories in Approach 2 (i.e., the “concrete” material group category).

### *Filtering for Relevant Materials and Avoiding Double Counting*

To avoid redundancy and ensure complementary integration of data sources, a material-specific inclusion strategy was employed. Material types projected through Approach 1 were retained only if they were either not represented or only partially represented in Approach 2. These included:

- Concrete components not covered in building-level assessments (e.g., infrastructure concrete, and all concrete not used

in new construction buildings),

- Steel materials not used in new construction buildings (which includes all other uses within the construction sector per USGS definition),
- Asphalt concrete, which is almost entirely used in road pavements,
- Road base and other construction aggregates that are neither used in concrete manufacturing nor asphalt production.

To reconcile overlapping materials such as concrete and steel, both of which appear in projections from Approaches 1 and 2, differential calculations were applied. Total projected quantities from Approach 2 were subtracted from their broader counterparts in Approach 1 to isolate quantities not otherwise captured in building-level data. The residuals were retained and labeled as “Concrete (not covered in Approach 2)” and “Steel (not covered in Approach 2)” to ensure clarity and prevent duplication.

### *Material Group Classification and Final Merging*

All material types, regardless of origin, were mapped to corresponding material groups based on the classification system used in the CLF WBLCA Benchmark Study. This allowed for coherent aggregation and comparison across sources, and for materials with uncertain or hybrid categories, a logical assignment was made based on dominant usage patterns.

The final combined dataset includes:

- Material quantities projected using building-level methods for major typologies (Approach 2),
- Aggregated historical projections for large-scale materials not captured at the building level (Approach 1),
- Residual quantities for overlapping categories to prevent overestimation,
- A consistent assignment of each material to a higher-level group for visualization and reporting.

### *Material Type Recategorization*

In order to align with the list of material-specific decarbonization strategies, the material types obtained from combining Approach 1 and 2 stock projections were recategorized. In that, material types were either kept intact or were assigned to a new, more generic category, called “wedge\_material\_category”. For example, all material types related to ready-mix concrete but with different classes (e.g., different compressive strengths or gradations) were aggregated and assigned a new category called “ready-mix concrete” since carbon reduction strategies developed in this study were generic to this type of concrete. Material stock projections were then summed per this new material categorization scheme to fully align with the decarbonization matrix that mapped material categories to carbon reduction strategies.

## **B.4 Material Groupings**

In total, approaches 1 and 2 include 30 material categories: four categories representing key materials used for civil infrastructure systems and other construction (using approach 1), and 26 representing materials commonly found in new construction buildings (using approach 2).

Benke et al (2025) categorized building materials into 122 distinct material types and 22 broader material groups, using life cycle assessment (LCA) data from 292 buildings across North America. Because carbon reduction strategies are generally designed around higher-level material categories (e.g., treating all ready-mix concrete classes as a single group), we adapted the material group categories to allow for more actionable mapping of carbon reduction strategies to the materials studied, resulting in 26 (rather than 122) material categories for new buildings.

**Table B.1** summarizes the 30 materials included in the analysis as well and how they are grouped for the visualizations used in sections 2 and 4.

**Table B.1 Construction material groupings used in the analysis.** “Building” refers to new building construction projected using Approach 2. “Infrastructure” refers to non-building infrastructure calculated using Approach 1. Material Groups 1 and 2 indicate how materials were grouped for summary purposes in the charts included in sections 2 and 4 of this report.

Material	Building or infrastructure	Material Group 1	Material Group 2
M1 - Acoustic ceilings	Building	Interior construction and finishes	Other
M2 - Aluminum	Building	Aluminum	Aluminum
M3 - Asphalt mixtures	Infrastructure	Asphalt mixtures	Asphalt
M4 - Cladding	Building	Cladding and roofing	Other
M5 - Coatings	Building	Interior construction and finishes	Plastic and chemicals
M6 - Concrete (incl cement)	Building	Concrete	Concrete
M7 - Concrete (infrastructure)	Infrastructure	Concrete	Concrete
M8 - Doors and frames	Building	Interior construction and finishes	Other
M9 - Flooring and tile (non-plastic)	Building	Interior construction and finishes	Other
M10 - Flooring and tile (rubber/plastic-based)	Building	Interior construction and finishes	Plastic and chemicals
M11 - Glazing	Building	Glass and Windows	Glass and Windows
M12 - Gypsum board	Building	Gypsum board	Gypsum board
M13 - Insulation (Non-plastic)	Building	Insulation	Other
M14 - Insulation (Plastic-based)	Building	Insulation	Plastic and chemicals
M15 - Masonry (CMU)	Building	Concrete	Concrete
M16 - Masonry (mortar and grout)	Building	Concrete	Concrete
M17 - Masonry (other)	Building	Cladding and roofing	Other
M18 - Other	Building	Other	Other
M19 - Other (metals)	Building	Other	Other
M20 - Other (plastics and chemicals)	Building	Other	Plastic and chemicals
M21 - Roofing and waterproofing (asphalt-based)	Building	Cladding and roofing	Asphalt
M22 - Roofing and waterproofing (plastics-based)	Building	Cladding and roofing	Plastic and chemicals
M23 - Sand and gravel (infrastructure)	Infrastructure	Sand and gravel	Other
M24 - Sand and gravel (other)	Building	Sand and gravel	Other
M25 - Steel (infrastructure/other)	Infrastructure	Steel	Steel
M26 - Steel (rebar and reinforcement)	Building	Steel	Steel
M27 - Steel (structural/other)	Building	Steel	Steel
M28 - Windows and frames	Building	Glass and Windows	Glass and Windows
M29 - Wood (engineered wood)	Building	Wood	Wood
M30 - Wood (softwood framing/panels/other)	Building	Wood	Wood

# Appendix C: Matrix Methodology and Data Collection

## C.1 Matrix Methodology

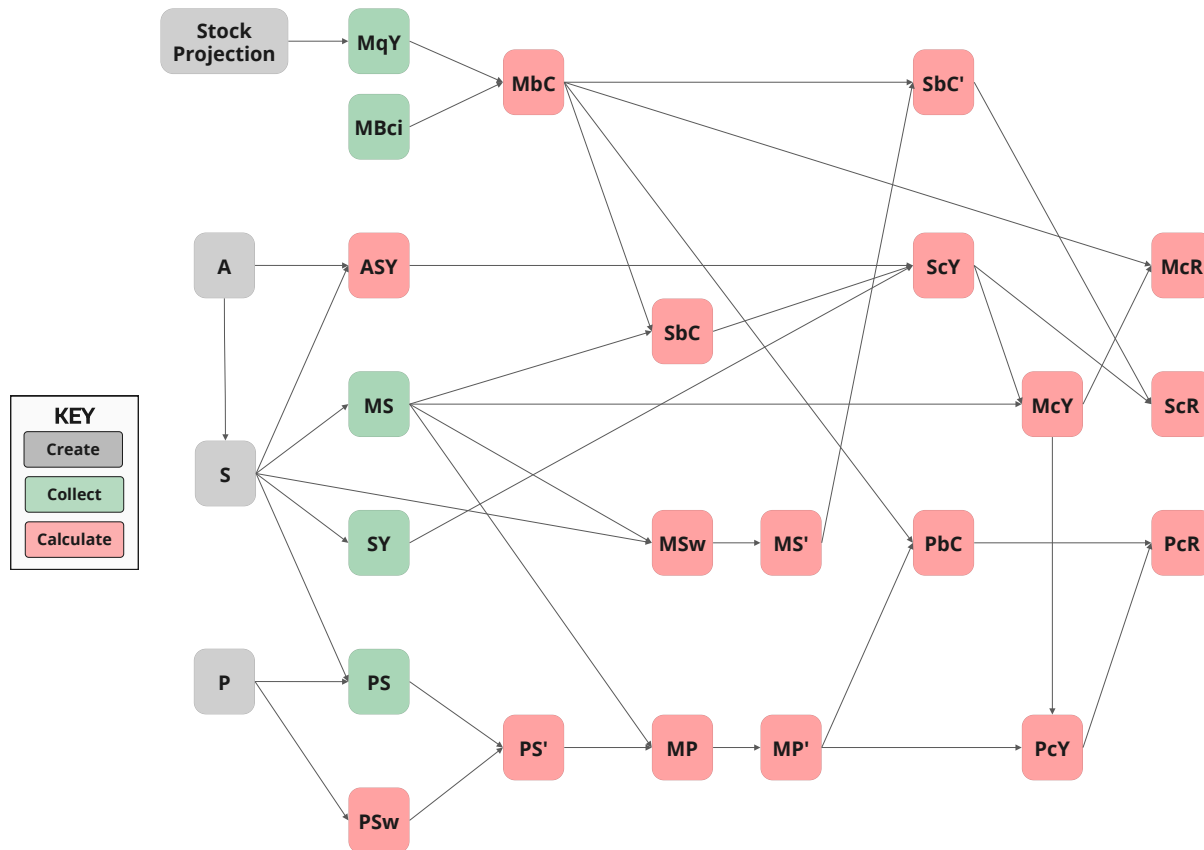
CLF used a matrix method to explore which strategies and policies hold the greatest potential at the scale of all US embodied emissions through 2050. In addition to the material list and stock projections described in Appendix B, there are three core lists that underpin much of the analysis:

- 1. Strategy List (S):** A list of 173 decarbonization and demand reduction strategies. Each strategy includes a description, a minimum and maximum reduction potential, an adoption rate category as collected from reviewed research. Each strategy is mapped to a specific material and a group. For example, “S11 - Aluminum: Recycled Feedstocks” and “S16 - Asphalt mixtures: Recycled feedstocks”) are two separate strategies both in the category of “Recycled Feedstocks (LCFS-C)”.
- 2. Adoption rate scenario (A):** Adoption rate curves with an adoption rate percentage assigned to each year between 2020 and 2050 for the five categories (R&D, Demonstration, Deployable (low), Deployable (medium), and Deployable (high)).
- 3. Policy List (P):** A list of 32 policies, which groups of strategies (e.g. energy efficiency, Recycled Feedstocks) they apply to, the uptake category (see below), and any additional methodology notes (i.e. whether they only apply to certain materials or projects).

**Figure C.1** provides a visual summary of the relationships between the matrices described in **Table C.1**, an overview of the matrices required to calculate the reduction scenarios described in Section 4.4. and highlights which elements were collected or calculated. The method for the “Collect” matrices are described in further detail elsewhere in this report: the material quantity by year and material baseline carbon intensity in section 2, the strategy list and adoption rate scenarios in section 4.1, and the policy list in section 4.2.

**Table C.1. Overview matrices, development method (create, collect or calculate) and relationship to other matrices.**

Matrix	Name	Method	Relationships
P	Policy List	Create	Links to PS
S	Strategy List	Create	Used to define SY and link to PS, MS
A	Adoption Rate Scenario	Create	Used to define AsY by year
MqY (m x y)	Material quantity by Year (MqY)	Collect	From Approach 1 and 2 material stock projections (see section 2.2)
MbCI (m x 1)	Material baseline Carbon Intensity (MbCI) - kgCO2e/kg	Collect	Used in MbC and McY
SY (s x y)	Strategy-carbon reduction percentage from baseline per Year	Collect	Informed by S and A
MS (m x s)	Material-Strategy (MS)	Collect	
PS (p x s)	Policy-Strategy (PS)	Collect	
MSw	Weights assigned to MS	Calculate	Maximum reduction potential found in S multiplied by its associated adoption rate found in A
MS'	Normalized weighted Material-Strategy matrix	Calculate	
PSw	Weights assigned to PS	Calculate	Policy uptake factors multiplied by PS for each element per building or infrastructure related strategy
PS'	Weighted Policy-Strategy Matrix	Calculate	$PS' = PS * PSw$ (element-wise multiplication)
MP (m x p)	Material-Policy (MP)	Calculate	$MP = MS \times PS'^T$
MP' (m x p)	Normalized Material-Policy (MP')	Calculate	
AsY (s x y)	Adoption rate of carbon reduction strategy per Year	Calculate	$AsY = \text{lookup}(S, A)$
MbC	Material Baseline Carbon	Calculate	$MbC = MqY \times MbCI$
SbC	Strategy Baseline Carbon	Calculate	$SbC = MS^T \times MbC$
SbC'	Weighted Strategy Baseline Carbon	Calculate	$SbC' = MS'^T \times MbC$
PbC	Policy Baseline Carbon	Calculate	$PbC = MP'^T \times MbC$
ScY (s x y)	Strategy-carbon reduction quantity per Year	Calculate	$ScY = -SY * AsY * SbC$ if $SY * AsY * SbC < SbC'$ ; otherwise $-SbC'$
McY (m x y)	Material-carbon reduction quantity per Year	Calculate	$McY = MS \times ScY$
PcY (p x y)	Policy-carbon reduction quantity per Year	Calculate	$PcY = MP'^T \times McY$
McR	Material Roadmap	Calculate	$McR = MbC + McY$
ScR	Strategy Roadmap	Calculate	$ScR = SbC' + ScY$
PcR	Policy Roadmap	Calculate	$PcR = PbC + PcY$



**Figure C.1. Summary of matrix methodology used to assess the cumulative reduction potential of available decarbonization strategies and related policies.**

## C.2 Data Collection: Strategies

The following general methods were used to create the final list of 173 strategies:

1. **Review of Available Research:** We reviewed of available academic literature, industry association roadmaps, and NGO reports on industrial decarbonization related to aluminum, asphalt, cement, concrete, copper, glass, gypsum drywall, insulation, masonry, plastics, sand and gravel, steel, and wood to identify (1) potential strategies to reduce A1-A3 emissions for each material and (2) the reduction potential of each of those strategies.
2. **Grouping strategies:** Each strategy was grouped into the eight categories described in Table 2 included in Section 4.1.1. These categories strategies enabled us to aggregate similar strategies that may otherwise create double counting in our model and increased our confidence in the reduction potential range for each strategy group, making the model less dependent on individual technologies being successful.
  - a. Example 1: We found research on the potential of inert anode technology and mechanical vapor recompression to increase the energy efficiency during smelting and bauxite digestion as well as on the potential generally for energy efficiency across alumina refining, smelting, and secondary production. These are all grouped into the ranges for “S07 - Aluminum: Energy Efficiency”.
  - b. Example 2: The full range for the “S34 - Concrete: Raw Material Substitution” strategy is 5% - 66%. This strategy incorporates a range of cement and clinker substitutes (e.g. fly ash, slag), alternative cements (e.g. limestone calcined clay cement (LC3)), and alternative chemistries (e.g. belite, sulphoaluminate, and other

engineered materials in development). There is a range of reduction potentials associated with the different material substitution opportunities within this strategy, and only some are additive (e.g. mixes can include *either* LC3 or alternative chemistries to achieve a 55% emissions reduction in concrete, but they cannot be added together to get a 110% reduction in practice).

- c. Where possible, we separated out the reduction potential of low carbon electricity from electrification. However, this was not always possible as much of the research cited in our model reports the reduction potential of electrification in combination with a completely clean power source.

**3. Applying raw material strategies to downstream products:** For some materials, we adjusted the percentages identified in literature to apply decarbonization strategies for raw materials to downstream products. This was done using data on the relative impact of that ingredient of life cycle stage on the total A1-A3 impact.

- a. Example 1: Concrete, concrete masonry units (CMU) and mortar and grout includes reductions from cement and clinker strategies. In order to ensure that the potential of strategies for upstream materials in the supply chain were not over counted, these were scaled based on their impact on A1-A3 emissions. A 100% maximum reduction potential for cement would only be a 90% maximum reduction potential for ready-mixed concrete, as cement is responsible for approximately 90% of the A1-A3 impacts of typical ready-mix concrete.
- b. Example 2: Decarbonization strategies for plastic and chemicals strategies are used for a range of building materials, including chemical or plastic-based paints and coatings, insulations, flooring and tile products, roofing and waterproofing, and synthetic composites. Similar to concrete products, the reduction potentials for plastic and chemicals were scaled to reflect their reduction potential on the final product.
- c. Note: In some cases, there is a mismatch between materials and the applied strategies due to data limitations. For example - the category of “windows” includes a mix of glass products and plastic/metals for the frames that we are not able to separate out. However, this whole category is grouped under glazing strategies. This is a limitation that was allowed only for categories that do not have a large impact on total results (i.e. comprise a small overall percentage of emissions reduction opportunities).

### C.3 Adoption Rates

Essential to the technical potential of each strategy to reduce emissions is the actual adoption of the strategy by the market. In our model, this is described as the adoption rate. The adoption rate describes the growth in deployment of the strategy in the US market. CLF allocated one of five “Adoption Rate Categories” to each strategy based technology readiness level, cited cost, and implementation timelines cited in the reviewed literature and reports. These categories include:

- 1. Research and Development (R&D):** Strategies that are currently still in the stages of R&D. These strategies have a technology readiness level (TRL) in the 2-5 range and may or may not have been tested in pilots. These strategies currently have little to no impact but could possibly have substantial impact 15-30 years from now.
- 2. Demonstration:** Strategies that have graduated from research and development but are still not commercially viable. They may have been tested through various pilots and typically have a TRL in the 4-7 range.
- 3. Deployable (low):** Deployable technologies that are cost prohibitive or have other commercial viability constraints (e.g. supply constraints) limiting full adoption. These strategies likely require significant policy change, subsidies and investment, and/or radical changes in demand to increase deployability.
- 4. Deployable (medium):** Deployable technologies that are less cost prohibitive but still new to the market; these strategies have been proven to work but still have lower market demand due to their lack of longevity in the market and/or perceived challenges by the construction sectors. These still require time to scale, but have potential to make emissions reduction in the near to medium term.

- 5. **Deployable (high):** Widely deployable strategies that have proven to reduce emissions, have low cost impacts and are ready to scale quickly (e.g. do not have supply constraints). They have the largest near-term potential for reductions.

Each of these five adoption rates follows the following logistic function formula using different growth rates ( $k$ ) and timelines for adoption (here noted by  $t_0$ ). This “S-Curve” is often used to model typical technology adoption, beginning slowly with innovators and then early adopters, accelerating with early and late majority adoption, and slowing growth as it reaches the late adopters (“laggards”):

$$f(t) = \frac{L}{1 + e^{-k(t-t_0)}}$$

Where:

- $t$  is years,
- $L$  is the theoretical maximum of the logistic function,
- $e$  represents the exponential function,
- $k$  is the growth rate constant (controls the steepness of the curve),
- $t_0$  is the halfway point of the curve (the point of maximum growth, in this case representing adoption of a strategy by 50% of the market), and
- $f(t)$  is the cumulative adoption rate.

All adoption rates begin at zero (no adoption) in year one in our model, as the model focuses on additional adoption beyond today.

## C.4 Data Collection: Policies

Our review included policies from five “sectors”: industrial policies, building policies, private sector, urban planning, and waste and circularity. These sector distinctions are helpful only in grouping policies by which stakeholders are most *directly* involved in complying with and managing a policy, as many policies have a broad range of impacts across a range of stakeholders. For example, industrial policies most directly impact manufacturers and their suppliers, setting direct requirements or incentives for facilities or products. In contrast, building policies directly impact newly constructed buildings (including private or public sector projects) by setting requirements or incentives at the building level, which may ultimately require changes from industrial facilities upstream but also allow for demand reduction strategies at the building-level.

Within these broader policy sectors, CLF categorized policies into five categories: standards, R&D/demonstration projects and grants, financing and incentives, clean procurement, and carbon pricing, with the bulk of policies fitting within the category of standards. CLF adapted these categories primarily from ACEEE’s *Enabling Industrial Decarbonization: A policy guidebook for U.S. State Policy Guidebook* (2022), which defines them as follows:

- **Standards:** Standards specify levels of performance that a project, business, or piece of equipment must achieve, and can be technology- or performance-based in design. Technology-based standards require the use of a specific technology to achieve emissions goals, whereas performance-based standards require achievement of a specific benchmark without prescribing technology to allow for innovation and flexibility. Standards also include regulations at the building level, such as building and zoning codes.
- **Financing and incentives:** Incentives come in a variety of forms, such as fiscal (e.g., tax credits, tax exemptions, subsidies), competitive financing (e.g., low-interest loans, loan guarantees, low-cost insurance), or competitive grants. These can help industry defray the upfront cost of investment in a new technology. Urban planning policies also include a suite of potential incentives often used to drive green building practices, such as density bonuses or expedited permitting.

- **Research, Development, and Demonstration (RD&D):** RD&D covers government incentives and support for developing and commercially scaling emerging industrial decarbonization solutions. Policies that support industrial decarbonization RD&D help drive down the cost of new technologies and complement other policies that scale demand for lower emissions facilities and products. While universities and corporations largely conduct early-stage research and development (R&D), government RD&D policies accelerate investment and the technology maturation and reduce market and financial barriers that the private sector will not overcome on its own.
- **Carbon pricing:** Carbon pricing policies, such as cap-and-trade programs and carbon taxes, establish a direct or indirect price on units of GHG emissions (dollars per ton) in a defined market. These policies offer a technology-neutral approach for driving down emissions and a cost-effective option for the diverse industrial sector. Carbon pricing programs can also generate revenue that state governments may redeploy toward other critical policy levers, such as industrial decarbonization RD&D, incentives, and technical assistance, and targeting investments towards disadvantaged communities.
- **Clean procurement:** Procurement (by public and private entities) offers near- to mid-term opportunities to drive demand and create new markets for low-carbon industrial products by rewarding industry’s investment in emissions reduction strategies and providing a price signal for manufacturers to preferentially produce lower-carbon materials. Procurement policies may also seed a viable market for future participation from private actors as well.

## Mapping policies to strategies

CLF mapped each policy and strategy to each other using several key steps:

1. *Can ‘X’ policy result in adoption of ‘X’ strategy?* Primarily, policies were mapped to strategies through the use of the eight categories described in Table 2 in section 4.1.1 (energy efficiency, electrification, etc.). For example, “Facility energy efficiency standards, targets, and mandatory audits” was mapped to strategies marked as Energy Efficiency.
2. **R&D/Demonstration:** Does this policy reach R&D and Demonstration strategies, or does it primarily encourage adoption of strategies that are already deployable (or vice versa)? Using the adoption rate category described in section 4.1.2, we excluded or included strategies from mapping based on their deployability. For example, “pilot projects” were mapped to R&D and Demonstration strategies, whereas embodied carbon requirements for materials in codes excluded R&D and Demonstration strategies, as these policies typically set very high limits that only exclude the most carbon intensive practices.
3. **Application:** Some policies apply only to building (not infrastructure) or vice versa. We excluded non-building related strategies for asphalt, concrete, steel, and sand and gravel from building and urban planning policies, and building materials from infrastructure-focused policies.
4. **Material-specific policies:** A small number of policies applied only to specific materials. For example, we only mapped book and claim systems to concrete and steel strategies, as we only found proposals to cover these materials in research.

Last, we applied a very simple weighting system to reflect the reality that different policy levers have radically different reach in terms of what percentage of the market is required to comply. Policies that influence all public and private sector construction received a “1”, the highest possible uptake weighting, as these requirements can theoretically impact the entire industrial and building sector in the US. For building materials, policies that impact only private sector construction received a weighting of 0.75 and policies that impact only public sector projects (e.g. green public procurement) received a 0.25 weighting. This reflects the fact that approximately 75% of emissions from construction of new buildings in the US are for private sector projects, and the other 25% are for public projects (Waldman 2024). This ratio is reversed for materials calculated using approach 1 (see section 2.2) as these primarily include infrastructure projects which are heavily public sector driven. Last, incentives received the lowest weighting (0.25) as these are non-mandatory and depend heavily on the value of the incentive as to their uptake.

# Appendix D: Description of Scenarios

This section provides a summary of the assumptions and results used in each scenario. Each scenario explores a different emissions reduction pathway for the building and industrial sectors over the next 25 years. **All six scenarios rely on the full suite of strategies included in our study, even in scenarios where a portion of strategies are a larger focus.**

Up to three aspects of the model are changed in each scenario. Table D1 and Figure D1 summarizes the assumptions across these six scenarios for the following three factors:

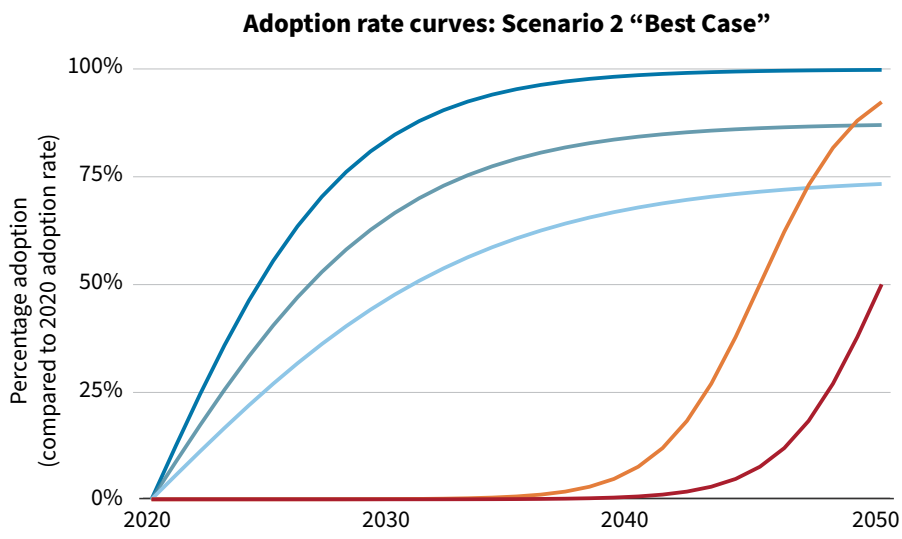
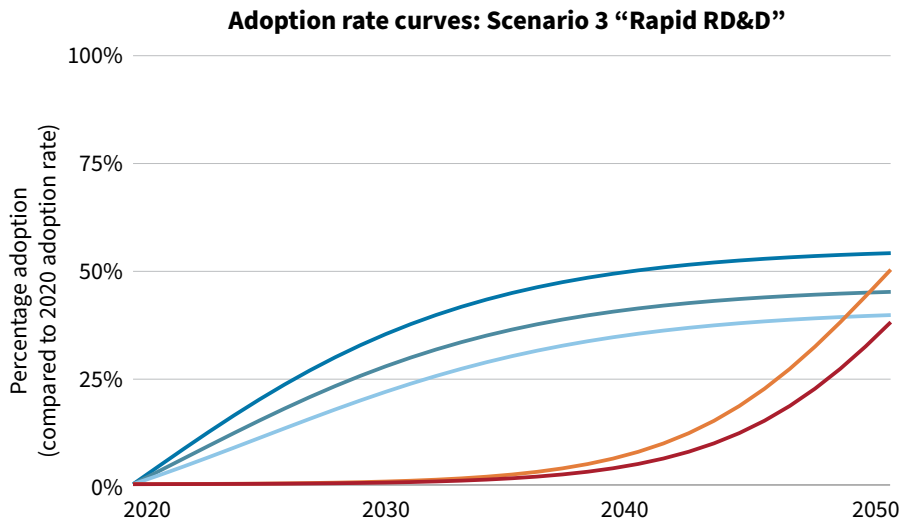
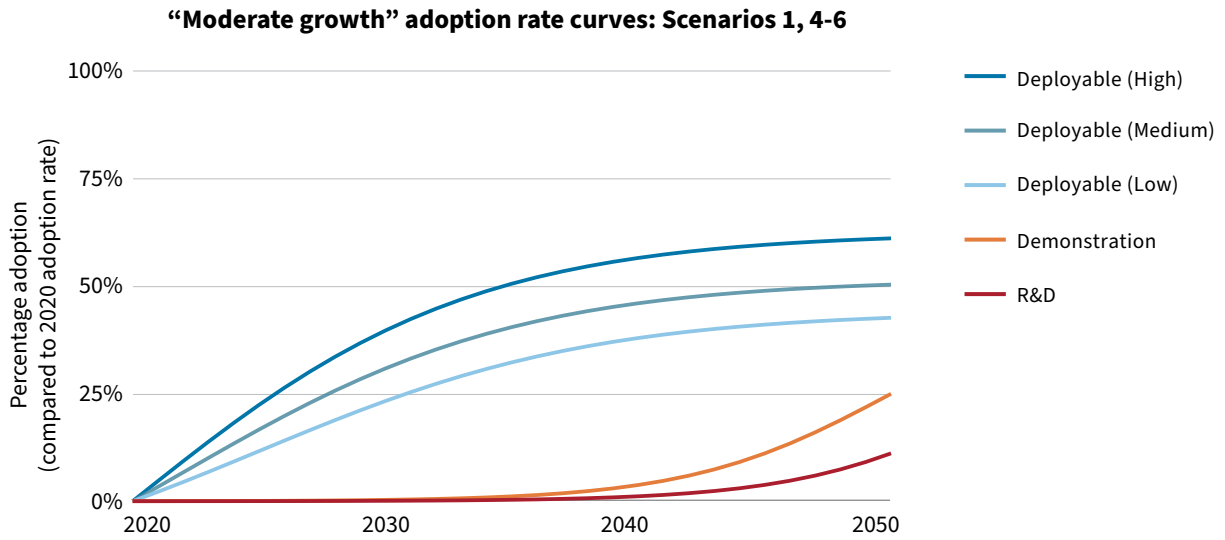
- 1. Reduction potential range used:** What range of emissions reduction potentials (within the range defined in Figure 12) was used in this scenario?
- 2. Level of Adoption:** What assumptions were made about the level of adoption for each of the five adoption categories in this scenario?
- 3. Deployability assumptions:** Were any of the assumptions about deployability adjusted for a subset of “focus” strategies?

Changes in assumptions were based on either adoption rate category or strategy group:

- **Adoption rate category** (see section 4.1.2 for descriptions)
  - Research and Development (R&D)
  - Demonstration
  - Deployable (low)
  - Deployable (medium)
  - Deployable (high)
- **Strategy category**
  - Energy (E)
    - Energy efficiency (EE)
    - Electrification (EL)
    - Low carbon electricity (RE)
    - Low carbon fuels (LCF)
  - Carbon capture (CC)
  - Material substitution (MS)
    - Low carbon feedstocks (LCFS)
    - Recycled feedstocks (LCFS-C)
    - Material/assembly substitution (MS-B)
  - Material circularity
    - Circularity (MC)
  - Material efficient design (ME)

**Table D1. Summary of modeling assumptions for six scenarios.** “Cited range” refers to the range of emissions reduction potential from benchmark levels identified in reviewed academic literature and industry roadmaps

Scenario #	Impacted strategies	Reduction potential range	Level of adoption	Deployability
<b>1 Moderate Deployment</b>	All strategies	Conservative mid-range (33% in 2020 to 50% in 2050) of the cited range	Moderate growth in adoption	No changes in deployability assumptions.
<b>2 Best Case</b>	All strategies	Maximum reduction potential from cited range	Aggressive growth in adoption	No changes in deployability assumptions.
<b>3 Rapid RD&amp;D</b>	R&D and Demonstration strategies	Maximum reduction potential from cited range	Aggressive growth in adoption	No changes in deployability assumptions.
	Remaining strategies ( <i>deployable low-med-high</i> )	Conservative mid-range (33% in 2020 to 50% in 2050) of the cited range	Moderate growth in adoption	
<b>4 Focus on Design Innovation</b>	Material efficiency design (ME) and substitution (LCFS, MS-B) strategies	Maximum reduction potential from cited range	Moderate growth in adoption	Upgraded one level in adoption rate.  <i>Example - A “deployable - low” strategy would be “upgraded” to “deployable-med”</i>
	Remaining strategies ( <i>E, CC, LCFS-C, MC</i> )	Conservative mid-range (33% in 2020 to 50% in 2050) of the cited range		No changes in deployability assumptions.
<b>5 Focus on Energy</b>	Energy strategies (EE, EL, RE, and LCF)	Maximum reduction potential from cited range	Moderate growth in adoption	Upgraded one level in adoption rate.
	Remaining strategies ( <i>CC, MS, MC, ME</i> )	Conservative mid-range (33% in 2020 to 50% in 2050) of the cited range		No changes in deployability assumptions.
<b>6 Focus on Circularity</b>	Circularity and recycled feedstocks (LCFS-C) strategies	Maximum reduction potential from cited range	Moderate growth in adoption	Upgraded one level in adoption rate.
	Remaining strategies ( <i>E, CC, MS, ME</i> )	Conservative mid-range (33% in 2020 to 50% in 2050) of the cited range		No changes in deployability assumptions.



**Figure D1. Adoption rate curves used in Scenario modeling.** Scenario 1 and 4-6 use “moderate growth” adoption rate curves. Scenario 2 “Best Case” and 3 “Rapid RD&D” have unique adoption rate curves.