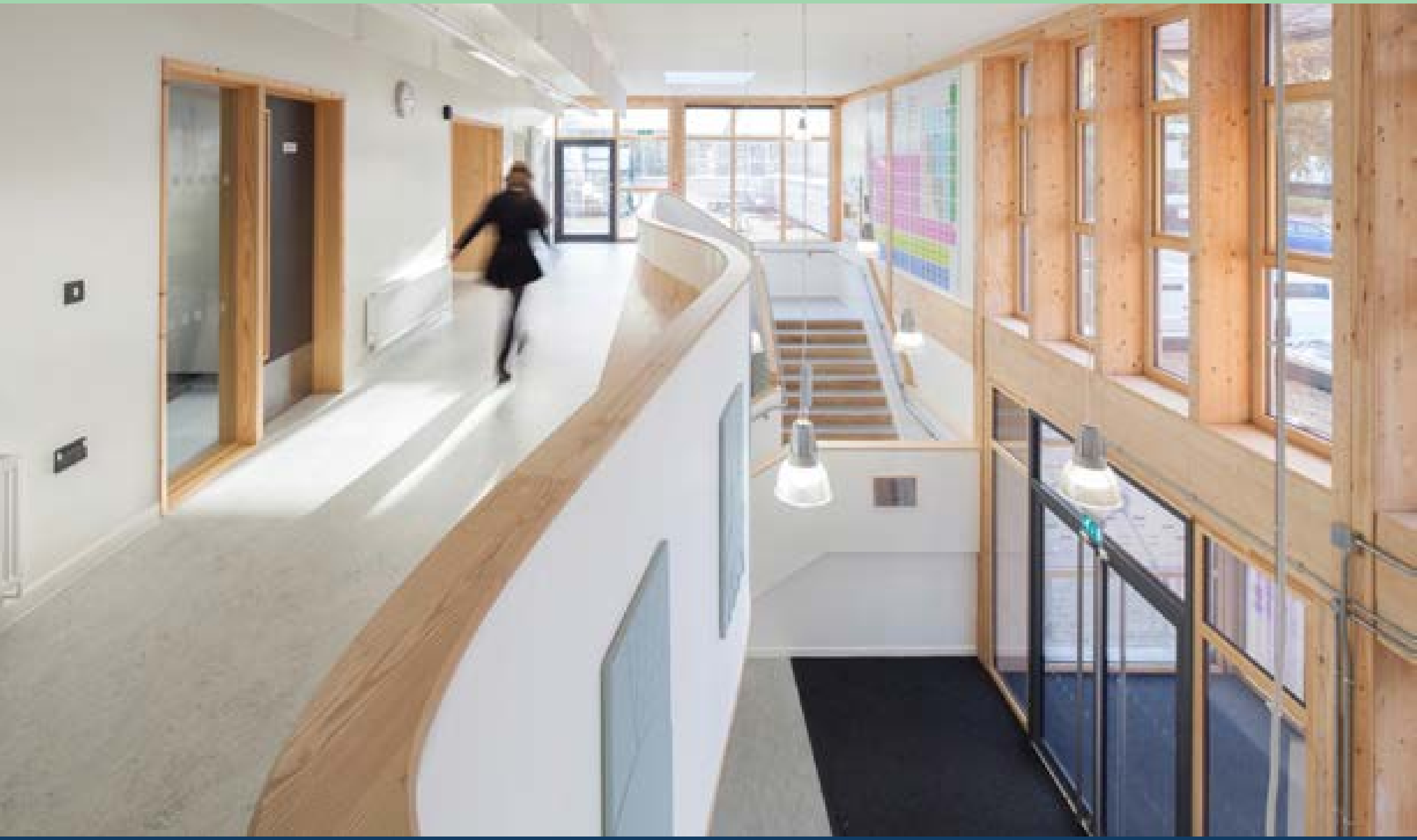
Driving Action on Embodied Carbon in Buildings

Answers to current questions about embodied carbon and key actions to accelerate the decarbonization of building construction



Report / September 2023

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Hayesfield School Nucleus Building, prefabricated straw bale cladding system.

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About USGBC

The U.S. Green Building Council (USGBC) is committed to a prosperous and sustainable future through cost-efficient and energy-saving green buildings. USGBC works toward its mission of market transformation through its LEED green building program, robust educational offerings, an international network of local community leaders, the annual Greenbuild International Conference and Expo, the Center for Green Schools and advocacy in support of public policy that encourages and enables green buildings and communities. For more information, visit usgbc.org and connect on X (formerly Twitter), Instagram, Facebook and LinkedIn.

About RMI

RMI is an independent nonprofit, founded in 1982 as Rocky Mountain Institute, that transforms global energy systems through market-driven solutions to align with a 1.5°C future and secure a clean, prosperous, zero-carbon future for all. We work in the world's most critical geographies and engage businesses, policymakers, communities, and NGOs to identify and scale energy system interventions that will cut greenhouse gas emissions at least 50 percent by 2030. RMI has offices in Basalt and Boulder, Colorado; New York City; Oakland, California; Washington, D.C.; and Beijing.

Contents

Executive Summary

This report aims to answer some of today's most asked questions about embodied carbon and highlights key actions based on what we know today to meaningfully decarbonize the building construction industry.

Over the past decade, embodied carbon emerged as a critical factor to consider in the planning and construction of buildings. Embodied carbon represents the millions of tons of Earth-warming carbon emissions released during the life cycle of building products. A product's full life cycle includes raw material extraction, refining and manufacturing, transport, construction, and final disposal.

Such products are widespread. They include the concrete used to form foundations, the steel in framing, the insulation in walls and ceilings, even glass, paint, and other interior finishes: they all contribute to a buildings' embodied carbon emissions and, ultimately, to the climate crisis.

It is time for everyone to get on board to reduce embodied carbon.

Simply meeting the energy needs to run — heat, cool, light, and operate — the world's building stock accounts for about 30 percent of annual energy-related emissions, **according to the IEA**. Yet that figure doesn't capture the full climate footprint of buildings. Manufacturing, transporting, installing, maintaining and, finally, disposing of the steel, cement, cladding, coatings, and other diverse materials needed to build new construction adds to the sector's toll. Embodied carbon alone accounts for 11 percent of global annual energy-related emissions, **the World Green Building Council estimates**.

Given the scale of the sector's climate impact, it is imperative that owners, designers, builders, manufacturers, and policymakers lead the market by prioritizing this issue. As our understanding of embodied carbon has steadily increased, so has the urgency of reducing all carbon emissions.

Now is the time to take decisive action using the best knowledge we have and, in parallel, to accelerate the sector's learning curve and achieve rapid market transformation. A major challenge that hinders faster progress is "analysis paralysis." Stakeholders need access to easily understandable scientific takeaways that cut through the noise and provide guidance on how to take immediate action in the building industry. On the other hand, we also must resist the urge to find a "silver bullet" by relying on a single material or design strategy to cut embodied carbon. We must take a critical eye to the science and find solutions that work, no matter where your leverage lies: in policy, on projects, or in product manufacturing. This report is our effort to answer 11 critical questions about embodied carbon and summarize them into clear and actionable takeaways for everyone.

Building decarbonization requires collective industry action: Forerunners are already demonstrating what is possible, but we need more leaders to push the boundaries to scale up swift and deep decarbonization. The industry is poised to make this leap, and there are substantial emissions reductions available today that are well within reach. Tools and guidance are widely available, low-hanging fruit have been identified, and new policies are creating greater market certainty. It is time for everyone to get on board to reduce embodied carbon.

11 critical questions addressed in this report

1	How big an opportunity is embodied carbon?	Millions of tons of emissions can be avoided with known strategies today! Measure and implement strategies for easy reductions.
2	Which should we priortize: operational or embodied emissions?	We can and must reduce both without pitting one against the other. Examine both to find the win-win scenarios for maximum reductions.
3	What should we prioritize to reduce embodied carbon today?	Reuse more, dematerialize, and substitute with low-embodied-carbon materials. Use life-cycle assessments (LCA) to find reduction strategies.
4	Do low-embodied-carbon materials cost more?	Opportunities exist today with little to no cost or schedule impact. Request costs for low-embodied-carbon products early and balance cost and carbon.
5	What should I measure and how?	Choose an appropriate LCA type. Decide on a scope of analysis for your calculations – you can start small!
6	Is the data good enough?	We know enough today to make meaningful reductions. Don't wait, act now! Support standardization efforts and filling the gaps.
7	Is there enough data on interiors and furnishings?	The data gap is big. The impact could be big and is worth paying attention to. Include interior elements in LCA and support their data collection.
8	What is the future of concrete and steel?	They will remain important in construction and are decarbonizing. Accelerate decarbonization with transition to renewables and low-carbon alternatives uptake.
9	Can wood products benefit the climate?	A net increase in regional forest carbon storage is good for the climate. Ask for more disclosure in wood products (e.g., source forest).
10	Is carbon storage in buildings really possible?	Buildings could become a carbon storage solution. Encourage the development of bio-based materials, carbon storing concrete, and others, by using them.
11	What does the policy landscape look like for embodied carbon?	Low-embodied-carbon material legislation exists, and whole building limits are coming. Familiarize with building LCA and material procurement regulations.

Introduction

Why USGBC and RMI Decided to Collaborate

In the past decade, the scale and importance of embodied carbon has come into the spotlight, bringing fresh scrutiny to the topic as a critical factor to consider in the planning and construction of buildings. As our understanding of embodied carbon rapidly increases, so does the urgency of reducing emissions to avoid the worst impacts of climate change. Although industry literacy about the existence of embodied carbon is becoming more commonplace, there remain open questions that can prevent action. In this decisive decade, there is no time to hesitate due to perceived roadblocks. Instead, the industry must move quickly to decarbonize, using the best knowledge we have today.

We must accelerate our position on this curve to meet climate thresholds

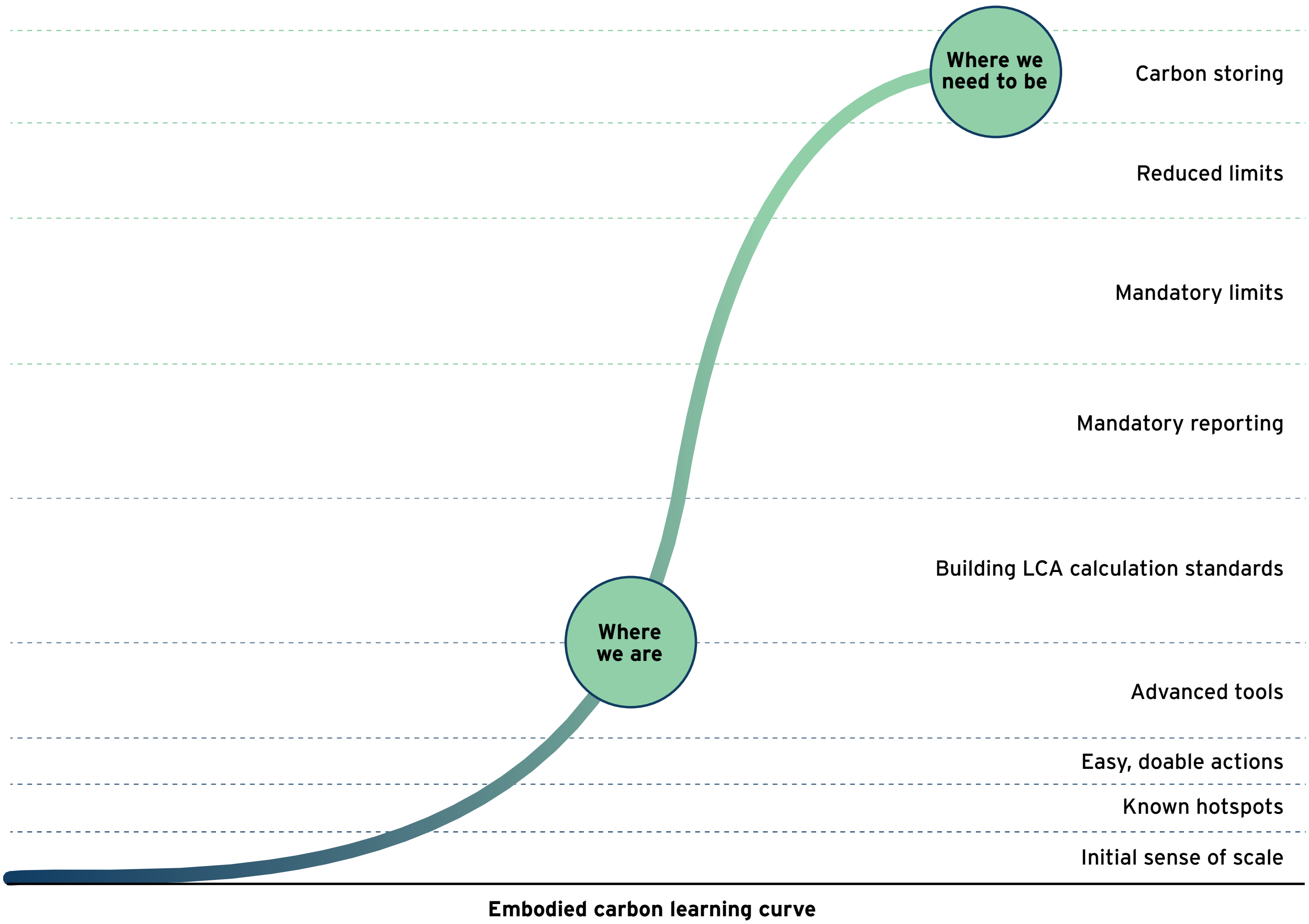

Exhibit 1 | RMI Graphic. Source: RMI analysis

Much Has Been Done, But We Are Still Early on the Learning Curve

In 2013, LEED v4 was approved. This new version of the LEED rating systems introduced credits that addressed embodied carbon with requirements for whole-building life-cycle assessments (WBCLAs) and disclosure of the environmental impact of products through environmental product declarations (EPDs). In 2017, a pioneering benchmark study of buildings in North America conducted by the Carbon Leadership Forum (CLF) demonstrated the potential range of a building's embodied carbon footprint.[1] In 2019, a report by the World Green Building Council laid out a framework for how the construction sector can tackle embodied carbon.[2] The American Institute of Architects' (AIA's) 2030 Commitment, based on Architecture 2030's framework, added the reporting of embodied carbon in its Design Data Exchange in 2020.

Policymakers, regulators, and investors are responding with incentives and policy signals about future adoption of mandatory requirements. Numerous embodied carbon roadmaps, guidance documents, and frameworks have since been published identifying structure, enclosure, concrete, and steel as major sources of embodied carbon in buildings.[i] However, there remain important gaps to be filled, including embodied carbon data on services (mechanical, electrical, and plumbing [MEP] equipment), fittings, furnishings, and equipment (FF&E), and ultra-low-embodied carbon biobased materials. Additionally, standardization is needed to improve consistency and comparability of embodied carbon assessments and narrow the residual variation in background data and underlying methodologies.

Forty years ago, building experts were only just beginning to learn how to improve energy efficiency. Easy gains were plentiful, and energy reductions of 20% to 30% were common. But back then, the tougher challenge of achieving net-zero energy consumption for big buildings was all but impossible. Gains made since that time mean that carbon-neutral building operations for all are now on the horizon. The building industry must achieve the same huge gains with embodied carbon — only this time, we don't have 40 years to figure it out!

Despite Being Early on the Learning Curve, Projects Can Make Significant Reductions Now

Several publications have shared case studies and specific strategies for reducing embodied carbon. An RMI report showed that reductions of up-front embodied carbon between 19% and 46% are possible for little to no cost on common types of new buildings.[3] One feature of being early on the learning curve is that there is a lot of low-hanging fruit to be garnered to reduce embodied carbon emissions. Numerous built examples have demonstrated how this can be done. To approach zero emissions by 2050, however, we must immediately pick the low-hanging fruit everywhere possible and simultaneously accelerate the embodied carbon learning curve to advance our knowledge beyond the easy reductions, uncover further decarbonization strategies, and turn buildings into climate solutions with carbon-storing materials.

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i Publications are from organizations including the Institution Engineers (iStructE), International Living Future Institute, Zero Emissions Building Exchange, RMI, Structural Engineering Institute, New Buildings Institute, Canadian Green Building Council, the Green Building Council Australia, City of Vancouver, World Business Council for Sustainable Development, and the Irish Green Building Council.

Chris Magwood photo

How to Accelerate Adoption

Successful decarbonization requires collective industry action from multiple players. We must expand industry knowledge of current best practices for low-embodied carbon buildings through programs, initiatives, and certifications. Manufacturers must publish more EPDs and develop low-embodied carbon building products. Leading designers must demonstrate effective low-embodied carbon building design strategies and share best practices. Developers must consider lower-carbon options, including adaptive reuse. Governments must prepare the way for embodied carbon regulation by investing in low-embodied-carbon public buildings and supporting research and market development of low-embodied carbon building products and practices, including incentivizing the circular economy through building reuse and deconstruction ordinances. The whole industry must collaborate to continually improve embodied carbon data, develop standards, fill gaps and unify tools and databases.

This Work

The first wave of embodied carbon research established the imperative for action and helped create initial benchmarks, identified key data gaps, and led to the emergence of important tools. This paper builds on the work that has come before and is part of the next wave in which action on embodied carbon becomes an industry norm.

By providing a synthesis of the latest understandings of embodied carbon, in this report we strive to answer key recurring questions that may be blocking much-needed action to reduce embodied emissions. The key takeaways and actions suggested in this report can help pave a path for designers, builders, policymakers, and green building certification programs like LEED to actively transform our building practices to become climate positive as quickly and intelligently as possible.

But first, a roadmap of acronyms and terms

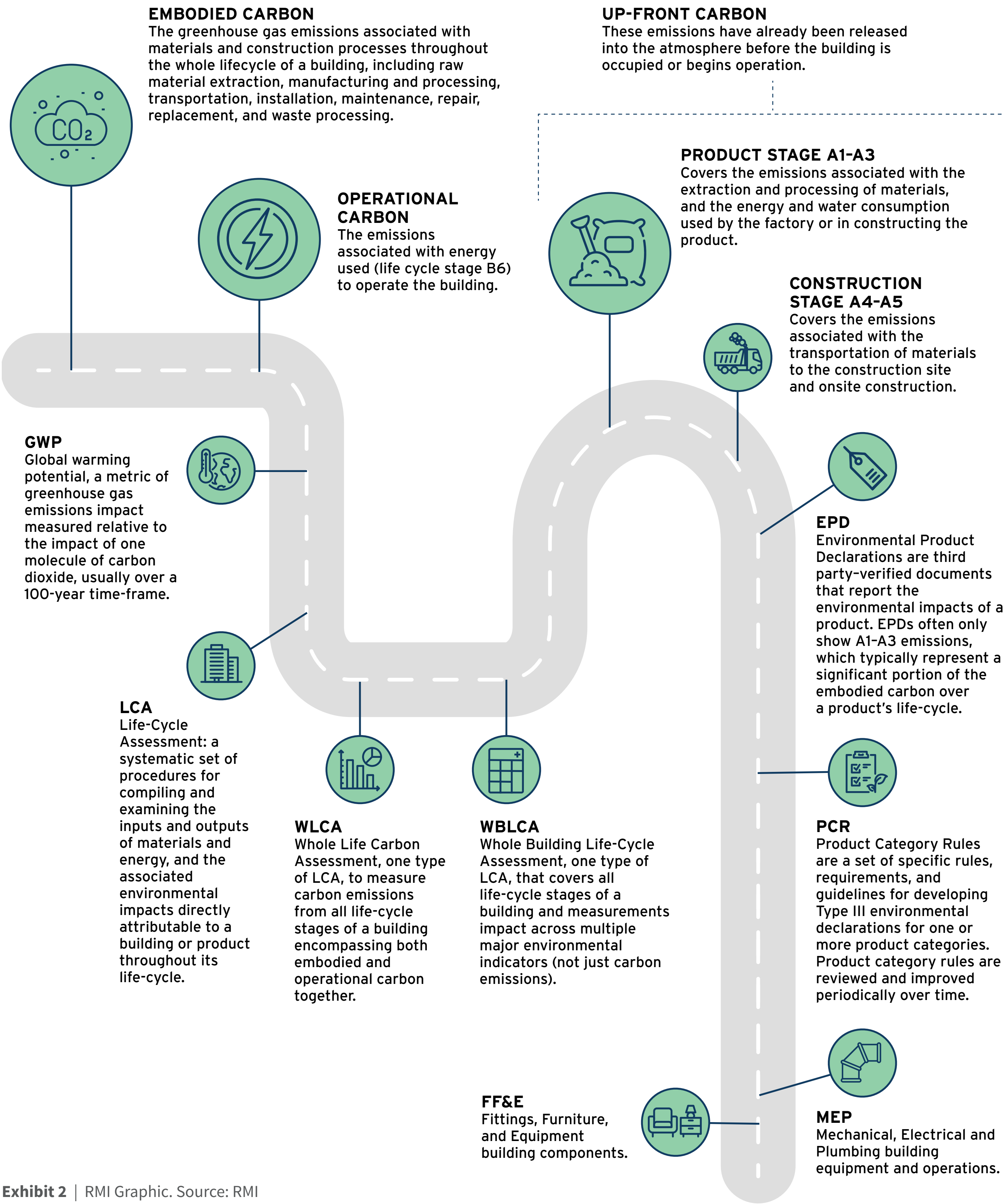


Exhibit 2 | RMI Graphic. Source: RMI

Endnotes

1 Kate Simonen et al., *Embodied Carbon Benchmark Study: LCA for Low Carbon Construction*, 2017, **http://hdl.handle.net/1773/38017**.

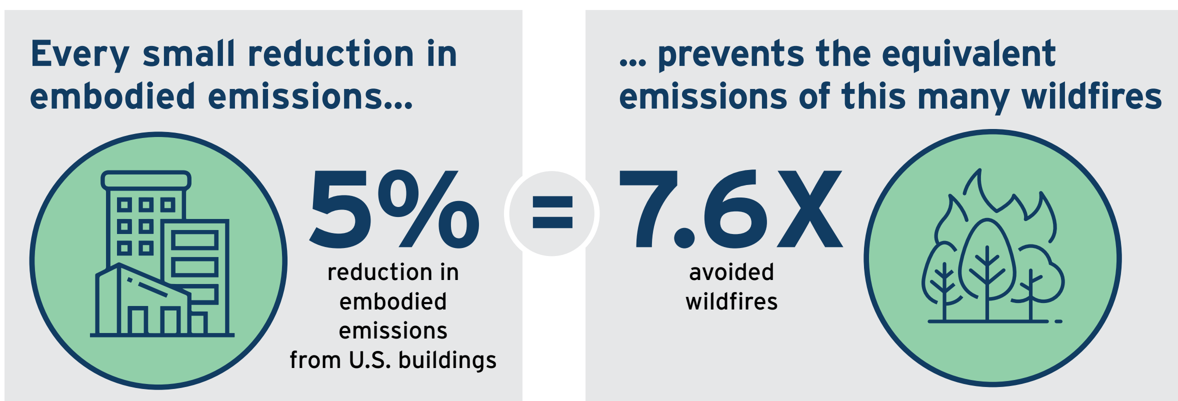
2 World Green Building Council, *Bringing Embodied Carbon Upfront*, 2019, **https://worldgbc.org/advancing-net-zero/embodied-carbon/**.

3 Matt Jungclaus et al., *Reducing Embodied Carbon in Buildings: Low-Cost, High-Value Opportunities*, RMI, 2021, **http://www.rmi.org/insight/reducing-embodied-carbon-in-buildings**.

How Big an Opportunity Is Embodied Carbon?

KEY TAKEAWAYS

- Embodied carbon emissions in buildings are a burst of emissions that accompany all aspects of construction activity (manufacturing, transportation, construction) and are a large contributor to national emissions (as much as 6% of US emissions and comparable to the emissions of all of California).
- We already know how to reduce embodied carbon emissions over 40% on some projects at little to no cost with logical and intuitive strategies readily available today.
- The building industry can set ambitious and reasonable targets to reach zero emissions in the coming decades, and emerge as leaders in climate change mitigation.



Note: Assuming average CO_2 emissions per wildfire based on the top 20 wildfires in 2021 in California, excluding Dixie.
Exhibit 1 | RMI Graphic. Source: California Air Resources Board, **https://ww2.arb.ca.gov/wildfire-emissions**

A Huge Opportunity

Up-front embodied carbon emissions from building construction in the United States is estimated at up to 370 million tons of CO_2e annually, or about 6% of total US GHG emissions per year.[1] This long-invisible source of emissions is large — comparable to all of California's current annual emissions.[2] Embodied carbon from less studied elements like mechanical equipment and tenant improvements would likely increase this percentage. At these levels, even small reductions in embodied emissions could prevent millions of tons of CO_2 emissions each year.

There's good news — sizable reductions are possible today. A 2021 study showed reductions of up-front embodied carbon between 19% and 46% are possible for **little to no cost** on common types of new buildings.[3] These reductions can be achieved with design and material choices available today by leveraging material-efficient design, dematerialization, and readily available low-embodied-carbon building materials.

Transitions to clean, renewable energy will begin to accelerate the decarbonization of high-emitting material manufacturing sectors, and a wide range of emerging technologies show promise for dramatic reductions in emissions intensity. The building industry has a unique opportunity to become a key player in global carbon dioxide removal efforts using incumbent and developing carbon-storing materials.

Although much of this report covers information and opportunities associated with the design and construction of new buildings, managing the industry's embodied carbon emissions requires us to examine the increasing importance of energy retrofits and tenant improvements with equal attention and vigor. Opportunities for reductions can be most dramatic when we consider the necessity of building something new in the first place. The reuse of existing buildings and materials frequently results in embodied carbon reductions of 75% compared with building new.[4]

The building industry has real potential to emerge as a leader in climate change mitigation by driving down embodied carbon of buildings. Doing so will take a concerted effort on behalf of everyone in the sector, from investors and owners to designers and builders. This publication is an attempt to rally this effort and provide an on-ramp for those wishing to take very important first steps toward meaningful action on the embodied carbon of building materials.

The time for action is now. Governments and investors are beginning to take notice of embodied carbon, with incentives, regulations, and corporate reporting requirements focused on this topic. Green building codes and certification programs are moving to catalyze action on embodied carbon. We can look to leading programs such as LEED to understand best practices in reducing embodied carbon and prioritize reductions today.

Read on to understand how.

ACTIONS

- Encourage all project team members to learn about embodied carbon and the main strategies for addressing it.
- Encourage all projects to accrue readily achievable reductions now, and support leading projects to go further.
- Support energy-efficient manufacturing, material-efficient design, and the uptake of low-embodied-carbon materials.
- Set embodied carbon reduction goals at the building level and at the product level in line with science-based climate goals, and engage with decarbonization programs and initiatives for guidance.

Endnotes

1 Larry Strain, *Time Value of Carbon*, 2017, **https://www.siegelstrain.com/wp-content/uploads/2017/09/Time-Value-of-Carbon-170530.pdf**.

2 California Air Resources Board, "Current California GHG Emissions Inventory Data," accessed August 9, 2023, **https://ww2.arb.ca.gov/ghg-inventory-data.**

3 Matt Jungclaus et al., *Reducing Embodied Carbon in Buildings: Low-Cost, High-Value Opportunities*, RMI, 2021, **http://www.rmi.org/insight/reducing-embodied-carbon-in-buildings**.

4 Larry Strain, "10 Steps to Reducing Embodied Carbon," accessed August 9, 2023, **https://www.aia.org/articles/70446-ten-steps-to-reducing-embodied-carbon**.

Which Should We Prioritize: Operational or Embodied Emissions?

KEY TAKEAWAYS

- We can and must reduce both operational and embodied carbon emissions in the next decades to avoid the worst effects of climate change.
- It is possible to achieve excellent climate performance in both embodied and operational emissions without pitting one against the other.
- Most embodied carbon is emitted up front during the manufacturing and construction of products and buildings and has an outsize climate impact in the first decade of a new building.

Tackling both operational and embodied carbon emissions is essential

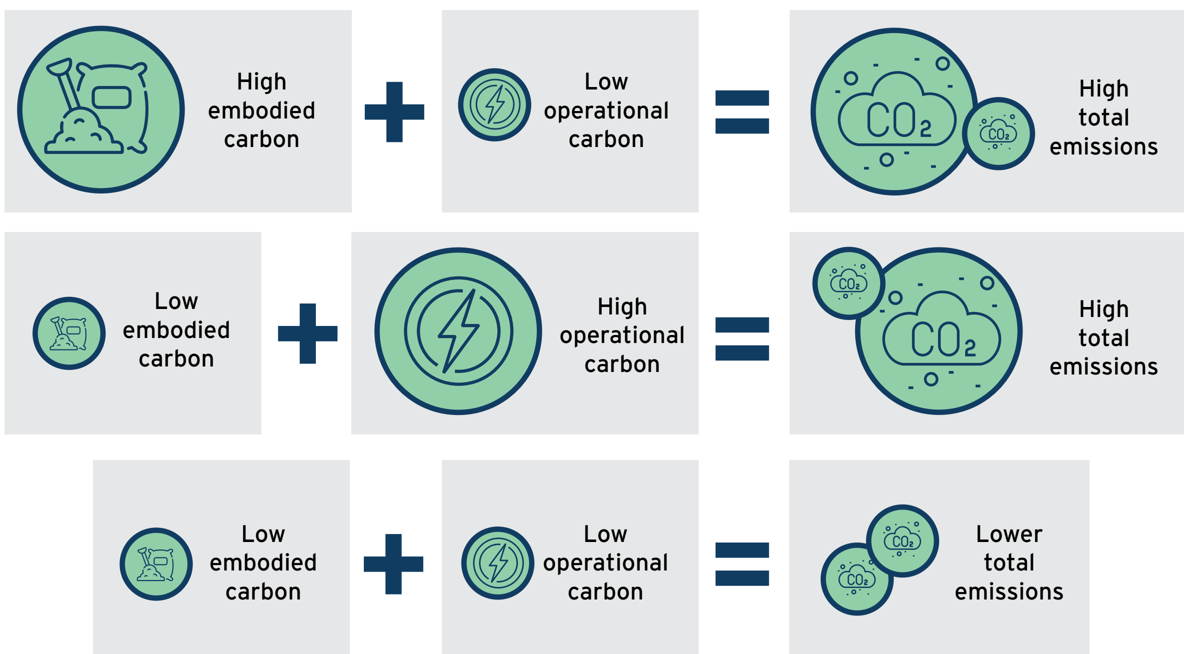


Exhibit 1 | RMI Graphic. Source: RMI analysis

We Can and Must Prioritize Both

For the past 45-50 years — since the energy crisis of the 1970s — sustainability efforts have largely focused on improving building energy efficiency, which has a direct result on both energy consumption and carbon emissions. That makes sense because building operational emissions constitute approximately 30%

of annual US GHG emissions, which amounts to approximately 1.9 billion tons of CO_2e annually for the ongoing operation of buildings.[1] Notable progress has been made on improving the energy efficiency of new construction through energy codes and programs like LEED, Energy Star, and standards like ASHRAE 90.1.[2] Progress is now being made on intentionally reducing carbon emissions from building operations as the electrical grid decarbonizes and on-site burning of fossil fuels is discouraged. Through policy and a lot of hard work from within the industry, a downward trajectory toward zero emissions from building operations is underway.

Unfortunately, operational reduction efforts alone will not be enough to meet climate targets. By mid-century, we must achieve zero emissions from ALL aspects of buildings, including embodied carbon. As we become more successful at addressing operational emissions, embodied carbon will become an increasing piece of a shrinking pie. Moreover, most embodied carbon is emitted up front during the manufacturing and construction of products and buildings, creating a large pulse of emissions with increased climate impact due to its immediate residency in the atmosphere.

Meeting global climate targets requires that today's buildings are designed for both low embodied and operating emissions.[3] This will require the advancement of action on embodied carbon comparable to the level of ambition in current and developing energy efficiency regulations, including the advancement of product manufacturing and design-team education. However, serious efforts on energy efficiency took decades to develop and become common practice, and we do not have the same time window to catch up on embodied carbon.

Fortunately, we have an excellent roadmap for action that has been built over the past decades addressing energy efficiency. Lessons learned from the overlapping impacts of education, incentives, voluntary standards and labels like LEED, and regulations point in an effective direction for rapidly bringing embodied carbon to the same level of attention and ambitious reductions as operational carbon.

Along this path, we must avoid seeing embodied and operational efforts as competing with one another. Rather, we can work to recognize the significance of both and enable coordinated and effective reductions in lock-step.

The good news is that win-win scenarios are very possible and can be mutually reinforcing. See the case studies on the next page demonstrating what win-win scenarios can look like.[4]

ACTIONS

- Include experts on both operational and embodied carbon on all project teams.
- Iterate on both embodied and operational carbon scenarios to understand how to incorporate the win-win scenarios (e.g., using insulation with low global warming potential [GWP]).
- Look to emerging standards such as ASHRAE/ICC 240 and programs such as LEED on how to better address embodied and operational carbon to maximize holistic emissions reductions.
- Actively support the advancement of impactful embodied carbon regulation toward the level of ambition current in energy efficiency regulations, energy efficient product manufacturing, and design team knowledge of energy conservation and efficiency.

WIN-WIN CASE STUDIES

Robert Benson photo

New House Residence Hall Renovation (MIT)

- Renovation of a 1974 residence hall
- Reuse and restoration of structure and envelope
- Building envelope upgrades (e.g., added insulation, new energy-efficient windows)
- Upgraded heating, ventilation, and air conditioning (HVAC) system to four-pipe hydronic system
- Wider temperature range accepted in corridor spaces, reducing loads on new systems
- 13% of the embodied carbon footprint of a hypothetical replacement building

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Vali Homes photo

Urban Infill Homes: The Mews

- Four zero-lot-line single-family homes
- Low-embodied-carbon materials include wood framing, wool and cellulose cavity insulation, wood fiberboard exterior insulation, and lime plaster finish
- Average up-front material embodied carbon intensity; 59 kg CO_2e/m^2 conditioned floor area, 68% less than average
- Built to Passive House standards
- Final blower door test result of 0.3 air changes per hour at 50 pascals
- 70% reduction of operational GHG emissions compared with code-built home

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Jeremy Bittermann / JBSA photo

Meyer Memorial Trust HQ

- Office building
- LEED Platinum certified
- Partnered with Sustainable Northwest for sustainable, regional wood sourcing criteria
- Uses 30% less energy over an Oregon and ASHRAE code building
- eGauge energy metering system displaying the building's energy use and solar electric production in real time
- 53-kilowatt solar array

Endnotes

1 US EPA, “Sources of Greenhouse Gas Emissions,” accessed August 9, 2023, **https://www.epa.gov/ghgemissions/sources-greenhouse-gas-emissions#commercial-and-residential.**

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What Should We Prioritize to Reduce Embodied Carbon Today?

KEY TAKEAWAYS

- A hierarchy of embodied carbon design interventions can be applied to all building projects.
- Positive interventions including better design and low-embodied-carbon materials can be stacked to achieve deeper reductions than pursuing just one.
- Using less of any material reduces embodied emissions; this can be achieved by building only what is necessary, building and material reuse, right-sizing buildings, and optimizing material use.
- Embodied carbon analysis can identify the hot spots that will most benefit from active reductions.
- The majority of a new building's whole life-cycle embodied emissions occur up front in the structure and enclosure, which emerge as the most logical stages and components for initial focus.

Top design interventions for embodied carbon reduction

1	Reuse	Reuse an entire building and/or components of a deconstructed building. Limit the scope of renovations to what is needed. Prioritize salvaged materials over new production.
2	Right-size	Optimize building size by using space more intensively and minimizing excess space. Design with better scheduling or dual-use spaces to decrease the building size.
3	Dematerialize	Expose structure instead of applying finishes. Optimize structural system to minimize excess material. Consider reducing overdesign by evaluating conservative load assumptions.
4	Carbon storing materials	Carbon storing materials can speed transition to zero embodied emissions. Building projects can ask for responsibly produced biobased and concrete materials that can store carbon durably.
5	Product substitutions	Make substitutions for the highest impact materials informed by a whole-building integrated approach or by low-material GWP limits when you cannot do an LCA.
6	Sourcing	Ensure products are coming from legal and sustainable or regenerative sources. Prioritize local materials when data reveals they have reduced impacts associated with transport.
7	Circular design	Reduce the impact over the building's life cycle and enable low-embodied-carbon future construction by prioritizing reusability, recyclability, design for disassembly, and durability.

Exhibit 1 | RMI Graphic. Source: RMI analysis

The first law of embodied carbon is really very simple to understand and follow: Less is less.

Observing A Hierarchy Of Interventions

There is no single strategy that will achieve the significant reductions of embodied carbon necessary to meet climate targets. But checking a hierarchy of embodied carbon interventions for every building project — and at every phase of a project — will highlight the meaningful actions that can be taken for every unique building.

The first law of embodied carbon is really very simple to understand and follow: **Less is less.** The top three interventions of the hierarchy are all focused on using less material to create less emissions. Pursuing these interventions not only reduces emissions, but typically **also reduces costs**: Less is less when it comes to purchasing materials too.

Reuse of existing buildings and/or materials will reduce emissions, often by as much as 75% compared with demolishing and building new.[1] While it is not always possible to reuse an existing building or use a substantial amount of reused material, the possibility is often never explored early in a project cycle. Taking time to establish whether a building and/or material reuse is viable can have substantial embodied carbon (and cost) payback.

Right-sizing involves building less by serving program needs with less total square footage and will reduce emissions in direct proportion; build 10% less area, reduce emissions by 10% without any material swapping. Right-sizing is not an uncommon strategy because it can help to reduce budgets, and the embodied carbon benefits can be an additional advantage to this exercise.

Dematerialization lowers material demand by maximizing material efficiency and minimizing excess, reducing embodied carbon proportionally. A leading dematerialization strategy is optimizing structural systems, which can maximize the utilization of structural components to reduce both the carbon footprint and overall costs of a project.[2] For example, design parameters such as concrete specification and grid choice may have a higher impact than material choice.[3] In fact, one study found the choice of grid and frame types has the largest influence on embodied carbon and cost.[4] The selection of structural materials that can remain exposed without requiring additional finishing material is another example of dematerialization, as is the use of thinner finishes or cladding, where appropriate.

Waste reduction is an effective dematerialization strategy because embodied emissions are associated with both the manufacturing of wasted materials as well as their disposal. Minimizing material surpluses when placing orders and sending unused materials for reuse will reduce waste and embodied carbon.[5] Offsite construction, such as panelized systems or modular components, is demonstrating promise as a waste reduction strategy and is worthy of exploration.[6] The Ellen MacArthur Foundation estimates that 10%–15% of construction materials are wasted during the construction process.[7] Every percent of material that can go unwasted by any strategy is a percent of embodied carbon shaved from a project.

Carbon storing materials can be incorporated on nearly every project, and project teams can make a concerted effort to identify and procure these materials. Biobased materials from agricultural residues and by-products can be used in many interior and exterior applications. Carbon-storing concrete products are entering the market today. Prioritizing these materials will speed up market transformation.

Material substitutions of products with higher emissions for comparable products with lower emissions is often top of mind when strategizing for embodied carbon reductions and for good reason: Well-chosen substitutions have been shown to achieve as much as 46% reduction in emissions. However, unlike the largely proportional impacts of the first three interventions of this hierarchy, the results of material substitutions are highly variable and require consideration and verification to ensure that meaningful reductions are achieved. Since building systems rarely operate in isolation, it is important to evaluate the emissions impacts of material substitutions holistically. This is where **life-cycle assessment (LCA)** becomes an important tool. Unlike specific material GWP limits, an LCA at the building level allows for more flexibility to make reductions in a way that is optimal for project teams.

There are two levels of material substitutions that can be explored on any project. The first involves design choices in which key elements of a building are compared for potential substitutions, including material selections for structural, enclosure, finishes, and mechanical systems. A common example is an embodied carbon comparison of concrete, steel, or timber frames as structural systems to select the option with the lowest emissions. The second involves comparison of different products that can serve the same function in an existing design. An example of this would be an embodied carbon comparison of metal, brick, or stone cladding.

The emissions impacts of material substitutions can be **measured over different life-cycle stages**. Most commonly, the product stage (life-cycle stages A1–A3) emissions are compared because studies have shown that the range of embodied emissions that occur in the product stage (also called cradle-to-gate stage) account for on average 50%–85% of total whole-life embodied emissions for building products.[8]

The majority of building product embodied emissions occur up front

Breakdown of product life-cycle, not including building operational emissions

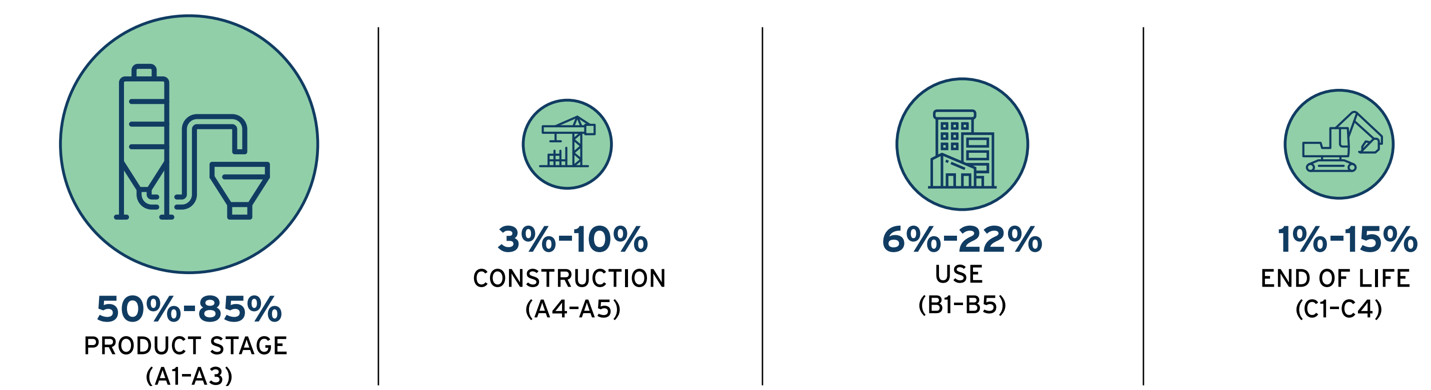

Exhibit 2 | RMI Graphic. Source: See endnote 7

Embodied carbon impacts need to be considered alongside more typical criteria such as cost and durability when deciding about material substitutions to ensure that low-embodied-carbon material replacements do not outweigh the initial climate impact of a durable but high-emissions material. As long as project teams understand the limitations of this approach in terms of trade-offs among interdependent building systems, they can make informed choices.

Sourcing of materials can have a considerable impact on the carbon footprint of a building. Within a particular category of building products, it is not unusual to have a substantial variation in embodied carbon emissions between competing products. Product-level differences can arise from raw material harvesting practices, manufacturing efficiency, fuel type and use, formulation and chemical processes, and transportation distances. Ensuring products are coming from legal and sustainable or regenerative sources and prioritizing local materials where data reveals that they have reduced impacts associated with transport can lower emissions substantially. As with material substitutions, embodied carbon impacts need to be considered alongside more typical criteria such as cost and durability when deciding about material sourcing.

Circular design principles contribute to low-embodied carbon construction by ensuring materials and assemblies can be readily reused at the end of their service life in a building. Design for disassembly can be applied to major building elements like structure and enclosure and also interior partitions and finishes, which are replaced more frequently. Additional considerations include choosing recyclable and reusable products and designing for adaptability of different building occupancies to prolong building use.

Addressing Major Sources of Embodied Carbon

Prioritizing embodied carbon interventions also involves identifying the elements of a project that are making the largest contribution to a project's emissions. The impacts of reuse, right-sizing, dematerialization, material substitutions, sourcing, and even circular design are amplified when applied to the highest-emitting portions of a project.

Every building project will have unique factors that will determine what elements contribute most to embodied carbon, but there are some well-established patterns. Studies have consistently shown structure, enclosure, and MEP are the leading elements for new buildings, and materials with the highest contribution are typically concrete and steel. For tenant improvements, elements such as gypsum wall board, carpets, and ceiling tiles along with fixtures and furnishings are likely to be leading contributors. The World Business Council for Sustainable Development's recent report, *Halving Construction Emissions Today*, provides an excellent overview of key technical design interventions for reducing embodied carbon for each major building layer (structure, enclosure, interiors, and services).[9] Taking the time to discover which elements and materials will contribute most to the embodied carbon of a project will enable the team to focus on making the decisions with the greatest reduction potential.

A combination of interventions can result in deeper reductions than pursuing just one

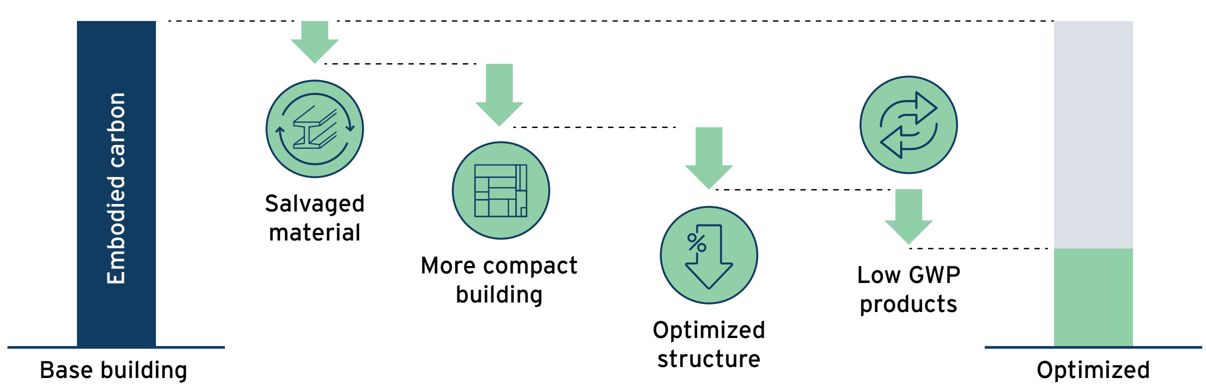

Exhibit 3 | RMI Graphic. Source: RMI analysis

The topic of embodied carbon is often framed as being highly technical, and indeed there is a great deal of technical knowledge that can clarify and maximize reduction efforts. However, project teams can get started by referencing this simple hierarchy of interventions and implementing these intuitive, readily available strategies to reduce embodied carbon. These strategies are not mutually exclusive. A combination of interventions can result in deeper reductions than pursuing just one.

ACTIONS

- Use the embodied carbon hierarchy of design interventions to consider the range of possible interventions to reduce embodied carbon, starting with considering reuse over new construction and using less material overall (dematerialization).
- Specify low-embodied-carbon materials where possible while weighing durability, reusability, recyclability, and impacts to other building systems to achieve the best whole-life outcome.
- Seek to use an integrated process like building-level LCA to identify strategies that minimize embodied carbon emissions holistically.
- Work with local or regional green building councils and professional groups to encourage local markets to develop more low-embodied-carbon materials locally and EPDs.
- Attempt to use at least one advanced carbon-storing or carbon-negative material on every project, even if just as a demonstration.

Endnotes

1. Matt Jungclaus et al., *Reducing Embodied Carbon in Buildings: Low-Cost, High-Value Opportunities*, RMI, 2021, **http://www.rmi.org/insight/reducing-embodied-carbon-in-buildings**.

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5. SF Environment, "Surplus Products in the Building Sector," accessed September 21, 2023, **https://sfenvironment.org/sites/default/files/events/agenda_item_5_surplus_study_commission.pdf**.

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7 Ellen MacArthur Foundation, *Growth Within: A Circular Economy Vision for a Competitive Europe*, 2015, **https://ellenmacarthurfoundation.org/growth-within-a-circular-economy-vision-for-a-competitive-europe**.

8 Chris Magwood and Tracy Huynh, *The Hidden Climate Impact of Residential Construction*, RMI, 2023, **https://rmi.org/insight/hidden-climate-impact-of-residential-construction/**; World Business Council for Sustainable Development, *Net-Zero Buildings: Where Do We Stand?*, July 2021, **https://www.wbcsd.org/Programs/Cities-and-Mobility/Sustainable-Cities/Transforming-the-Built-Environment/Decarbonization/Resources/Net-zero-buildings-Where-do-we-stand**; John Orr, Orlando Gibbons, and Will Arnold, *A Brief Guide to Calculating Embodied Carbon*, iStructE, July 2020, **https://www.istructe.org/IStructE/media/Public/TSE-Archive/2020/A-brief-guide-to-calculating-embodied-carbon.pdf**; Matt Bowick and Jennifer O'Connor, *Carbon Footprint Benchmarking of BC Multi-Unit Residential Buildings*, Athena Sustainable Materials Institute, May 2017, **http://www.athenasmi.org/wp-content/uploads/2017/09/BC_MURB_carbon_benchmarking_final_report.pdf**; Ramboll, "Embodied Carbon in the Building Sector," accessed August 9, 2023, **https://c.ramboll.com/lets-reduce-embodied-carbon.**

9 World Business Council for Sustainable Development, *Net-Zero Buildings: Halving Construction Emissions Today*, January 2023, **https://www.wbcsd.org/Pathways/Built-Environment/Resources/Net-zero-buildings-Halving-construction-emissions-today**.

Do Low-Embodied-Carbon Materials Cost More?

KEY TAKEAWAYS

- There is no consistent correlation between the embodied carbon and cost of a material or product.
- An informed project team can effectively research options and find cost-effective low-embodied carbon materials and products.
- Win-win scenarios exist: Some low-embodied-carbon strategies, such as right-sizing projects or optimizing the structural sizing, result in decreased materials amounts and hence lower embodied carbon and lower cost.

Substantial reductions are available today at cost parity

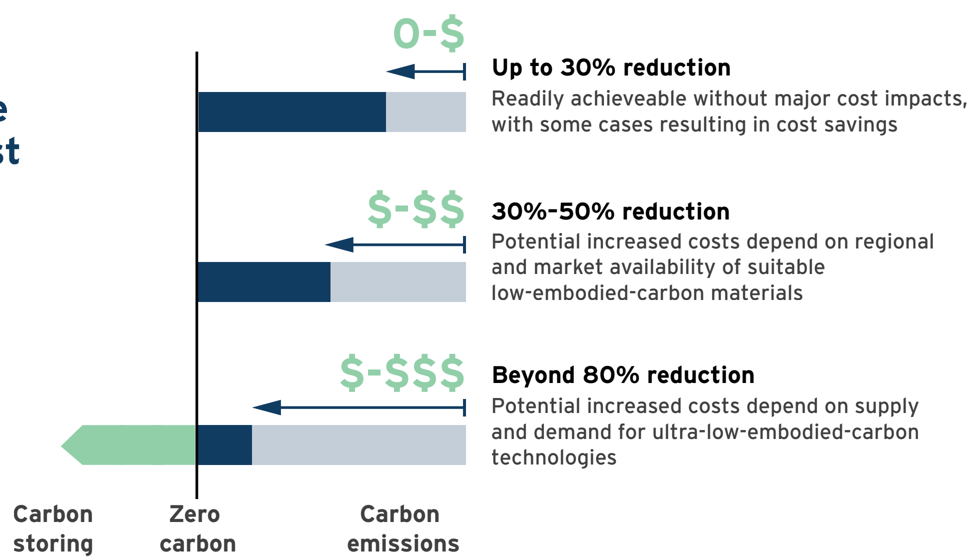


Exhibit 1 | RMI Graphic. Source: RMI analysis

Not Necessarily

Reducing embodied carbon in buildings is doable today without necessarily impacting hard costs or construction schedule. Case studies have shown reductions of up-front embodied carbon from 20% to 46% are possible with less than 1% cost premium.[1] A study of homes in Canada compared material costs for various types of insulation and exterior cladding and found cost and embodied carbon had no consistent correlation. The product with the lowest carbon footprint could have lower or equivalent costs in many material categories.[2]

LESS IS LESS: A strategy that often gets overlooked is to use less material, which also results in major cost savings. Low-embodied-carbon strategies, such as right-sizing projects or optimizing the structural sizing, result in decreased materials amounts and hence lower embodied carbon and lower cost (a win-win scenario!).

To understand the cost implications of achieving lower embodied carbon, project teams must understand costs *and* carbon intensity of designs and products. Cost is already well understood at both an intuitive and technical level because it is a primary criterion for most projects. Design teams will make choices based on their cost literacy, and then test and refine those decisions through several rounds of cost studies to meet budget requirements.

Achieving embodied carbon literacy is no more difficult than achieving the level of cost literacy held by most building professionals. As with costs, there is technical guidance, case studies, and product literature that can be examined to develop a fluency of understanding about embodied carbon in common assemblies and product types. Once a professional learns about the embodied carbon intensity of a particular design and/or product, this information becomes a reference point for future decisions. And as with cost, there are **tools and guides** that can be accessed as new designs and products are added to the knowledge base. Design teams optimizing cost and low-embodied-carbon materials in tandem may be pleasantly surprised by the low cost or even cost savings that might be entailed with low-embodied-carbon designs. In many cases, common exercises for lowering project costs will inherently lower embodied carbon. Right-sizing spaces and optimizing structural components and finishes will reduce the amount of material required for a project and therefore reduce embodied carbon proportionally. Cost optimization may not look like embodied carbon reduction, but it very often will be.

Having a target budget is critical for making informed cost-based decisions, and similarly having an embodied carbon “budget” will enable project teams to strategize appropriately. With budgets for cost and embodied carbon set and information about cost and carbon intensity at hand, it is relatively easy to combine the two effectively. Project teams will discover where low cost and low carbon intensity intersect and where they do not. And as with all design and construction decisions, judgment calls will be required to meet whatever cost and carbon budgets have been set. Wins made in one area can offset additional costs and/or emissions in another.

Costs and embodied carbon share a similar approach to informing design. Early class D budgets provide an outline of potential solutions indicative of final project costs. This enables rankings to be made for the options being considered. Subsequent estimates for budget classes C through A provide ever-narrower degrees of specificity.[3] Embodied carbon analysis can follow a very similar process or even be twinned with budget classes’ estimates. Each project team member needs only to focus on the level of embodied carbon detail that is appropriate at a particular project phase.

It is important to remember that low-embodied-carbon materials are not inherently different from high-embodied-carbon materials. In many cases, they are the same products that teams have been using regularly and just did not know they were choosing a low-embodied-carbon option. Like all building products, low-embodied-carbon materials are subject to testing requirements and performance standards. And like all building products, they will have specifications, limits, and supply chain and market dependencies that differentiate them from their competitors and require unique considerations before selection and installation. As with cost, there is no consistent correlation between performance or durability and embodied carbon, but there will always be unique considerations for every building product to be used successfully.

It is all too easy to assume reducing embodied carbon will come with higher costs. Instead, it is just one of many variables that must be explored and understood to take effective action. Project teams are experienced in making decisions based on a wide range of factors, all of which must be balanced according to the goals of each unique project. Up-front costs are never the only factor, with energy efficiency, constructability, construction speed, indoor environment quality, durability, and aesthetics among the factors debated by project teams, many of which have their own cost implications. Adding embodied carbon to these considerations is no more difficult, requiring a similar effort to learn and incorporate into practice.

Let us let the numbers speak for themselves: Summarized on the next page are three case studies demonstrating that embodied carbon reductions can be achieved without major increases in overall project costs.[4]

SOFT COSTS

Although finding low-embodied-carbon materials at cost parity is possible today, there can be soft cost increases for project teams that pursue low-embodied-carbon options. Hiring expert consultants comes with a price tag, though often a moderate one. Promisingly, associated costs with external consultation and carbon assessments are coming down rapidly and can be almost negligible at less than 0.1% of total construction costs.[5]

Training team members to research and understand embodied carbon and use that knowledge in-house is also getting easier. A growing array of free introductory and in-depth webinars, resources, and **tools** offer abundant opportunities to begin learning about embodied carbon with a minimal investment.[i] Investments in learning new tools and updating specifications are not uncommon practices for any project team as the industry advances and can be seen as part of professional due diligence. Over the past decades, project teams have engaged in in-house learning and hiring consultants as new considerations such as energy efficiency, material health, and building science have all been incorporated into practice.

The climate crisis is not going away, and the response from the building industry is going to grow rapidly, by voluntary efforts or, in the near future, by **regulation**. Moderate investments in soft costs to build expertise on embodied carbon today will help position project teams for a low-carbon future.

i There are useful tools that exist to make the search for low-embodied-carbon products easier, such as the UL Sustainable Product Database (SPOT), Sustainable Minds Transparency Catalog, and Ecomedes. Free tools exist for both WBLCA (Athena) and up-front carbon assessments (EC3, One Click Planetary), while others have licensing and user fees.

CASE STUDIES: EC REDUCTION WITHOUT MAJOR COST INCREASES

Peter Molick Photography photo

Houston Advanced Research Center

EC REDUCTION

20%

structural and enclosure

- Structural system optimization
- Lighter overall structure
- Minimized long spans which reduced foundation requirements
- Minimized concrete slab thicknesses
- Longer strength development mixes and cement substitutions
- LEED Platinum certification

COST IMPACT

0% No cost premium

Diamond Schmitt / gh3* rendering

Toronto Emergency Medical Services Station

EC REDUCTION

30%

- Lower-impact extruded polystyrene (XPS) insulation
- Higher supplementary cementitious materials (SCM) % concrete mix
- Low-impact concrete slab sealant
- High recycled content steel
- Hempcrete block instead of concrete masonry unit (CMU)
- Recycled glass gravel insulation

COST IMPACT

0% No cost premium

Mixed Use Mid-Rise Office Building

EC REDUCTION

46%

- Lower cement concrete mixes
- Longer concrete cure time mixes
- Polyiso/mineral wool instead of XPS
- High recycled content steel
- Gypsum sheathing substitution
- Lower-carbon glazing products

COST IMPACT

0%

Premiums due to lower carbon glazing products and strategic procurement of steel

Exhibit 2 | RMI Graphic. Source: various (see endnote 5).

ACTIONS

- Consider embodied carbon budgets with the same rigor and strategies as financial budgets.
- Examine case studies with low-carbon materials, leverage product databases to find low-embodied-carbon products, and check with vendors on cost early in the project planning process.
- Use LCA tools to balance project costs and embodied carbon to discover cost-neutral and low-cost strategies.
- Prioritize embodied carbon training for project team members to increase literacy and open pathways to effective action.

Endnotes

1 Matt Jungclaus et al., *Reducing Embodied Carbon in Buildings: Low-Cost, High-Value Opportunities*, RMI, 2021, **http://www.rmi.org/insight/reducing-embodied-carbon-in-buildings**.

2 Chris Magwood et al., *Achieving Real Net-Zero Emission Homes: Embodied Carbon Scenario Analysis of the Upper Tiers of Performance in the 2020 Canadian National Building Code*, 2021, **https://www.buildersforclimateaction.org/report---nrcan-study.html**.

3 Royal Architecture Institute of Canada, "Appendix A: Description of the Classes of Estimates Used by PSPC for Construction Costing of Building Projects," accessed August 9, 2023, **https://chop.raic.ca/appendix-a-description-of-the-classes-of-estimates-used-by-pspc-for-construction-costing-of-building-projects**.

4 Ryan Zizzo and Kelly Doran, *Regulating Embodied Emissions of Buildings: Insights for Ontario's Municipal Governments*, August 2022, **https://drive.google.com/file/d/1VD7RvQdLg7PWAUF2N97Q0-PAhes-k80Z/view**; Matt Jungclaus et al., *Reducing Embodied Carbon in Buildings: Low-Cost, High-Value Opportunitie*s, RMI, 2021, **http://www.rmi.org/insight/reducing-embodied-carbon-in-buildings**; and Dirk Kestner and Kileigh Shea, *Redefining Net Zero*, AISC, 2018, **https://www.aisc.org/globalassets/modern-steel/archives/2018/11/redefiningnetzero.pdf**.

5 California Department of General Services, "Amend the 2022 California Green Building Standards Code, CCR, Title 24, Part 11," March 2023, **https://www.dgs.ca.gov/-/media/Divisions/BSC/03-Rulemaking/2022-Intervening-Cycle/Public-Comments/GREEN-45-Day/BSC/BSC-04-22-399-PT11-Attachment-C-R1-45day.pdf?la=en&hash=E1121CBF2FEA6D07492DCD1E962D8AA1AFC43618**.

What Should I Measure and How?

KEY TAKEAWAYS

- There are three main questions to ask to identify the most appropriate assessment type:
  1. Do you want to assess carbon emissions alone or a wider range of environmental impacts?
  2. What time frame in the building's life span do you want to consider?
  3. What design stage is the project in, and what decisions can you influence at that stage?
- Different tools exist to answer all the above questions. Choosing a tool comes after choosing the type of environmental impact study you want to perform.
- Embodied carbon accounting on a building scale is relatively simple math, multiplying material quantities by emissions factors and summing the results.

Assessment types differ by environmental impacts studied and life-cycle stages covered

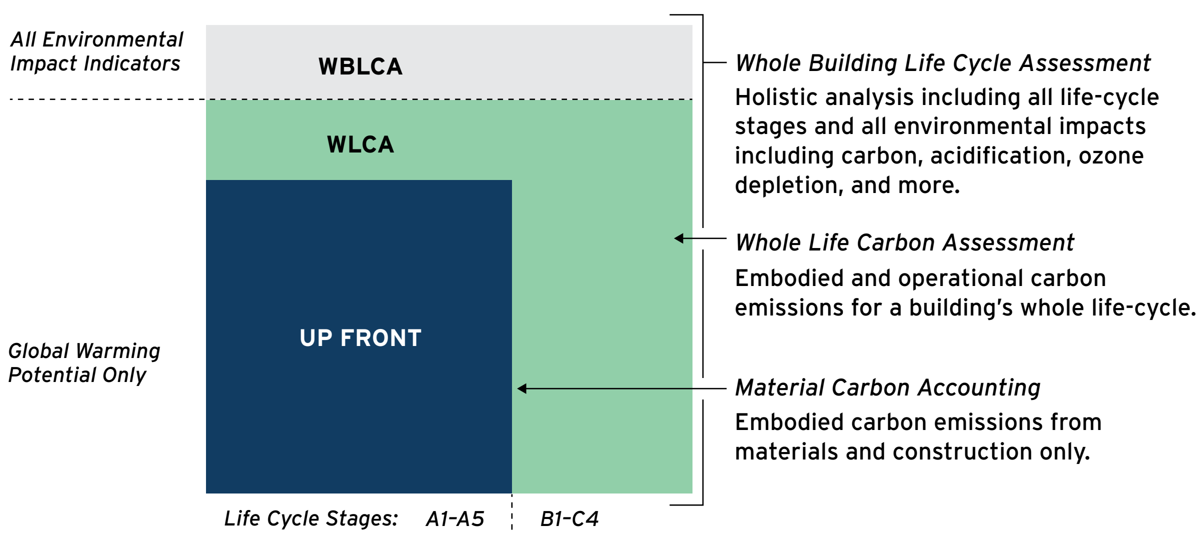


Exhibit 1 | RMI Graphic. Source: RMI analysis

Embodied Carbon Results Will Be Different Depending on What Is Being Measured and Over What Time Frame

With various resources citing "whole building," "whole life cycle," and "whole life carbon" assessments, it is no wonder some of our heads are spinning when thinking of starting to measure the carbon footprint of buildings. These are not competing approaches; rather, each will provide unique insights depending on what you want to know and where you are in the project cycle.

Let us demystify the assessment process itself. A building LCA consists of taking metrics from building models and project data (e.g., installed material quantities, miles traveled by transportation vehicles) and multiplying them by environmental impact factors. These factors are dependent on which impacts are being measured (for example, GWP is important for understanding the impact of embodied carbon emissions), the building life-cycle stages considered, and the stage of the project.

An LCA can be performed at the product level and/or at the building level. Conducting an LCA on the building level is essentially simple math, just like cost estimates: Material quantity is multiplied by a cost (or environmental) factor, and the results are summed across all included building categories. All LCA software programs operate on this principle but will differ in the type of inputs required from users and the types of background data used for performing calculations. The usefulness of the results depends on the quality of your inputs and the relevance of the background data that is informing the LCA calculations (see next page).

WHAT DO WE LEARN FROM EACH LIFE-CYCLE STAGE?

There are three major life-cycle stages for products and buildings:

- **A-stage emissions** occur before the building is occupied and are divided into five stages. The cradle-to-gate stages (A1–A3) are the climate impacts from the materials and products used to construct the building. These emissions occur when products are being manufactured, before the building is even occupied, and are based on data from manufacturers and life-cycle inventories. The construction stages (A4–A5) estimate the climate impact of transporting materials to site and on-site construction activities.

- **B-stage emissions** occur in the use stage of the product or building and are indicative of two major sources: those due to the use and maintenance of products (including refrigerant leakage of appliances and HVAC equipment and blowing agent leakages from some insulation types), and those due to the manufacturing and transport of repair and replacement and components. An LCA conducted before a building is occupied will provide estimates for the quantity and timing of these use-stage emissions.

- **C-stage emissions** estimate the impacts of how a product or building is typically dealt with at the end of its life cycle (demolition, deconstruction, waste processing, recycling, and reuse). Current LCA rules require that C-stage emissions be calculated according to standard waste handling practices at the time of the assessment and may not reflect the actual emissions scenario that will occur some decades in the future.

Any embodied carbon study must include a declaration regarding which of these life-cycle stages are reported because these choices will impact the results. There is no right or wrong selection of life-cycle stages for a study, but it is important to ensure that comparisons between products or building designs be aligned to include the same life-cycle stages or else the results will not be comparable.

The usefulness of LCA calculations depend on the quality of your inputs and the relevance of the background data

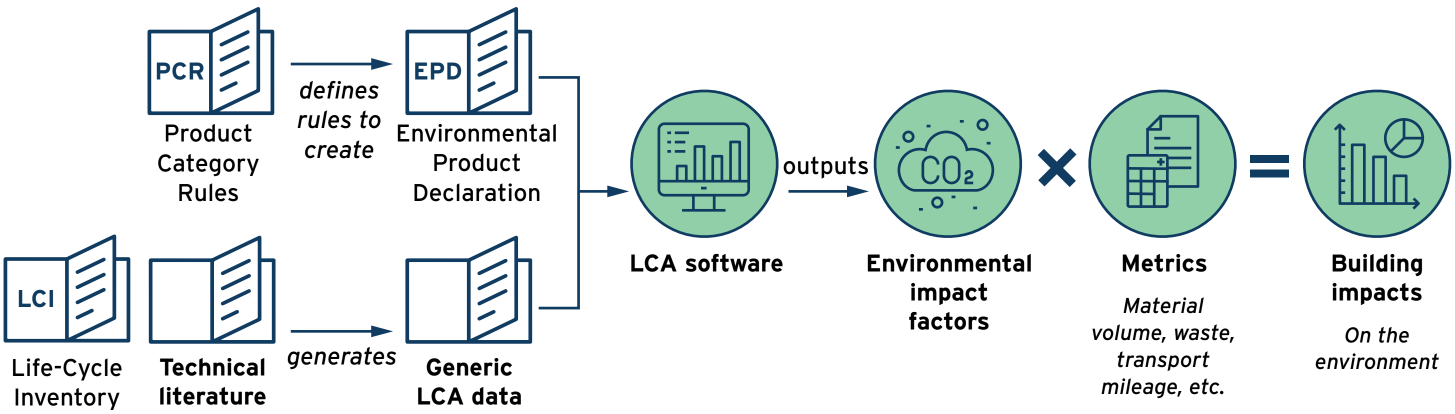


Exhibit 2 | RMI Graphic. Source RMI analysis

Although it is possible to customize LCA studies in many ways, there are some common approaches that are becoming common standards in the industry:

Whole Building Life-Cycle Assessment (WBLCA) is the term used to describe a study that covers all life-cycle stages of a building (from manufacturing to end of life, A–C) and measures impacts across all environmental indicators, including acidification, ozone depletion, GWP, eutrophication, formation of tropospheric ozone, and depletion of nonrenewable energy resources.

Whole-life carbon assessment (WLCA) covers all life-cycle stages (A–C) but focuses on only the embodied carbon component, called global warming potential (GWP).

Cradle-to-gate analysis considers only the product-stage emissions (A1–A3) and is often based on emissions factors from EPDs. More holistically, up-front carbon accounting includes all the A-stage emissions or cradle-to-completion (A1–A5) and will use estimates for transportation and construction emissions if conducted before the project starts or actual data is collected during the project.

Once a project team has identified the type of study they require, the next step is to utilize the appropriate software tool for analysis. It is important to learn how to match the intended scope of an embodied carbon study (life-cycle stages, environmental impacts, and project stage) to the tool best suited for the scope. Once the scope and the tool are aligned, a study becomes most efficient and informative. It is also important to recognize the standards for which the tools are compliant.

There are several notable international standards for LCA frameworks, including ISO 14040, ISO 14044, ISO 21931, and EN 15978. These are differentiated from WBLCA standards, like RICS Whole Life Carbon Assessment, which offer more specific guidance on calculations that improve consistency and comparability. Regardless of what tool is used for a project, the most important practice is to only conduct comparisons with results from the same tool.

Depending on the design stage of the project, different analytic tools are appropriate.

In early design development, information about the project is less detailed, but an LCA can be helpful for making decisions to align with embodied carbon goals, such as comparing structural systems or whether to retrofit or build new. Generic LCA background data, often referred to as life-cycle inventory (LCI) data, can be useful at this stage to provide understanding of directions that have better or worse embodied carbon outcomes. Early-phase tools can give useful feedback based on minimal inputs and enable quick comparisons to guide decisions (see Exhibit 3, next page).

As the design of a building grows in detail, LCA models that are based on Building Information Modeling (BIM) takeoffs can apply generic LCA data to more accurate quantities of materials.[i] Throughout this stage of design, LCA results can guide choices of structural systems, facades, glazing, and other major design and material options, enabling comparisons based on embodied carbon. At the later stages of design, tools that can provide comparisons between actual products will enable more refined comparisons.

ABSOLUTE VS. COMPARATIVE APPROACHES

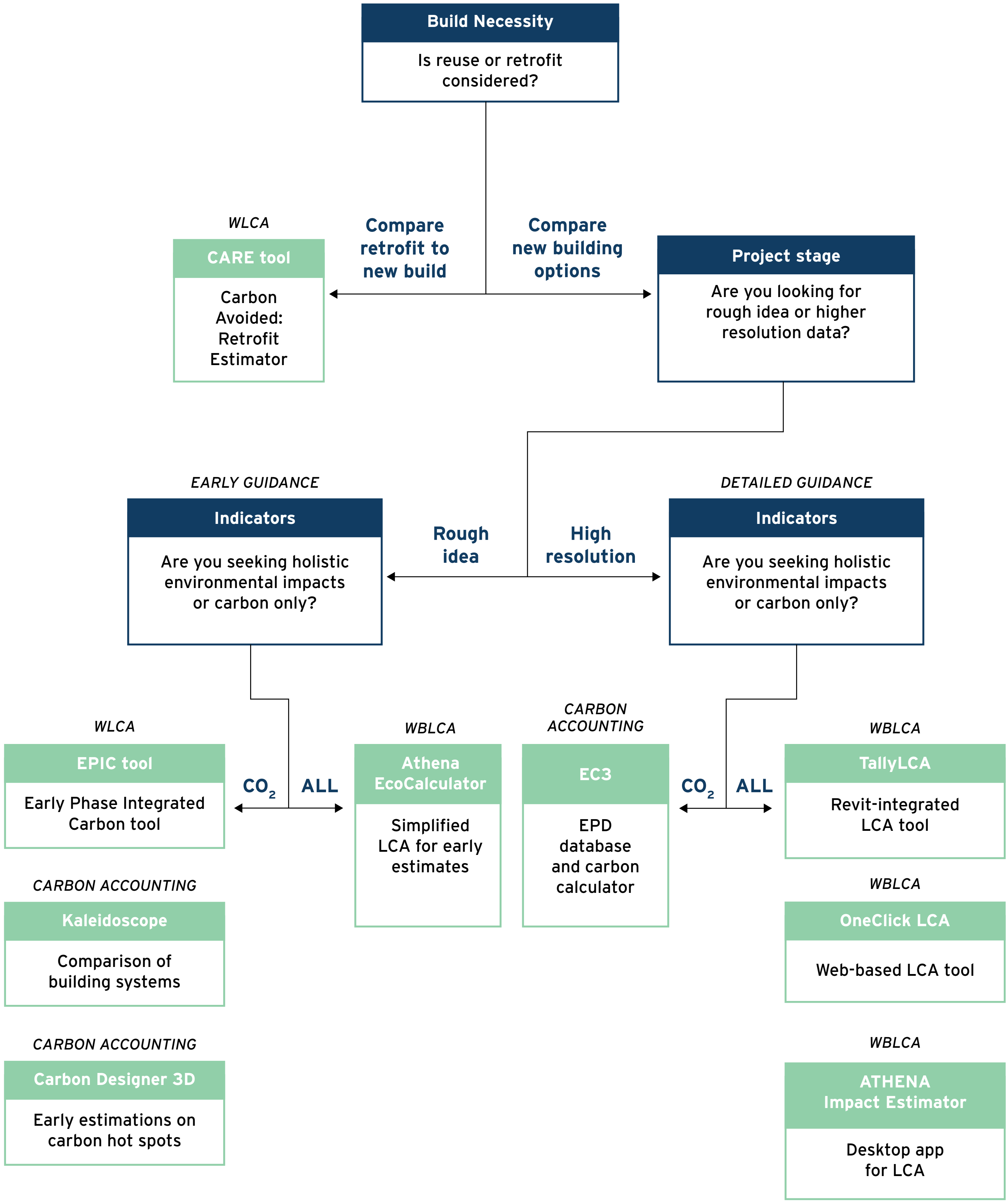
Building LCA is often used to compare a building's massing or structure and enclosure composition against comparable construction materials or methods. When doing this type of analysis against a baseline building, it is important to ensure accurate baseline assumptions. For example, assuming a one-story building with wood stud construction makes sense, but assuming a mid-rise building of 12 stories of wood stud construction would not be typical practice and therefore set an unrealistic baseline. Guidance exists to define baseline models; for example, the City of Vancouver's Embodied Carbon Guidelines, the Royal Institution of Chartered Surveyors (RICS) Standard on Whole Life Carbon Assessments, and the American Society of Civil Engineers' WBLCA Guide.[1]

Building LCA is also used to determine a building's carbon footprint to compare to and meet recommended or prescribed limits. Absolute whole-building carbon targets are more common in Europe, while historically a comparative approach (calculation of a baseline specific to the project and meeting a percent reduction from the baseline) has been more common in North America.[ii] There are some caveats to be aware of with the comparative approach, including the potential for various interpretations of defining a baseline model and the added administrative burden of creating and verifying baseline models. Absolute targets will be the most straightforward and effective approach to sector decarbonization, but the comparative approach may still be useful for buildings with unique designs and site conditions.

ii For example, the London Plan Appendix 2 provides WLC benchmarks for different building typologies, **https://www.london.gov.uk/sites/default/files/lpg_-_wlca_guidance.pdf**

i Industry-average EPD data and generic LCA data are useful at early stages of design, while manufacturer-specific data where available can more effectively inform later stages of design. This is an area that is evolving rapidly, with explicit specifications on what data types to use and when expected from emerging LCA standards such as ASHRAE/ICC 240p.

Decision tree for embodied carbon analysis



Note: This is not an exhaustive list of available tools. Visit Carbon Leadership Forum's (CLF) resources page for more tools: https://carbonleadershipforum.org/tools-for-measuring-embodied-carbon/

Exhibit 3 | RMI Graphic. Source: RMI analysis

Accurate material quantities combined with product-specific data such as EPDs allow final decisions to maximize embodied carbon reductions.[iii] Post-construction, a detailed study can be completed using as-built material quantities and as much project-specific data as possible (such as product brands, transportation and construction fuel use, and material wastage). This will provide the most accurate report of embodied carbon.

At each of these project stages, it is possible to examine embodied carbon as an isolated factor or include the wider range of environmental impacts included in an LCA. The decision map below can help understand what analyses and tools are more suitable at different project stages.[2]

ACTIONS

- Make early decisions regarding what scope(s) of analysis to consider, and use consistent scopes and tools for comparisons. It is possible to start with a smaller scope focusing on the areas with largest impacts and expand the scope of analysis as desired.
- Use an existing standard to estimate and report embodied carbon, such as the World Business Council for Sustainable Development's Building System Carbon Framework.
- Make embodied carbon impacts from LCA studies a key decision-making factor from early design through procurement.

Endnotes

1 City of Vancouver, *Embodied Carbon Guidelines v0.2*, accessed August 9, 2023, **https://docs.google.com/forms/d/e/1FAIpQLScjiwCrTCA-lmb47f_bAMTXXQbBDmUkWphbzP3qdPdQLp4o_w/viewform**; **RICS,** *Whole Life Carbon Assessment for the Build Environment, 1st Edition,* **2017, https://www.rics.org/profession-standards/rics-standards-and-guidance/sector-standards/building-surveying-standards/whole-life-carbon-assessment-for-the-built-environment;** and ASCE, *Whole Building Life Cycle Assessment: Reference Building Structure and Strategies*, 2018, **https://ascelibrary.org/doi/book/10.1061/9780784415054**.

2 Carbon Leadership Forum, “Tools for Measuring Embodied Carbon,” accessed August 9, 2023, **https://carbonleadershipforum.org/tools-for-measuring-embodied-carbon/.**

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iii Not all EPDs are suitable for LCAs due to variations in their development such as source of background data and use of different functional units. Efforts are underway to address these challenges; for example, the American Center for Life Cycle Assessment PCR Guidance aims to provide criteria for developing EPDs that are appropriate as data sources for WBLCA.

Is the Data Good Enough?

KEY TAKEAWAYS

- We know enough today to make meaningful decisions that reduce building embodied carbon emissions and should not let data gaps stop rapid uptake of low-embodied-carbon strategies in rating systems, policies, and codes.
- As with cost estimates, decisions can be made appropriate to the accuracy of the data available.
- We must prioritize efforts to fill remaining data gaps, which include measured construction data and embodied carbon emissions factors for MEP equipment (especially refrigerants), FF&E, and novel biobased materials.
- Standardization is needed to improve consistency and comparability of LCAs and narrow the residual variation in background data and underlying methodologies. Efforts are underway to improve LCA standardization.

What we know today: We can make decisions with meaningful impacts

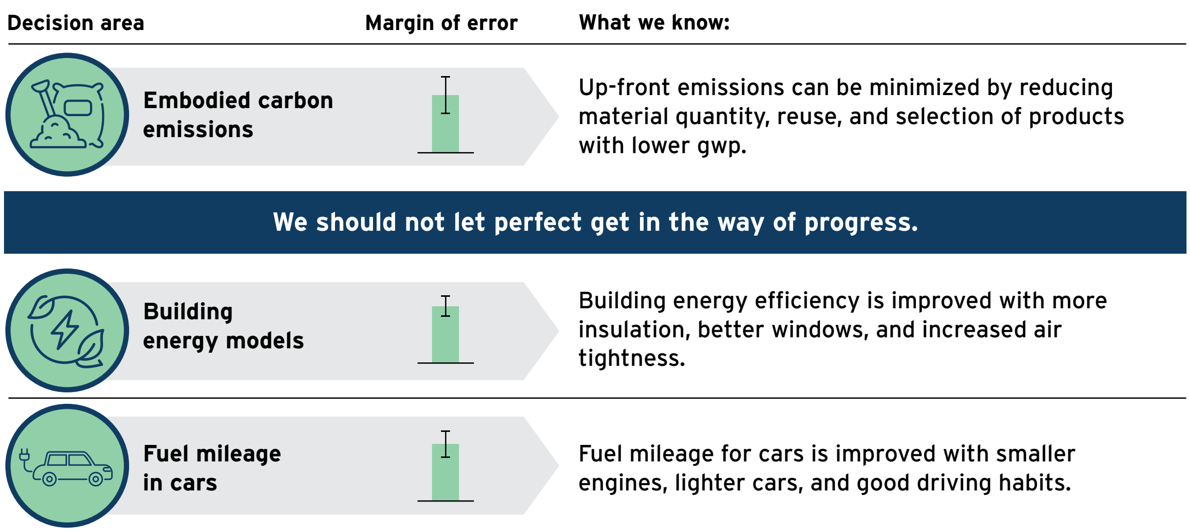

Exhibit 1 | RMI Graphic. Source: RMI analysis

Good Enough to Guide Us in the Right Direction

Though we tend to talk about embodied carbon “calculations,” it is more accurate to describe these as “estimates” of emissions. As with all estimates, it is critical to understand what kind of error bars to put around results. Embodied carbon is not unique in this regard, and design teams are well practiced

in making sound decisions based on varying levels of data quality and resolution. Major project decisions are made based on class D, or indicative, cost estimates, where ±20% allowances are reasonable, and on early-stage energy models, where performance is predicted before all the relevant parameters are known. As with these examples, project teams analyzing embodied carbon must be clear about the types of comparisons that are useful at a given resolution. If the error bars are ±20%, decisions indicating a difference of 20% or more are likely to be relevant and impactful, whereas choices that indicate less than 20% difference may not. Informed by a clear understanding of embodied carbon data quality issues, it is possible to make impactful decisions with today's data while developing practices that will benefit from data quality improvement that is currently on a sharp upward trajectory.

REDUCING MATERIAL QUANTITIES

One of the leading ways to minimize embodied carbon is not data-dependent and is always a good place to start decarbonization efforts. Reducing material quantities — especially high-impact structural and enclosure materials — to achieve the same level of performance will always reduce embodied carbon. Reusing buildings and building materials is another high-level strategy that most often results in substantial embodied carbon reductions.

WHERE AND WHAT ARE THOSE GAPS?

Embodied carbon data gaps occur in two distinct manners: gaps in some of the life-cycle stages for some material categories and a lack of data in all life-cycle stages for other material categories.

Currently, the most accurate datapoints exist for cradle-to-gate (A1–A3) emissions in key building material categories including concrete, masonry, steel, aluminum, gypsum board, insulation, cladding, flooring, ceiling tiles, and paint. Variations arise due to differences in product category rules (PCRs) and/or the specificity of data used (factory specific or generic), but in these categories, A1–A3 emissions estimates often fall within a relatively narrow range, enabling strategic decisions to be taken for these major building components. Some embodied carbon tools will provide users with an appropriate error bar around results for these material categories to help refine decision-making. For this reason, a cradle-to-gate embodied carbon analysis focused on well-documented material categories is often considered to be the most accurate and reliable.

Many product EPDs do not provide estimates for life-cycle stages A4 to C4, creating one of the critical data gaps for embodied carbon. Even if EPDs do include A4 to C4 estimates, the PCRs may rely on different assumptions to generate emissions values, limiting the ability to compare results. Generic LCA data sets will typically use more consistent assumptions to provide estimates for A4–C4, enabling better comparisons but at the expense of specificity.

Data is never perfect, but imperfect data can still provide a valuable basis for action if the imperfections are well understood.

Some material categories, particularly MEP equipment, offer considerably less data at all life-cycle stages. Currently, many embodied carbon analyses omit MEP entirely because of this data gap, resulting in incomplete estimates of emissions. Embodied carbon data uncertainty also exists in specific life-cycle stages. Maintenance, repair, and replacement estimations are based on industry averages or manufacturer recommendations but may not reflect actual cycles, especially for interior materials that are often replaced not out of necessity but because of tenant needs or turnover.

The treatments of refrigerant leakage from mechanical systems and of GHGs from foamed insulation are also points of uncertainty. One report uncovered the significant contribution of refrigerant leakage to the whole life-cycle embodied carbon impact of mechanical cooling systems (up to 80%).[1] This highlights a notable data gap with a potentially significant impact and underscores the importance of specifying refrigerants with low GWP.

Accurate as-built results for A4 (transportation) and A5 (construction) emissions are, in theory, possible to achieve but are not typically tracked reliably enough to provide solid data. As more project teams request detailed information about transportation and construction fuel use, this data can build more robust estimates for preconstruction embodied carbon analyses.

Data is never perfect, but imperfect data can still provide a valuable basis for action if the imperfections are well understood.

Data Resolution of Different Life Cycle Stages

Although limiting embodied carbon analysis to only stages A1–A3 can provide the best resolution and cover a high percentage of total emissions, narrowing the time lens to the present day can obscure important climate impacts that occur later in the life cycle.

Expanding the time horizon — to a whole-life carbon study or some portion of impacts beyond A1–A3 — can provide additional embodied carbon insights but also introduce greater uncertainty the further into the future the analysis is extended. This can make for a tricky balancing act, but if we ask the right questions and bracket the timeline appropriately, we can maximize the usefulness and mitigate the noise.

If we simply add up all the embodied carbon over all life-cycle stages and for all material categories, and examine a single number as an answer, we will not know what elements contributed the most, nor when they make their contribution. There is little action that can be taken based on comparing one whole-life carbon number with another.

Instead, we need to compare results from whole-life carbon studies one life-cycle stage at a time and one material type or category at a time and examine these results through our best understanding of the uncertainties involved. Using more material to achieve greater thermal performance is an example of a strategy that can be examined using a whole-life approach. The embodied carbon from the additional material (perhaps insulation or glazing or a more intensive heating system) can be assessed from the A1–A5 stages, and the difference in operational emissions can be assessed over a number of years. If total emissions are significantly less for one option than another, that is an actionable insight.

As we move this analysis further into the future, we need to be cautious of the increasing uncertainties, which can include replacement cycles for systems and materials, assumptions

WHAT ABOUT EPD DATA?

EPDs play a crucial role in identifying high-impact materials and enabling comparisons between materials that perform the same function in a building. However, it is important to recognize that there remain sources of variation in their development and results. One source is the product category rules (PCRs) that prescribe the instructions on the creation of EPDs for each product type. There are sometimes several PCRs for one product category, and sometimes the PCR itself is not specific enough and leaves room for choosing assumptions to use. Another source of variation lies in which background data set (LCI data) is used to conduct an LCA for a product. However, when an EPD describes facility- and product-specific information, the remaining margin of error as a result of the variation in background data and data collecting processes is estimated between 4% and 21% for many common construction materials.[i] Fortunately, this does not stop us from seeing major material impact trends. As more and more product- and plant-specific EPDs become commonplace, accuracy should improve.

i This range considers only the uncertainties for batch-specific, supply-chain, life-cycle impact assessment method and residual factors for all materials in the **EC3 Uncertainty Factors table** excluding aluminum. Considering all uncertainty factors, the uncertainty range is up to 41%. Note that the uncertainty range depends on the product type and factors such as how large the relative contribution is of upstream materials and processes, and the extent of variation behind the industry averages for upstream processes.

about the carbon intensities of fuel types, and even changing patterns or types of building use. By the time we get to end-of-life predictions, based as they are on today's end-of-life norms, the uncertainties will have multiplied to the point where they are indicators of potential emissions rather than predictors of likely emissions. The further into the future a whole-life carbon study is cast, the wider the error bars we might apply for decision-making.

It is crucial that we do not delay progress on reducing embodied carbon while waiting for perfection in data quality. The building industry made significant progress on reducing energy use in buildings long before we had the refined, sophisticated tools we have today. Back then, we could see key interventions such as additional insulation, better windows, and improved air tightness made a real difference even if we could not measure their impacts as precisely as we do today. We need to act on insights from today's data while working to improve its quality. We must continue measuring embodied carbon to uncover impactful decarbonization strategies and ensure those measures reflect the latest practices and understandings.

The creation and adoption of national and international WBLCA and WLCA standards for the measurement of embodied carbon (such as the ASHRAE/ICC 240 standard currently in development[2]) will improve the consistency, comparability, and comprehensiveness of embodied carbon analysis. This is a crucial step toward setting ambitious embodied carbon benchmarks that will meet climate thresholds. In fact, several entities in European (London, France) and Canadian cities (Toronto, Vancouver) have already done so through various voluntary programs and even mandatory regulations.

YOU ARE NOT ALONE!

Several organizations and initiatives have made commitments to decarbonize buildings and building products.

- **Architecture 2030 Embodied Carbon Challenge**: zero GWP of buildings, infrastructure, and associated materials by 2040
- **AIA 2030**: net-zero emissions of the built environment by 2030
- **Structural Engineers SE2050:** net-zero embodied carbon structural systems by 2050
- **MEP 2040**: net-zero operational and embodied carbon MEP systems by 2040
- **World Green Building Council's Net-Zero Carbon Buildings Commitment**: reduce all operational and embodied operational carbon emissions by 2030[3]
- **National Ready Mix Concrete Association**: net-zero carbon emissions industry by 2050 (worldwide effort launched by Global Cement and Concrete Association)
- **SteelZero**: a global initiative, led by the Climate Group in partnership with ResponsibleSteel, to drive market demand for net-zero steel with commitments to procure 100% net-zero steel by 2050

Many efforts are being undertaken to improve and coordinate data, such as the US Environmental Protection Agency's (EPA's) EPD Assistance Program and the ACLCA'S PCR Guidance. Furthermore, building rating systems, building codes, research groups, and professional associations can work together to adopt and collect data in ways that foster consistency and lead to great standardization of data and analysis in building LCA and product EPDs. There is a group already beginning this work in North America, called the Embodied Carbon Harmonization and Optimization (ECHO) project, of which USGBC is a convening organization.[4]

ACTIONS

- Do not wait to take action — start evaluating embodied carbon in your projects and making the most impactful design decisions to maximize emissions reductions.
- Request EPDs from suppliers for all building materials and products including MEP equipment, furniture, and finishes, facility-specific or at least product-specific EPDs.
- Engage in efforts to improve data and analysis standardization to reduce friction and speed action on decarbonization.

Endnotes

1 World Business Council for Sustainable Development, *Net-Zero Buildings: Halving Construction Emissions Today*, January 2023, **https://www.wbcsd.org/Pathways/Built-Environment/Resources/Net-zero-buildings-Halving-construction-emissions-today**.

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Is There Enough Data on Interiors Renovations?

KEY TAKEAWAYS

- The embodied carbon impacts of retrofits and renovations are poorly understood but could be a major driver of emissions if left unaddressed.
- Even in the absence of better data, we know a lot about how to reduce carbon emissions from interiors and furnishing, including reuse, recycling, and using less material.
- Interior finishes represent some of the best opportunities to incorporate carbon-storing, rapidly renewable, biobased materials in low-risk areas.
- We can reduce emissions by focusing on a few key products that are removed in renovations every day and are not typically recycled but could be, such as carpet, ceiling tiles, gypsum wall board, and furniture.

We still do not know the full scale of carbon impacts from interior materials

New construction

Initial up-front impact of new buildings

Up to:

370

million tons CO_2e per year in the U.S.

Interior renovations

Continual impacts of all buildings

Up to:

?

million tons CO_2e per year in the U.S.

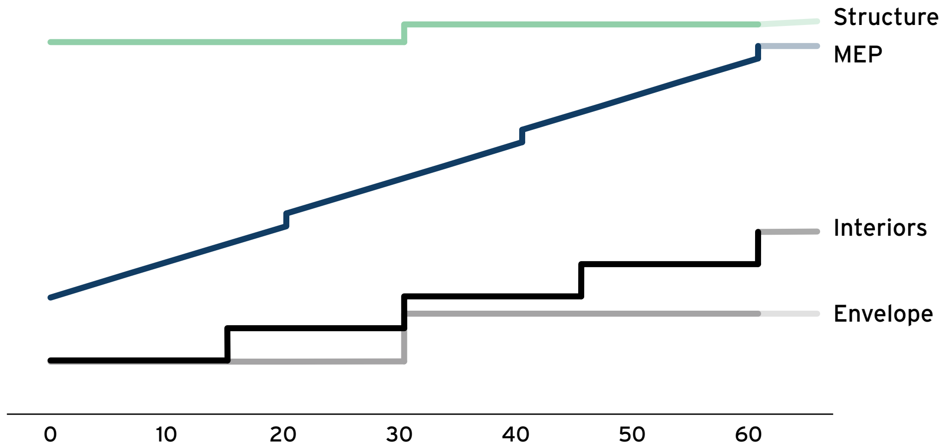
Exhibit 1 | RMI Graphic. Source: Larry Strain, "Time Value of Carbon," 2017, **https://www.siegelstrain.com/wp-content/uploads/2017/09/Time-Value-of-Carbon-170530.pdf**

The Full Scale of Embodied Carbon from Interior Elements Is Unknown

Assuming a typical service life cycle of interior elements of 12 to 15 years, one study suggests the cumulative embodied carbon from these elements over a building's life could equal or exceed the initial carbon footprint of structure and enclosure construction.[1] Interiors and furnishings deserve closer examination.

Cumulative Impact Over A Building's Lifetime

Emissions broken down by building layer, kg CO_2e/m^2



Note: Cumulative impact of embodied carbon due to material and equipment replacements, including the continual emissions of refrigerant leakage of MEP equipment.

Exhibit 2 | RMI Graphic. Source: World Business Council on Sustainable Development, *Net Zero Where Do We Stand*, Case Study 03

Embodied carbon is most often estimated for new building projects, and in these studies the frequency of interior replacements is based on the anticipated service life of the material themselves. However, material failure is less often the reason for replacement than the changing needs and tastes of owners and tenants.[2] In all likelihood, this source of embodied carbon is highly underestimated. The true magnitude of existing building area in the United States undergoing regular retrofits and improvements is unclear. It is estimated the current global retrofit rate is 1% of building stock.[3] Meanwhile, the growth rate in the number of new buildings in the US is estimated as a little over 1% per year.[4] When we consider tenant improvements and soft renovations, the scale of interior material impacts could grow even more, resulting in a vast amount of construction activity occurring for which there is no embodied carbon analysis. Understanding and reducing these emissions presents a major challenge and opportunity.

As with embodied carbon from new construction, we know a lot about how to reduce carbon emissions from interiors and furnishings. Less is less: Avoiding unnecessary renovations and limiting the scope of renovations will reduce emissions.

A second major strategy is to maximize recycling during the demolition phase of interior renovations. Many commonly replaced materials, such as ceiling tiles, carpets and gypsum wallboard, can be recycled into the same products by manufacturers, but today they usually aren't. Project teams can consider a pre-demolition phase where carpet and ceiling tiles are removed and sent back to the manufacturer. Contact manufacturers and local recycling outfits to discover available programs and encourage new ones.

Disassembling rather than demolishing interiors can provide materials with another life span in a new context. Interiors that are designed for disassembly today will reduce embodied carbon in the coming decades. Such designs for flexibility, as seen in the LEED credit Interiors Life-Cycle Impact Reduction, can make the impact of interior renovations lesser each time.[5] Given that 7.7 million tons (17 billion pounds) of office assets end up in landfills each year, the building industry should consider circular principles when it comes to purchasing and manufacturing finishes and furniture including design for disassembly, reusability, durability, recyclability, and take-back programs. One study found the embodied carbon footprint of the renovation was reduced by 33% by the use of reused furniture.[6]

Finally, interior finishes represent some of the best opportunities to incorporate carbon-storing, rapidly renewable, **biobased materials** that are not subject to exterior weathering. There are numerous incumbent biobased finish products including bamboo and cork flooring, wood and cellulose composite acoustic panels, and cement-free earth-based wall tiles made from quarry by-products.

Building-industry sectors that focus on interior renovations and tenant improvements can be leaders in overall efforts to reduce embodied carbon, beginning with a commitment to simple principles of reducing by design and to measuring embodied carbon with the same rigor as new construction. While there are data gaps for some product categories within interiors and furnishings, tools and resources are being developed to help inform decision making. There is a need for manufacturers to publish more EPDs for furniture and some finishes to help understand impacts and fill in remaining data gaps.

ACTIONS

- Minimize the emissions impact of retrofits by retaining more existing materials and retrofitting on less frequent cycles.
- Collect and report embodied carbon data for retrofit projects to contribute to the understanding of the impact of these projects.
- Request EPDs for all products used on interior retrofits.
- Prioritize low-embodied-carbon, durable, reusable, low volatile organic compound emitting, and recyclable products whenever possible, and designing for disassembly and reconfiguration.

Endnotes

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What is the Future of Concrete and Steel?

KEY TAKEAWAYS

- Concrete and steel are high-emitting materials that will remain important in building construction for the foreseeable future. As low-embodied carbon products enter the market, project teams can support and spur innovation by using these improved products.
- Dramatic changes are underway in these two industries. Transition away from fossil fuel production of concrete and steel combined with the rapid decarbonization of the grid portends a future where the embodied carbon of these materials can approach zero emissions.
- Innovations in the production of cement and aggregate suggest that in the foreseeable future, concrete may become a carbon storage material rather than a huge emitter of carbon.

This is potentially a story of radical improvement

The concrete and steel sectors have decarbonization pathways toward net zero by 2050.

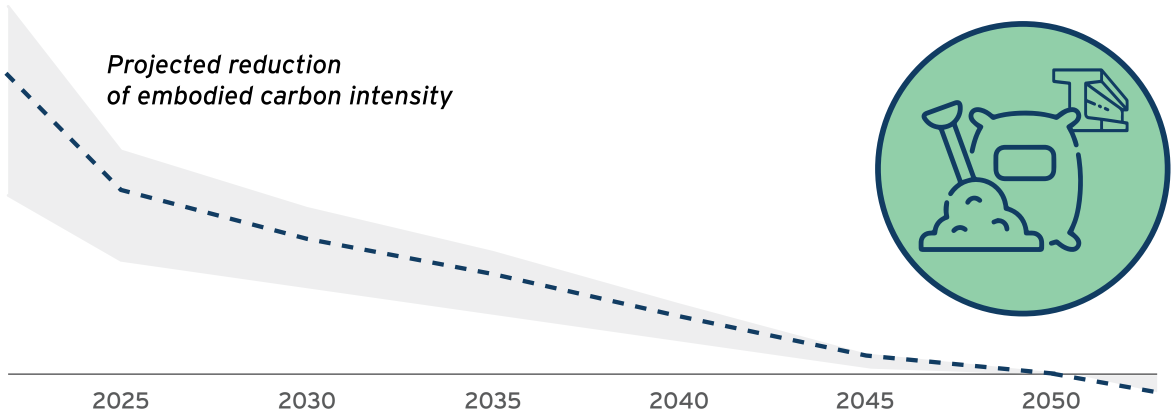

Exhibit 1 | RMI Graphic. Source: RMI, *Roadmap to Reaching Zero Embodied Carbon In Federal Building Projects*, https://rmi.org/insight/roadmap-to-reaching-zero-embodied-carbon-in-federal-building-projects/

Both Sectors Have Decarbonization Pathways Toward Net Zero By 2050

Globally, concrete and steel production represent about 13.5% of global carbon emissions.[1] While concrete and steel are among the most carbon-emissions-intensive construction materials, they will remain important in building construction for the foreseeable future. As such, it is crucial that construction trends encourage the continual decarbonization of these sectors rather than stunt their progress. Ordinances and

Encouragingly, there are many innovations taking place in the concrete and steel industries to help meet climate goals. However, it will require public commitments, regulations, and a strong pipeline of both supply and demand to make the shift happen.

regulations such as Buy Clean have begun targeting high-GWP materials including concrete and steel. Although they can be effective levers for decarbonization, it is important the design of such policies does not unintentionally constrain carbon-cutting investments for these sectors. This could drive segments of the industry out of business without lowering overall emissions intensity of the industry or even leak emissions abroad.[2]

These industries have already committed to several public reports and commitments to net-zero pathways, including the Global Cement and Concrete Association, the National Ready Mix Concrete Association, and Steel Zero.[3] While such public commitments are constructive, many of the prospective carbon reductions for both industries rely on technologies that may be a decade or more away (like carbon capture and storage and hydrogen-based steel technologies). Encouragingly, there are many innovations taking place in the concrete and steel industries to help meet climate goals. However, it will require public commitments, regulations, and a strong pipeline of both supply and demand to make the shift happen. Regulators, building owners, and rating systems must help catalyze action immediately.

Concrete Solutions

A necessary near-term step on the path to net zero is increasing the efficiency of building design and material usage to minimize the overall volume of concrete needed. On the manufacturing side, the primary means of reducing the carbon intensity of concrete currently is by reducing the cement content, which accounts for up to 90% of concrete's embodied carbon.[4,i]

Outside of substituting cement, additional methods to reduce the carbon intensity of concrete include using recycled aggregates, considering longer strength development mixes, specifying portland limestone cement, increased efficiency in concrete production (better quality assurance and quality control), decarbonization of the electricity grid, and savings in clinker production processes (increased thermal efficiency and use of alternative fuels).[5]

Emerging technologies that have the potential to realize carbon-neutral concrete include carbon capture technologies on-site and CO_2 recarbonization. There are also prospects of carbon-storing concrete products that feature biomineralization from natural components like algae and mycelium. A study on federal buildings' material procurement examines how the net zero by 2050 pathway can be achieved through key specific methods for the concrete sector, summarized on the next page in Exhibit 2.[6]

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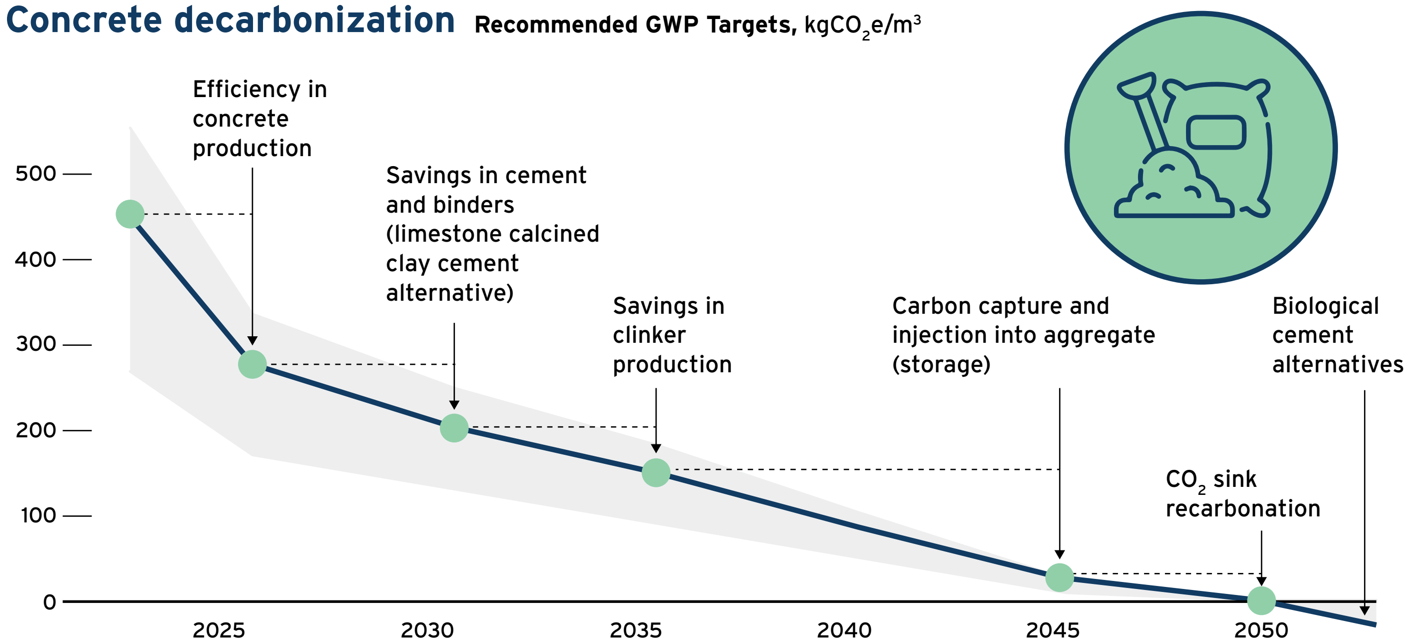
i Note that not all supplementary cementitious materials are created equal. They must be chosen carefully to ensure that overall GHG emissions are reduced. For example, one study involving iStructE, the Institution of Civil Engineers, Climate Group, MPA The Concrete Centre, and the UK Low Carbon Concrete Group found the use of ground granulated blast furnace slag, a co-product of the iron and steel industry, is likely to be ineffective in reducing GHG emissions when increasing its use locally above current levels.



Note: The line represents concrete strength 4,001-5,000 psi concrete. The shaded region represents the range of GWP values for all other strengths of concrete.

Exhibit 2 | RMI Graphic. Source: RMI, *Roadmap to Reaching Zero Embodied Carbon In Federal Building Projects*, https://rmi.org/insight/roadmap-to-reaching-zero-embodied-carbon-in-federal-building-projects/

Steel Solutions

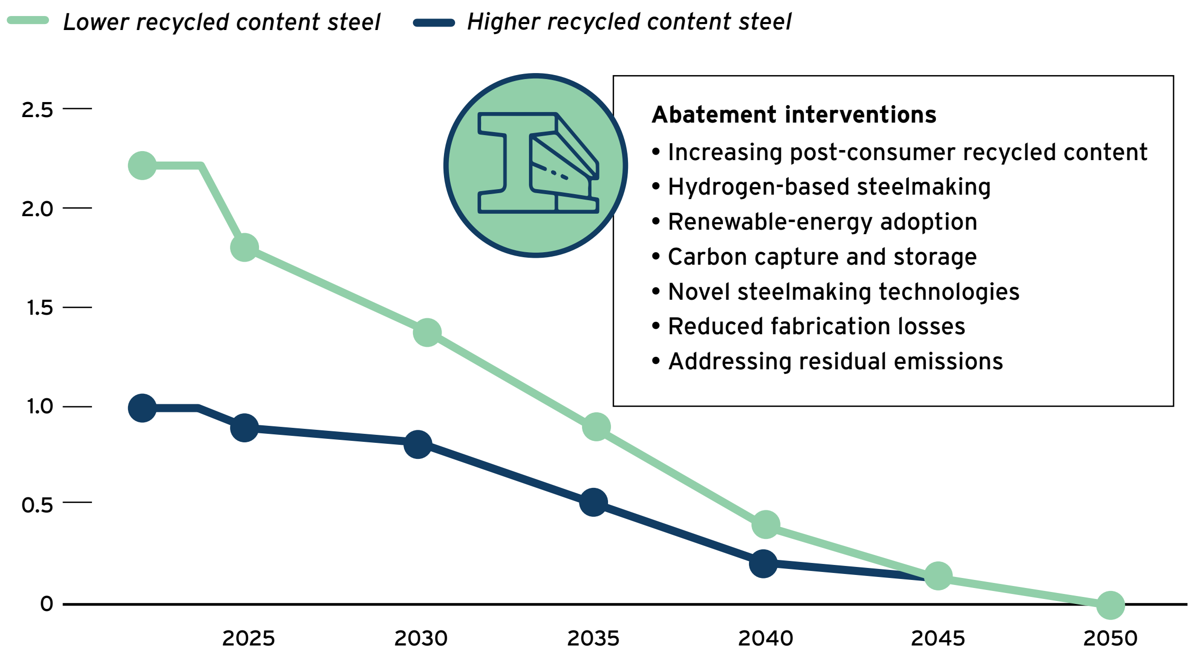
In the steel sector, it is important to acknowledge that steel products may have different pathways to near zero depending on their scrap ratio. Reinforcement bars (rebar) typically have high recycled steel content and thus warrant different target values toward net zero because they will have a lower GWP baseline than steel products with higher percentages of primary steel (ore-based material). Regardless of the steel type, the best strategies to further reduce the carbon intensity of steel include increasing secondary (recycled) steel content when feasible, transitioning to clean renewable energy, hydrogen fuel sources for production, technological improvements in the processes of making steel, and on-site carbon capture.[7] It is worth noting that the US steel industry generally already uses recycled content steel at the maximum amounts possible, so while specifying recycled steel is a necessary strategy, it's not likely affecting movement beyond standard practice. Innovations to cut the high embodied energy intensities of steel need to prioritize next generation solutions beyond recycled content.

The production process of steel has a great impact on carbon intensity. Of the two main production methods, the basic oxygen furnace (BOF) production of steel is widely known to be more emissions-intensive than electric arc furnace (EAF). However, explicit requirements for one type of production may have unintended consequences that would not optimize the decarbonization of steel production. US domestic primary steel production will remain a key component of the steel industry well into the future because the entire demand for steel products cannot be met with EAF processes alone.[8]

As more efficient manufacturing is recommended, it is important to include BOF smelters in the requirements, so those high-intensity processes are also decarbonized instead of escaping to regions with less strict regulations for people and the environment. Example requirements that apply to both types of manufacturing include hydrogen-based steel production and specifying a certain level of renewable energy sources in manufacturing. This can be considered when the facility is certified by ResponsibleSteel above the lowest level, participates in the US EPA Green Power Partnership program (renewable power procurement registry), or provides records of renewable energy sourcing.[ii] A potential path to near zero for the steel sector is depicted in Exhibit 3.[9]

Steel decarbonization

GWP pathway based on technology transitions and other considerations, $kgCO_2e/m^3$



Note: This trajectory shows steel reaching absolute zero by 2050 and includes carbon removals against residual emissions.

Exhibit 3 | RMI Graphic. Source: RMI, *Roadmap to Reaching Zero Embodied Carbon In Federal Building Projects*, https://rmi.org/insight/roadmap-to-reaching-zero-embodied-carbon-in-federal-building-projects/

Encouragingly, low-carbon concrete and steel products are already starting to enter the market. Some ancient techniques like the use of earthen materials (e.g., rammed earth) are emerging as viable sustainable alternatives to concrete and masonry with help of advanced manufacturing techniques. A few of many promising technologies for lower-carbon material alternatives are summarized in Exhibit 4 (next page).

ii Documentation can come from on-site or off-site renewable energy systems, community renewable energy facilities, or through physical or financial renewable energy power purchase agreements.

Promising technologies for lower-embodied carbon material alternatives

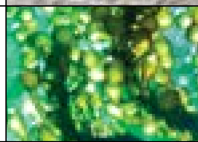
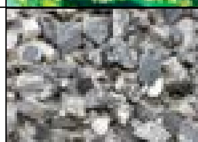
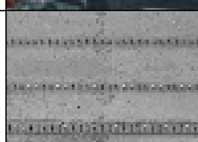
LC3 cement		Limestone calcined clay cement: uses current cement kiln technology but replaces much clinker content with clay (40% clinker reduction)
Bio-cement/ bio-concrete		Ultra-low-embodied-carbon biocement and bio-concrete from microalgae and other natural components (90% carbon footprint reduction)
Synthetic limestone aggregate		Carbon capture and mineralization into aggregate (-494 kg CO_2 stored per cubic yard of concrete)
Rammed Earth components		Walls made of 100% natural and recyclable earthen material that can be sourced directly from building excavation sites
Automated prefabrication of rebar		Automated assembly of simple and complex steel reinforcement bar cages, shipped to site fully prefabricated
Lightweight Steel girders		Lightweight steel plate girder using a corrugated web (30% less steel for the same strength)
Electrolysis technology		Molton oxide electrolysis technology to separate iron from ore without releasing CO_2, eliminating the need for coal in steel production

Exhibit 4 | RMI Graphic. Source: RMI analysis

ACTIONS

- Research and specify low-embodied-carbon options for concrete and steel when available. Go beyond standard practice of recycled fly ash and steel to spur next-level solutions.
- Less is more: Even when low-embodied-carbon alternatives are used, consider ways to minimize material volume by optimizing building design for efficient material usage and space requirements.
- Accelerate the development and support the advancement of low-embodied-carbon materials for the industry by using innovative low-embodied-carbon and carbon-storing materials where possible.

Endnotes

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Can Wood Products Benefit the Climate?

KEY TAKEAWAYS

- Embodied carbon benefits from the increased use of wood products in buildings are being debated now, but there are clear wins and strategies project teams can implement to ensure wood products are legal, yields are sustainable, and forestry practices are trending toward climate-resilient outcomes.
- Climate-responsible forestry practices maximize the net climate benefit of forests by increasing net-carbon stocks (i.e., reducing atmospheric carbon) and balancing land use and other ecological impacts.
- It is best practice today to report biogenic carbon storage values separately to enable effective comparisons and discourage the inefficient use of timber.
- Increased disclosure for wood products including information about the source forests and mills can encourage responsible forest management practices with higher sustainability standards than current regulatory requirements.

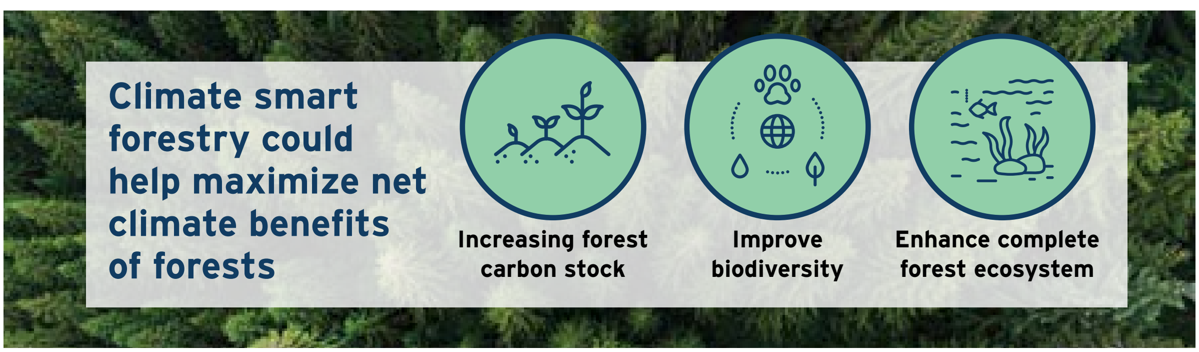

Exhibit 1 | RMI Graphic. Source: RMI analysis

It All Comes Down to the Sourcing

Wood used in building products has the potential to be a renewable, and perhaps carbon-storing material that can help drive down embodied carbon emissions when efficiently substituted for high-impact materials. However, there are aspects of wood sourcing—such as forestry practices with poor climate outcomes, wider land-use impacts, and energy-intensive product manufacturing—that can lead wood to have high emission and ecological impacts. For these reasons, the jury is still out on whether an expanded use of wood products in building structures and enclosures is a net carbon benefit or a carbon penalty on

Many in the forestry industry recognize that new and conscientious management practices are necessary to protect, restore, and grow the world's forests due to our changing climate and land-related human interventions.

a global scale. It may be that either answer is true, and the building industry will need to learn to tell the difference between wood products with good or bad climate consequences.

Many in the forestry industry recognize that new and conscientious management practices are necessary to protect, restore, and grow the world's forests due to our changing climate and land-related human interventions. A new crop of “climate responsible” or climate resilient forestry practices and standards are beginning to take hold. Wood will continue to be an important material for construction, and there are best practices to ensure wood comes from documented well-managed sources. Greater life-cycle impacts data and transparency of wood products such as EPDs are needed to make better informed choices. Wood products must be sourced and manufactured in ways that go beyond regulatory minimums and foster regenerative and climate-resilient solutions.

Wood is fundamentally different from commodity mineral supply chains and therefore warrants a more diverse approach. Central to the understanding of sustainable wood is the assurance the use of timber-based materials gives “maximum genuine benefit in terms of reducing atmospheric carbon.”[1] When forests are sustainably managed such that there is a net increase in regional carbon storage and forest health, resulting wood products used in buildings can prolong net carbon storage.

Forests with increasing carbon stocks behave as resilient sinks for atmospheric carbon.[2] Forest health also relies on the preservation of ecological diversity and fostering of climate change resilience (e.g., against wildfires) through sustainable forest management.[3] The key indicators of ecologically managed forests are practices that improve wildlife habitat, protect high conservation value forests, minimize logging roads, protect waterways, reduce the use of pesticides, reforest responsibly after cutting, avoid displacing land usage elsewhere, and manage lands to mitigate impacts from climate change. Efforts are underway to better define practices that benefit forests in a changing climate, such as Climate Smart Forestry practices and the New England Exemplary Forestry program.[4]

The use of wood products in buildings can correlate with net emissions rather than net storage when forests are managed in a way that does not replenish the carbon cycle. Poor forest management practices include illegal logging, forest conversion to other uses, extensive use of herbicides, and clear-cutting on short rotation cycles.[i] These practices can reduce the carbon storage potential of forests and lead to net carbon emissions along with negative effects on water quality and fish habitat, increases in soil erosion and landslide risk, and chemical contamination. Several of these non-carbon impacts are captured in WBLCA, which examines additional environmental impacts such as acidification and eutrophication. At the end of life, wood products tend to end up in incinerators or landfills, generating GHG emissions and diminishing the benefits of having removed carbon from the atmosphere.

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i Note that what is considered a short rotation cycle depends on the tree species and climates.

TREE-LEVEL CARBON FLOWS

Let us examine carbon flows at the tree level to understand how there can be net emissions with forestry operations. How a tree is used is critical because carbon is stored not only in the trunk of the tree, but also in all the branches and the soil as well as parts of the tree that will be trimmed during milling. By the time a tree is harvested, sawn, and manufactured into a wood product, the Climate Smart Wood Procurement Guide estimates only 25% of the carbon held in the living tree will be retained in finished lumber products.[5] The remaining carbon will likely return to the atmosphere relatively quickly through the decay of slash and root mass left in the forest, incineration of sawmill waste, and emissions from disturbed and eroded soil. All carbon flows from a tree need to be considered for an accurate understanding of the carbon footprint of harvests and resulting wood products.

Exhibit 2 | RMI Graphic. Source: Climate Smart Wood Procurement Guide, https://www.climatesmartwood.net/procurement/.

Wood certifications like the Forest Stewardship Council and Sustainable Forestry Initiative indicate products sourced from forests with improved management practices, but only recently are these standards beginning to address climate mitigation specifically. Although better climate outcomes have been attributed to improved management practices, direct climate benefits are not necessarily assured by wood certifications. A recent study suggests forest harvests have net carbon emissions even when accounting for forest regrowth, benefits of avoided emissions through wood substitution for higher-impact materials, and other changes in carbon pools over time.[6] Sourcing wood products from certified forests is best practice and achieves a lot of positive impacts, but it is too soon to attribute meaningful carbon storage to all certified wood.

For many product categories, project teams can turn to EPDs to get a robust sense of the emissions — and, unevenly, the carbon storage — in a product. However, EPDs for wood products do not currently account for all the carbon flows associated with wood harvesting. Excluded from EPDs for wood products are emissions from soil degradation, slash decomposition, and leftover forest wood waste and residue incineration. Information about forest management practices and source forests is typically not included.

What is included and not included in a wood product EPD?

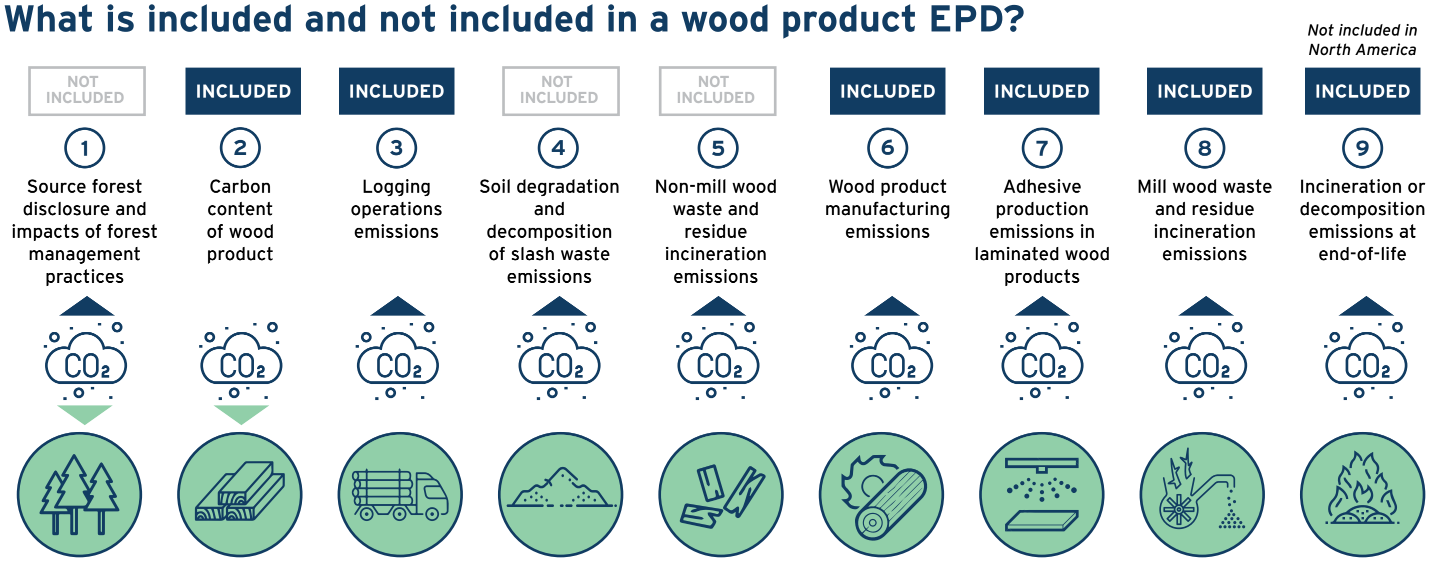

Exhibit 3 | RMI Graphic. Source: RMI analysis

Estimating biogenic carbon storage for wood products is complicated by time factors as well. Each tree accumulates atmospheric carbon slowly over decades, and there is no consensus on whether this type of long-cycle carbon storage should be calculated in a backward-looking manner — where carbon removals from past decades are measured by the amount of historic carbon contained in a product — or in a forward-looking manner — where carbon removals are estimated by the regrowth of new trees.[7] In the former case, all the carbon storage is considered to have happened up front, providing a potentially large attribution to a new building. In the latter case, the carbon storage will accrue slowly over decades and will be attributed to the building only in a WLCA, achieving full carbon storage value when the replanted trees reach maturity. Clearly, these two approaches will result in very different embodied carbon results, adding further uncertainty to claims for carbon storage in wood products.

So, when is timber a good strategy for reducing embodied carbon? An important prerequisite is identifying the source forest as sustainably managed by the highest possible standard. With this condition met, an embodied carbon assessment of a project can be conducted to determine whether the substitution of wood products for high-intensity materials results in a lower carbon footprint. Today's best practice would

CARBON NEUTRALITY ASSUMPTION

ISO 21930 defines sustainably managed forests as those with stable or increasing forest carbon stocks, which should help ensure positive climate impacts. This sounds good in theory, but forest carbon stocks are measured on either a national or regional level rather than at the forest level. Wood is a highly site-specific material, and national levels of forest carbon stocks do not properly represent the health of local forest practices. Additionally, this broad averaging definition of carbon neutrality on a continental scale has limited usefulness in guiding impactful procurement choices.[8] As one of the world's largest carbon sinks, forests play a critical role in regulating the climate, and it is crucial to not degrade the health of any regional forests due to a false sense of adequate forestry practices.

be to exclude biogenic carbon storage in the comparison, due to the uncertainties described above. This allows for effective comparisons, discourages the inefficient use of timber, and maintains focus on the important challenge of reducing the amount of building construction material overall.[9]

As with all embodied carbon decisions, specifying reused wood products will have positive impacts from avoiding the end-of-life emissions and reducing the need for new timber harvest. Programs are developing to create new timber products from recycled sources and from forest thinnings and wildfire prevention practices, which should have very favorable outcomes in terms of embodied carbon.

The market plays an important role in enabling and encouraging sustainable forestry due to limited regulation ensuring best practice for climate-responsible forest management. Wood sourcing should be prioritized from areas where risks to forest health, including fire and pests, require the management and harvest of trees (targeted harvest). This can lead to a positive effect on the ecological and climate health of forests, while positively contributing to timber markets and prolonged storage in long-lived products. Due to the complexity of wood sourcing impacts, supply chains with net positive climate impacts will vary locally. Foresters are trained with a deep understanding of the numerous diverse and local needs of forests. Deeper engagement with local foresters can help identify prime sources of wood that are byproducts of active management or waste products. Organizations like Climate Smart Wood Group and Cambium Carbon provide support with climate responsible wood procurement.[10]

The 3S Framework, a useful framework proposed by the Climate Smart Forest Economy Program, identifies three key climate impact categories from wood products: sink, storage, and substitution.[11] More comprehensive, accurate, and locally differentiated quantification of the sink, storage, and substitution impacts of wood supply chains can help shed light on the degree to which a given use of wood in construction has net climate benefits or negative impacts.

The question of whether harvesting timber for building construction provides an overall climate benefit is one of enormous complexity. Some sources point to sizable carbon benefits, while others suggest the use of more timber should be approached with caution. While the debate continues, there is no doubt that greater disclosure is required from supply chains and project teams to add more transparency and traceability to the wood supply chain and encourage best forest management practices with higher sustainability standards than regulatory requirements. In the meantime, we can take steps to source wood from the best possible sources given what we know and ask for additional disclosure and information to fill in any knowledge gaps.

ACTIONS

- Avoid illegally logged wood by seeking certifications and rigorously documented sources.
- Seek opportunities to incorporate local salvaged wood or waste wood products (e.g., thinnings from management of wildfire risks) by proactively engaging with forest managers to understand what needs (and opportunities) there are in terms of targeted wood utilization in their region.
- Prioritize specification and procurement of sustainably harvested wood and increase wood source transparency by requesting EPDs that include information about source forests and forest management practices.
- Perform holistic embodied carbon analysis of scenarios where wood might replace other materials and ensure there is an overall climate benefit prior to including biogenic carbon storage.

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Is Carbon Storage in Buildings Really Possible?

KEY TAKEAWAYS

- Carbon-storing building products, whether biogenic or mineral, offer the building industry an unprecedented opportunity to not only reduce emissions but also to eventually reverse the carbon flow from the sector.
- Only a small percentage of building construction material would need to be carbon storing to become a leading climate drawdown solution.
- Although some carbon-storing materials are nascent, others are well-established incumbents with proven histories. Support is needed to increase the uptake of carbon-storing materials.

Carbon storage is a necessary new paradigm

See more detail on end-of-life scenarios on Page 62

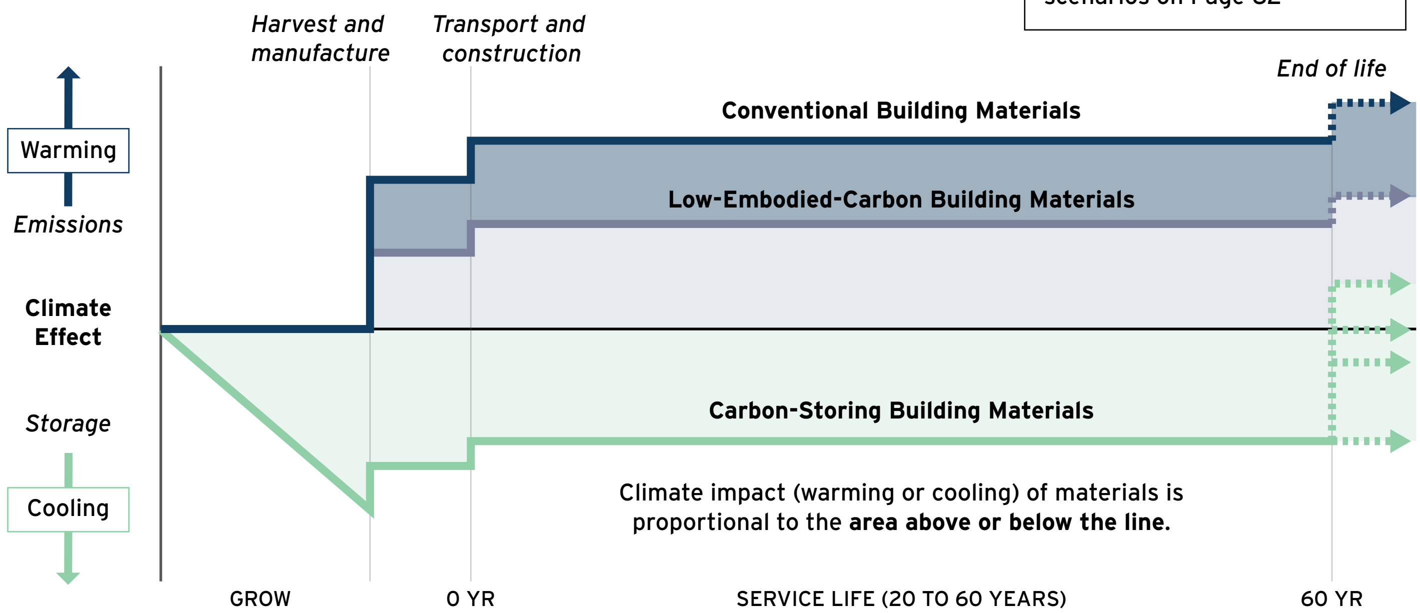


Exhibit 1 | RMI Graphic. Source: Bruce King and Chris Magwood, *Build Beyond Zero*

Yes!

The potential for buildings to become sites for vast amounts of carbon storage is only now starting to be recognized and presents the potential for a major paradigm shift in embodied carbon from buildings. In our lifetimes, we could see buildings move from being leading drivers of climate change to safely and durably storing gigatons of atmospheric carbon. There is a long way to go to achieve such an ambitious goal, but it is not as far-fetched as it may seem. Buildings currently account for nearly 50% of global material flows.[1] In the United States, nearly 75% of the 4.5 billion tons of raw material flows are destined for use in buildings and infrastructure each year.[2] Only a small percentage of that material would need to store carbon to become a leading climate drawdown solution.

The topic of carbon storage in building materials is currently not well understood and suffers from inconsistent treatment in LCA standards and carbon-removal schemes. The first thing to understand about carbon-storing building materials is they come in many forms, and each form has unique life-cycle considerations with distinct advantages and disadvantages. There are two broad categories of carbon-storing materials, with unique subcategories in both.

Categories of carbon-storing materials

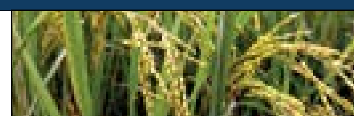
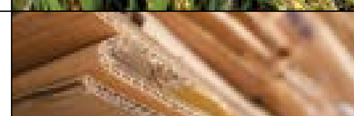
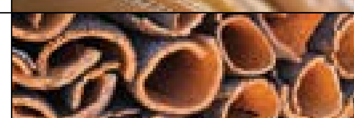
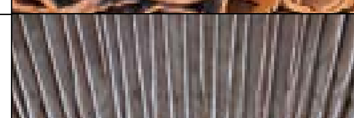
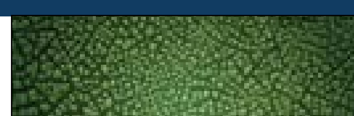
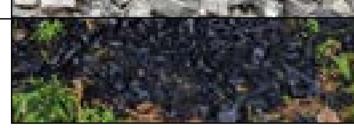
SOURCES			PRODUCTS
Biogenic Carbon Storage			
Agricultural and forestry residues and by-products	Straw (rice, wheat), hulls (rice), shells (nuts), stalks		Board products, insulation, cladding, aggregate
Waste stream fibers	Paper, cardboard, textiles		Board products, insulation
Purpose-grown crops	Cork, bamboo, hemp		Boards, flooring, insulation, structure, cladding
Lab-grown materials	Mycelium composites		Insulation, structure
Timber	Lumber, mass timber, sheet goods		Structure, board products, flooring, cladding
Mineralized Carbon Storage			
Biomineralization	Algae and microbe-grown cement		Concrete, concrete masonry unit (CMU), brick
Captured carbon	Synthetic limestone aggregate and accelerated carbonation		Concrete, CMU, brick
Biochar	Biogenic carbon transformed into stable, pyrogenic carbon through combustion in the absence of oxygen		Aggregate, tiles, bricks

Exhibit 2 | RMI Graphic. Source: RMI Analysis.

Biogenic materials achieve carbon storage via photosynthesis. As plants grow, they absorb carbon dioxide from the atmosphere and keep the carbon atoms while expelling the oxygen. The amount of atmospheric carbon embodied in dry plant matter is significant, ranging from 35% to 55% of the mass. Uninterrupted, this carbon typically ends up back in the atmosphere relatively quickly, through digestion, combustion, and/or decomposition. By interrupting this cycle and durably storing this carbon in buildings, it is possible to reduce the amount of CO_2 in the atmosphere, helping avoid further buildup and assisting in the upcoming decades of mitigation and carbon removal necessary to meet climate targets.

The category of biogenic materials includes many longtime construction industry incumbents like timber, cellulose insulation, bamboo, and cork, as well as many options that have a long history in buildings but not mainstream uptake, such as straw and hemp. These resources are often regionally available and need minimal processing, avoiding manufacturing processes that typically add carbon emissions. Innovative work is blossoming with newer materials using a wide range of feedstocks, including shells (from palm oil and coconut), hulls, annual grasses, and mycelium.

Biogenic feedstocks accumulate in the billions of tons annually (grain straw alone draws down nearly 4 billion tons of CO_2 each year, the equivalent of removing all of India's emissions), providing a unique opportunity for atmospheric carbon removal when converted into building materials.[3] An analysis of new homes in Canada indicates annual net carbon storage in this sector could feasibly grow to 3 million tons per year, using available materials that have been employed in code-approved buildings.[4] Opportunities in larger countries and those with rapidly growing housing stock could increase this to hundreds of millions of tons per year.

WHAT BIOGENIC MATERIALS IN BUILDINGS LOOK LIKE

Until recently, innovative, biogenic materials have been applied mostly on small buildings, but this has been changing in recent years. Today, there are examples of multistory and large buildings using large quantities of non-wood biogenic materials, often as components of prefabricated wall and roof panel systems. Straw and hemp building systems have been included in the International Residential Code, and the depth of testing data is growing rapidly. Increased demand from the building industry and support for R&D and manufacturing could enable these materials to scale quickly.

Strategic use of biogenic materials that provide insulation offers opportunities to address energy efficiency improvements and provide carbon storage at the same time. A recent analysis of multifamily deep-energy retrofits showed currently available biogenic insulation materials could be used to reduce energy consumption by more than 50% while storing more than 5 tons of carbon.[5] Given the vast number of buildings in the United States that have been identified as requiring additional insulation, the use of biogenic insulation materials offers a win-win scenario.

Many biogenic materials are used for interior finishes. The high amount of surface area requiring finishes in buildings offers another opportunity for large-scale carbon storage in buildings using incumbent materials. Surface-finish applications require lower thresholds of testing and performance compared with structural and enclosure materials and are therefore a faster path to commercialization for new and developing biogenic products.

ACCOUNTING FOR BIOGENIC CARBON STORAGE

Accounting for biogenic carbon has, to date, been inconsistent and therefore confusing. LCA standards have accepted three different ways of reporting biogenic carbon flows, which provide very different results. Current best practice reports biogenic carbon flows into and out of a product's life cycle as distinct values, enabling a transparent view of how much carbon is stored in a product and providing indicators of the timeline of storage and potential outflow back to the atmosphere. As this reporting format becomes standard, it will become easier to identify and understand biogenic carbon in building products.

Ascribing climate impacts to relatively short-term carbon storage (ranging from one decade to one century or more, depending on the product) has also been inconsistent and confusing. Carbon dioxide removal (CDR) has been identified by the Intergovernmental Panel on Climate Change as necessary to meet the targets for limiting the rise in global temperatures to 1.5°C, but the vast potential of biogenic building materials to help achieve large-scale CDR has not been widely identified. Complicating efforts to value biogenic carbon storage are different factors associated with each category of biogenic feedstock. It is likely unique calculations will need to be developed for each based on a range of factors that include:

- **Growth cycle:** Biomass that grows annually in a single season has a different emissions profile than that with a growth cycle of years or decades.
- **Farming practices:** Attention needs to be paid to potential impacts from the use of fertilizer, pesticides, and water. Many of these factors can be captured in an EPD if included by the manufacturer. Organic certification of crops can help ensure minimized impacts, and sourcing from regenerative farms is ideal.
- **Land-use change:** Biomass that is a co-product or residue of existing crops or product cycles differs in land-use-change emissions from that which requires significant new or additional land-use change (such as cutting down forests to grow crops).
- **Afforestation and reforestation:** Repairing damaged or degraded forests that have been converted to other uses that do not store carbon is essential.
- **Diversion from existing uses:** Using biomass stocks with an existing end use can create competition and unintentional emissions increases compared with stocks that are currently burned or rotted.
- **Emissions from production:** Biogenic products with high emissions from harvesting and/or processing will offer less net storage. This will be captured in an EPD.
- **Life span in building:** Biogenic products with a long life in a building offer more impactful climate benefits than those that need frequent replacement.
- **End-of-life scenarios:** Biogenic products that can be reused or recycled differ from those destined to reemit carbon due to incineration or methane from landfill, with radically different results in embodied carbon. Currently, LCA practice assumes incineration and/or landfill will be the fate of all biogenic materials, resulting in some amount of carbon release back to the atmosphere. However, conversion to biochar (incineration in the absence of oxygen) and incineration with carbon capture can both result in minimal release and continued long-term storage for most of the carbon content. Recycling and reuse of biogenic materials will continue the duration of carbon storage and bring additional benefits.

SEE EXHIBIT 3, NEXT PAGE

End-of-life scenarios for bio-based materials

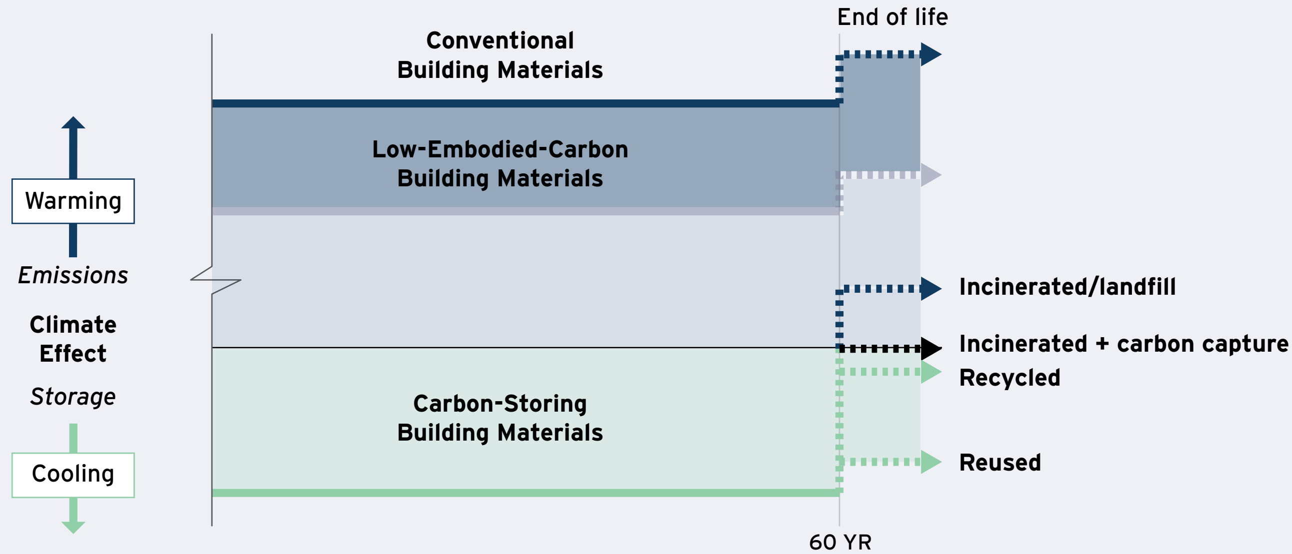


Exhibit 3 | RMI Graphic. Source: RMI analysis

Each of these factors needs to be properly weighed to provide a more nuanced understanding of the potential climate benefits of a particular biogenic product.

The market for biogenic building products other than timber is currently quite small. But the technology and production knowledge to enable rapid scaling are well understood, affordable, and achievable, often with much less investment than required for abatement of emissions from conventional products or other CDR technologies currently being explored and developed. The world needs both building materials and as many CDR opportunities as possible. A move to increase the use of biogenic building products can provide both.

The performance characteristics of biogenic materials are often misunderstood and lead to skepticism regarding their use, despite the long-term success of incumbent biogenic materials such as timber and cellulose insulation. Fire, structural, and/or thermal performance and durability are subject to the same testing regimens as all building materials and need to be applied according to their performance characteristics and manufacturer recommendations.

Guidance about the positive climate impact of biogenic carbon storage is developing but is still inconsistent. Some standards, such as the Integrity Council for the Voluntary Carbon Market, suggest a minimum of 40 years of storage duration, while others, such as Puro.Earth, require 100 years.[6] Agreement on duration of carbon storage could unlock valuable carbon storage credits for biogenic carbon in buildings, incentivizing development and uptake of biogenic materials.

Biogenic materials will not solve our embodied carbon problem. As with timber products, the climate and social impacts of bio-based building materials can vary widely. The most promising bio-based materials use waste-stream fibers or agricultural residues, making use of biomass that has already been created for other purposes and preventing these by-products from returning to the atmosphere. Purpose-grown and lab-grown crops need to come from climate-smart, well-managed sources. Some certifications, such as organic and regenerative farming labels, exist to help identify reputable sources, but most biogenic raw materials do not achieve certification. The building industry should demand the same level of transparency for all bio-based materials as forest products.

Mineralized materials achieve carbon storage using atmospheric carbon as a feedstock in a chemical process that binds the carbon atoms into a stable mineral form. This can be achieved by using biological processes (as with coral growth) or technological processes that use captured CO_2 as an ingredient (as with synthetic limestone production). If the emissions required to turn atmospheric carbon into a rocklike substance are less than the amount of CO_2 absorbed in the process, such materials can offer net carbon storage in a building product.

Today, mineralized products are less common than their biogenic counterparts, but there is a great deal of research and innovation taking place in this field, especially in the cement and aggregate industries. Some early products – such as bio-based cement and geo-mimetic mineralization – are beginning to find their way to the market in limited quantities and are generating excitement about the potential for high volumes of carbon storage in concrete, dramatically changing the emissions paradigm of this ubiquitous material.

Mineralized products lock up atmospheric carbon for centuries, avoiding the question of durability that can plague biogenic materials. Unlike efforts to store carbon underground or in deep ocean reservoirs, these types of products create value-added uses for carbon. It makes more sense to invest in carbon storage if it is in a product with inherent market value than to have that feedstock locked away in the Earth's crust, often at substantial financial cost. Mineral building and infrastructure products — largely rock, gravel, and sand — make up more than 50% of global material flows, and replacing even a small percentage of this tonnage with stored carbon offers a major climate solution.

Carbon-storing building products, whether biogenic or mineral, offer the building industry an unprecedented opportunity to not only reduce emissions but also eventually reverse the carbon flow from the sector.

ACTIONS

- Actively engage in education about incumbent and emerging carbon-storing materials to understand how they can best be incorporated into projects.
- Consider sustainably sourced, rapidly renewable biobased or mineralized materials to replace high-emitting materials across all sections of a building and for all types of buildings.
- Publicize the use of carbon-storing materials in your projects through case studies and documentation.
- Aim to offset carbon-emitting impacts with carbon-storing materials in every project.

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What Does the Policy Landscape Look Like for Embodied Carbon?

KEY TAKEAWAYS

- There are numerous federal and state-level legislations in the United States passed to promote the procurement of low-embodied-carbon materials for construction, with more on the way.
- Globally, regulations on whole-building carbon footprint limits are gaining momentum.
- Although material-level approaches are more common in the United States currently, we can expect a transition toward building-level approaches in the near future as the developments in Europe and Canada provide an indication of what is to come in other markets around the world.

Regulations have different starting points, but are headed toward whole building GWP limits

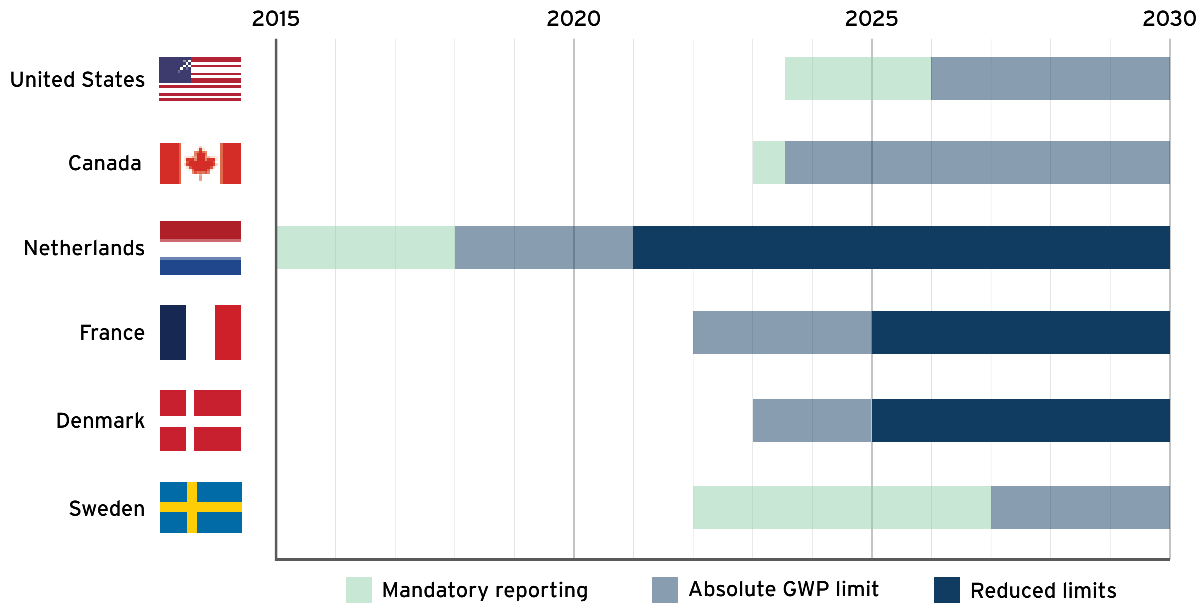

Exhibit 1 | RMI Graphic. Source: Jannik Giesekam, http://www.jannikgiesekam.co.uk/embodiedcarbon/

Embodied Carbon Policy Limits Are Coming

Momentum in initiatives and regulations on embodied carbon in building construction started picking up around 2017, when CLF's pivotal benchmarking study came out in the United States and the Level(s) Framework was published in Europe.[1] Since then, there have been a number of public roadmaps, published

In August 2023, California became the first state in the United States to approve a whole-building embodied carbon policy in CALGreen, effective from July 2024.

guidance and standards, voluntary programs for low-embodied-carbon construction, and even national legislation to reduce the carbon footprint of buildings. Part of this was spurred by local action on declaring a climate emergency by local governments. These actions have shone a light on the need to cut carbon fast, and many now recognize embodied carbon is low-hanging fruit ripe for the picking.

The United States has seen a surge of federal and state-level action plans and programs aimed at reducing the embodied carbon of construction materials. At the federal level, in May of 2023, the General Services Administration's (GSA's) began piloting "Buy Clean Inflation Reduction Act Requirements" for low-embodied-carbon construction materials in government projects.[2] As of June 2023, several states including California, Colorado, and Maryland have passed Buy Clean acts that promote the procurement of low-embodied-carbon construction materials. There are also financial incentive programs aimed at rewarding projects with low-embodied-carbon footprints, such as the Massachusetts Clean Energy Center's embodied carbon reduction challenge.[3] In a similar vein, Vancouver's NearZero program includes a stream that rewards low-embodied-carbon, low-rise residential home construction with varying compensation amounts depending on the percentage of embodied carbon reduction.[4]

In August 2023, California became the first state in the United States to approve a whole-building embodied carbon policy in CALGreen, effective starting in July 2024. This policy is applicable to most large buildings and has three possible compliance pathways, one of which is the demonstration of a 10% reduction of GWP from a baseline.[5]

Globally, we see similar rigorous regulations. Toronto recently became the first jurisdiction in North America to enact whole-building embodied carbon caps on new city-owned buildings, prescribing embodied carbon caps for structure and enclosure.[6] The City of Vancouver, British Columbia, requires project teams submitting a rezoning permit to calculate their whole-building life-cycle embodied carbon intensity.[7] RE2020 is an environmental regulation in France requiring new building projects be below maximum GWP values with assessments covering an extensive scope of building life-cycle stages and building layers. This policy takes a dynamic approach to benchmarking, decreasing the maximum GWP values every few years.[8] The London Plan Policy SI 2 requires mandatory WLCAs for large-scale developments with suggested GWP limits for different building typologies and life-cycle stages.[9]

On the other hand, limits can be established from science-based targets, for example, determining what the allowable carbon budget is to avoid the worst effects of climate change. The Science Based Targets Initiative is developing guidance on embodied carbon for the buildings sector that abides by the whole-building approach.[10] The guide provides up-front emissions pathways for different building typologies from 2025 to 2050 in line with the global carbon budget. This provides an indication not of where the building sector wants to be, but where it needs to be. Certifications, such as LEED, can amplify the impact of these leading regulations by referencing them or building from them, helping ensure that all major systems are pulling in the same direction.

Timeline of addressing embodied carbon

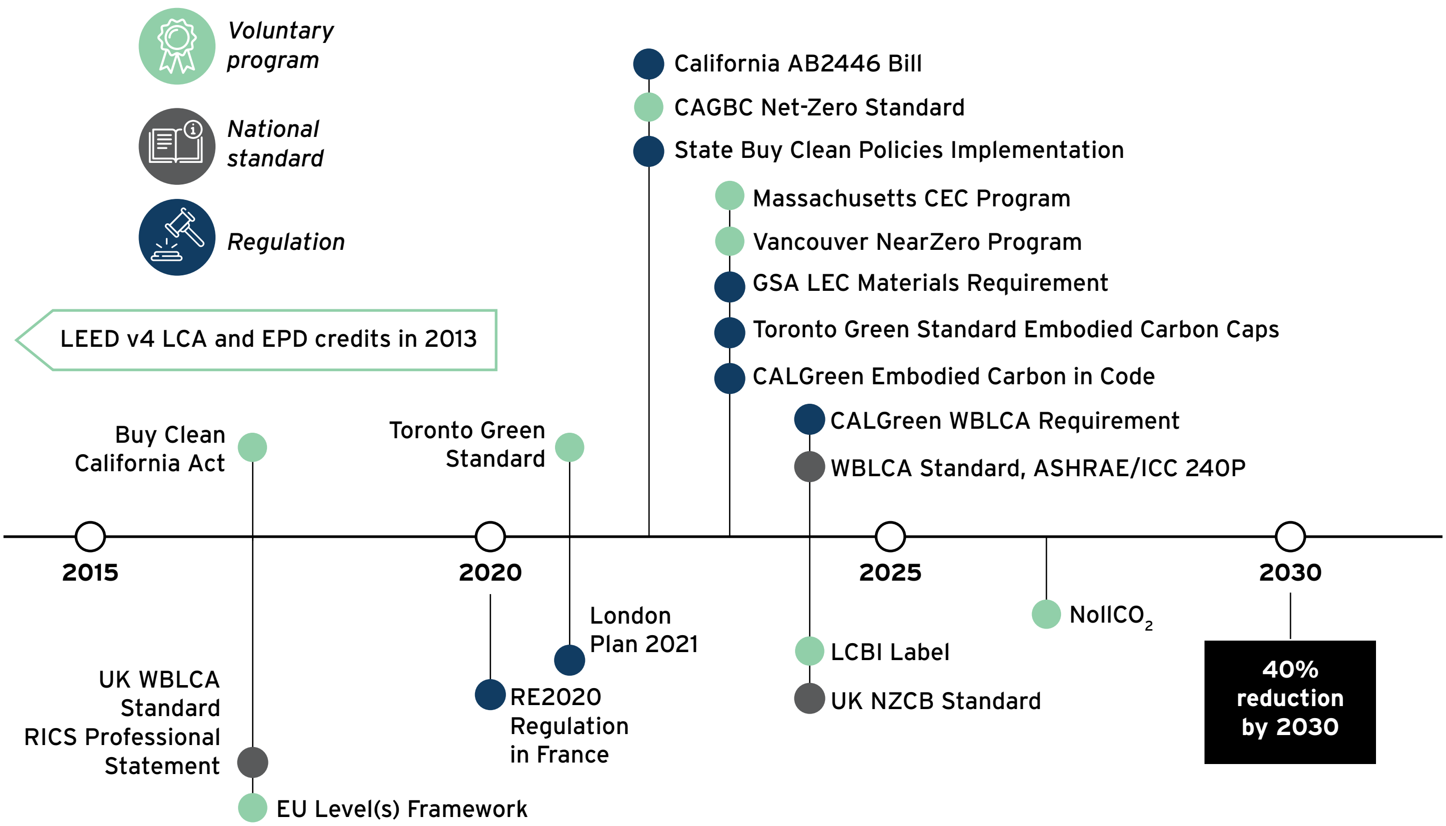

Exhibit 2 | RMI Graphic. Source: RMI analysis

Underpinning these various regulations are a number of carbon accounting standards, frameworks, and voluntary labels for high performers. In Canada, the Canadian Green Building Council's Zero Carbon Building Design Standard is a voluntary standard with both absolute and comparative compliance options.[11] The Toronto Green Standard mirrors the city-owned buildings requirements as voluntary tiers for the private sector. The most comprehensive published whole-life carbon standard to date is the RICS Professional Statement on Whole Life Carbon Assessment in the UK.[12] A similar standard with international applicability is currently in development, known as the ASHRAE/ICC 240p standard.[13]

Emerging low-embodied-carbon building labels include Europe's LCBI label (which aligns with the EU-wide Level(s) Framework) and Sweden's NollCO$_2$ Certification, providing benchmarks at different performance levels. Additional initiatives to progress benchmarking efforts, common definitions of net-zero, standardized reporting, and data collection include World Business Council for Sustainable Development's Building System Carbon Framework, the Built Environment Carbon Database in the UK, and the UK Net Zero Building Carbon Standard. There is also an effort among rating systems, professional pledge organizations, and researchers to align criteria in North America.[14]

CIRCULAR ECONOMY ORDINANCES

Circularity approaches such as recycling, material reuse from deconstruction, and adaptive building reuse to increase material recovery and reuse have a considerable impact on reducing the carbon footprint of the built environment. There are several policy opportunities to increase material circularity in the built environment, some of which are already in place today.[15,i]

ADAPTIVE REUSE	WASTE MANAGEMENT	DECONSTRUCTION	EXTENDED PRODUCER RESPONSIBILITY
■ Fairfax County Adaptive Reuse Program ■ Long Beach Municipal Code Adaptive Reuse Ordinance ■ East Colfax Adaptive Reuse Program ■ City of Phoenix adaptive reuse incentives	■ California Green Building Code waste diversion ■ Toronto Green Standard waste diversion ■ ICC International Green Construction Code waste diversion ■ ASHRAE Standard 189.1 waste diversion and demolition plan	■ Seattle Public Utilities and Hennepin County incentives ■ San Antonio; Portland, Oregon; Milwaukee; Palo Alto, California, deconstruction ordinances ■ Pittsburgh deconstruction pilot programs ■ Vancouver Green Demolition Bylaw	■ California various stewardship programs (paint, carpet, mattresses) ■ France's Anti-Waste and Circular Economy Law

The developments in Europe and Canada provide an indication of what is to come in other markets around the world. Although material-focused approaches are more common in the United States currently, we can expect a transition toward building-level approaches in the near future. This is already the case in California with the passing of the AB 2446 bill targeting a 40% reduction in embodied carbon by 2035 and measured through building LCA with a focus on product stages A1–A3. Additionally, CLF is currently working on a rigorous benchmarking study with the goal to enable building owners, designers, policymakers, and building certification schemes to set benchmarks and evaluate environmental impacts of buildings. Performance targets may emerge from the data provided, and practitioners can get ahead by starting to conduct and understand the results of building LCA.

i Opportunities include providing incentives for building reuse, prescriptive design standards to use future adaptability for new construction, improved construction and demolition waste management ordinances, deconstruction ordinances, and introducing the concept of material passports.

ACTIONS

- Prepare for future regulations by familiarizing with building-level LCA, referring to national standards such as the developing ASHARAE/ICC 240p standard.
- Review federal and state regulations aimed at low-embodied-carbon construction material procurement and try to meet published limits such as the GSA benchmarks for construction materials.
- Actively support local, regional, and national policies that address embodied carbon through the development and implementation of climate action plans, updated zoning requirements, procurement guidelines, updated building codes, and voluntary programs.
- Where possible, align on key terminology, reporting methodology, and datasets to speed action in the same direction.

Endnotes

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What Are Some Examples of Action on Embodied Carbon?

Case studies can help bridge gaps between ideas about addressing embodied carbon and actions that begin to create measurable results. Each of the three case studies presented here demonstrates action on key themes: building re-use, design and procurement solutions, and the use of carbon storing materials. All three share a commitment to addressing operational emissions, reinforcing the point that operational and embodied carbon need not compete for attention but rather can be addressed holistically.

Every building project is unique, and lessons learned in case studies cannot always be applied directly to another project. Underlying all three case studies is a common approach: setting measurable embodied carbon targets at the outset of a project and then iterating throughout design, procurement and construction to ensure targets are being met (and often exceeded). It is this type of ambition and commitment that is best demonstrated in case studies and translated out to more and more projects.

CASE STUDY 1:
BUILDING REUSE/RETROFIT (70% REDUCTION)

AIA Headquarters Renovation, Washington, D.C., U.S., 2022

EHDD Architects rendering

The American Institute of Architects (AIA) believes "the leadership of architects is critical in demonstrating the power of design to address society's most pressing challenges, from climate action to racial and social justice." The renovation of its headquarters in Washington, D.C., built in 1973, provided an opportunity to put its Framework for Design Excellence into practice.

Operational Carbon: As with many retrofit projects, existing conditions made it difficult to achieve significant energy use reductions. By focusing on electrification, on-site solar PV arrays, and procurement of local renewable energy, the project was able to achieve net zero operational carbon even if it wasn't feasible to achieve net zero energy.

Embodied Carbon: Faced with a building that is difficult to retrofit for modern levels of energy efficiency, it is common to tear down the existing building and replace it with a newer, more efficient building. The project team set an embodied carbon budget during the interview phase and EHDD, the architecture firm leading the project, used the open access Early Phase Integrated Carbon (EPIC) Assessment tool to demonstrate that retrofitting the existing building offered a much better embodied carbon strategy than demolition and rebuilding.

Having determined a building reuse pathway to be the best option for overall embodied carbon reductions, the team used whole building life cycle assessment (WBLCA) iteratively through the design process to ensure the project stayed within the initial "carbon budget."

The concurrent strategies of retrofitting instead of building new, resource-efficient design, and careful specification of materials (using open access tools like EC3) have been modeled to predict the embodied carbon outcomes. A typical new building (plus demolition of the existing building) was shown to generate approximately 10,400 tCO_2e, while a retrofit of the existing building with typical materials would be 5,800 tCO_2e. As-designed with low-embodied-carbon materials specified where possible, the project is anticipated to generate about 3,200 tCO_2e, nearly 70 percent less than the demolish and rebuild scenario.

All remaining embodied carbon in the project is offset through the purchase of solar arrays on a local affordable housing project, connecting the AIA's goals of decarbonization and social equity.

The up-front embodied carbon of new buildings is significant, and as this project demonstrates, the reductions that come from keeping as much of an existing building as practical is often the best way to reduce embodied carbon. Combined with strategic low-embodied-carbon specification and procurement the impact can be significant.

AIA headquarters: Net-zero whole life carbon

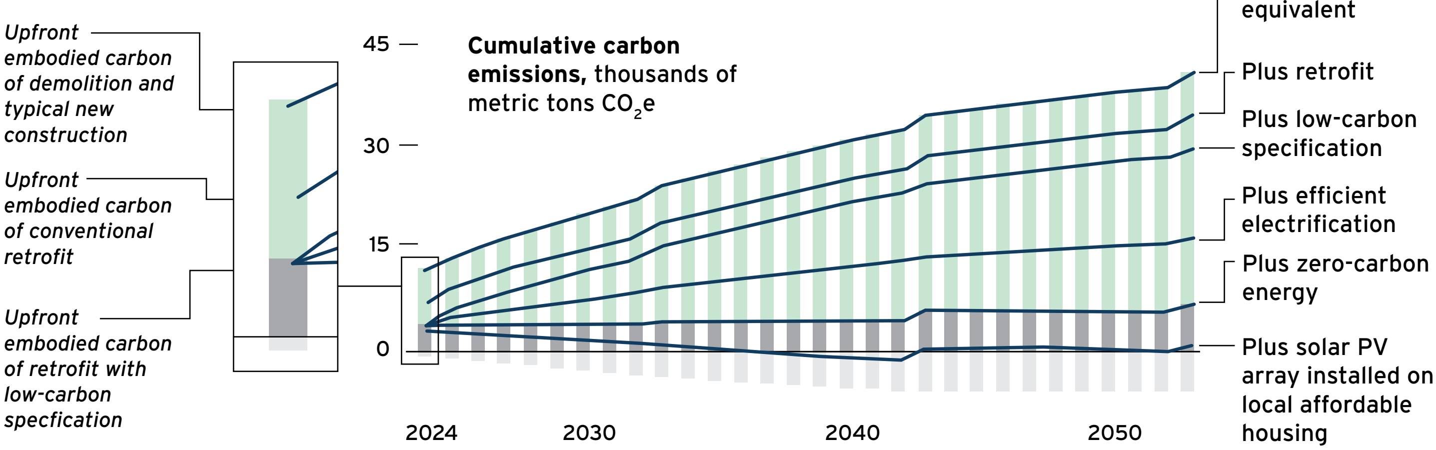

Exhibit 1 | Source: EHDD Architects

CASE STUDY 2: DESIGN AND PROCUREMENT SOLUTIONS (45% REDUCTION)

Mount Vernon Library Commons, Mount Vernon, Washington, U.S., 2023

HKP Architects, MVLC rendering

The Mount Vernon Library Commons (MVLC) is ground-breaking on many levels. The 133,000 square foot project consists of a new public library and community center for the City of Mount Vernon (on the ground floor) with three levels of structured parking above. From the outset, the entire project team was focused on reducing the climate impact of the building.

Operational Carbon: MVLC is one of the first publicly bid projects in the US to pursue Passive House certification. The Library and Community Center portion on the ground floor is 29,234 square feet and is designed to meet PHIUS 2018+ level of energy efficiency with an Energy Use Intensity estimated at 12, compared to Washington State Energy Code requirement of 47. The building is fully electrified and will be the largest public EV Charging station in the country. With the relatively low-carbon electricity grid in the state of Washington, operational emissions will be very low.

Embodied Carbon: The project team used a "hot spot" analysis during the Whole Building Life Cycle Assessment, to focus on those areas of the project with the largest return on GWP reduction. The most substantial of these was concrete. The initial embodied carbon goal during design was to reduce the carbon footprint of the concrete by 30%–35%, with the upper end being a stretch goal. Collaborating with KPFF Engineers and local concrete suppliers, the team anticipates a reduced GWP by 40% due to an innovative approach to the concrete mix designs. The team strategically optimized the ability of each of the final seven mix designs to maximize use of Limestone cement (Type 1L), Supplemental Cement Materials (SCMs), and longer cure times depending on where they were being placed, what type of finishes were required, and construction schedule needs.

Including some additional low-embodied-carbon design and procurement decisions, MVLC is estimated to reduce upfront embodied carbon by 45% compared to typical construction. The focus on high-performance, resilience, carbon-reduction, and energy savings approach decarbonization in a holistic way. This project took a dedicated team of architects and engineers to design, and a skilled and informed contractor to build. As a public bid, the team needed to build drawings and specifications that clearly laid out the intent and requirements of the Passive House certification and the ambitious embodied carbon reduction targets.

Other sustainable features include a 112kW solar array, net-zero pervious surface increase, stormwater treatment with biocells and modular wetlands, native plantings, naturally ventilated parking garage, and material transparency.

The city of Mount Vernon took a forward-thinking approach to this project from the beginning, looking to push the envelope on what it meant to invest in their community and provide a facility that is built for the future and will serve as a demonstration project to show others in our region, and in the country, that building to the Passive House standard and low-carbon targets is not only achievable, but necessary to reach climate pledge goals.

HKP Architects is the lead for the design team and the project CPHC. Julie Kriegh is an architect and CPHC, owner of Kriegh Architecture Studio (KAS), who is acting as the lead sustainability consultant. WSP served as the lead for the WBLCA and concrete assessment.

Mount Vernon Library Commons: High performance low carbon

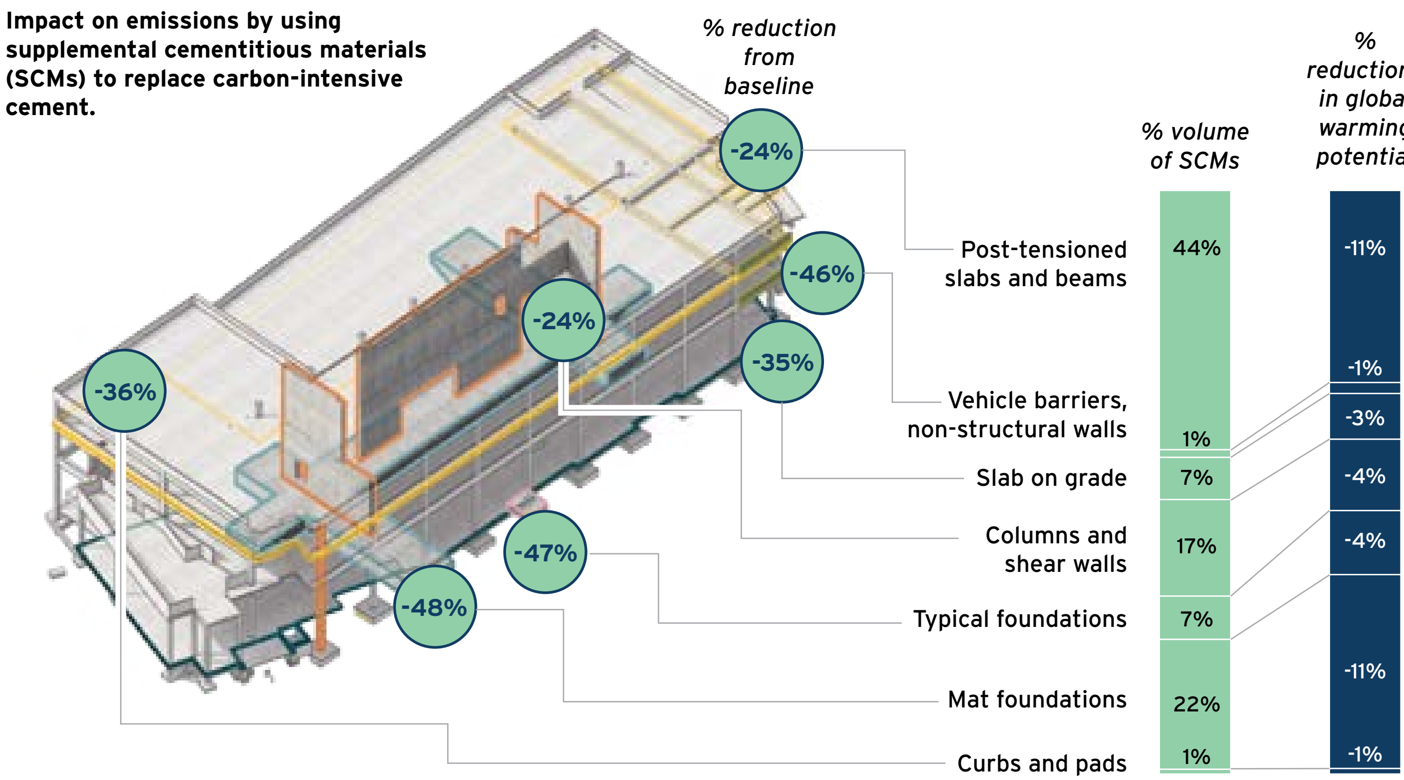

Exhibit 2 | Source: HKP Architects, MVLC

CASE STUDY 3: ACHIEVING SIGNIFICANT CARBON STORAGE (88%-116% REDUCTION)

Trent University Forensics Crime Scene Facility, Ontario, Canada, 2021

Trent University photo

Trent University made a bold commitment to achieving zero whole-life carbon when designing their new, 4,100 square foot forensic crime scene facility in 2020. The building is an attempt to show that action on climate impacts can go beyond incrementalism and with today's technology and materials approach zero carbon.

Operational Carbon: The project team pursued International Living Future Institute Zero Carbon certification (pending) for operational emissions, creating a robust framework for achieving zero operational emissions, met with a combination of improved insulation and air tightness to dramatically reduce loads, electrification, and 43 kW of rooftop photovoltaic panels to provide the lowest possible operational emissions.

Embodied Carbon: The university decided to attempt to reach net-zero embodied emissions by maximizing biogenic carbon storage to the degree it would offset all cradle-to-gate material-related emissions.

The design team started out by addressing assemblies and materials that are typically the largest emitters. Concrete for the foundation and slab floor used high supplementary cementitious materials (SCM) concrete and a biobased insulated concrete form, with foam glass aggregate replacing both gravel and petrochemical foam insulation below the slab. These measures alone reduced embodied carbon by more than 33 tons, shrinking the amount needed to be offset via biogenic carbon storage.

Carbon-storing materials included precast hempcrete blocks for the load-bearing walls, hemp batt insulation (exterior walls and soundproofing for interior walls), cellulose insulation in the attic, and wood fiberboard insulation on the gable ends. Together, this suite of biogenic materials provided nearly 61 tons of total carbon storage, enough to reduce overall embodied carbon by 88% from the university's baseline building.

Carbon storage for timber products was considered distinctly from other biogenic materials. While the team worked to source local and/or certified wood products to improve the likelihood carbon stored in wood had meaningful climate impacts, the uncertainties in calculation methods made them cautious of assuming such benefits. For this reason, wood-based storage was calculated separately and represented 40 tons of potential additional carbon storage.

The baseline building was anticipated to have an embodied carbon intensity of 498 kg CO_2e/m^2, which was reduced to 60 kg CO_2e/m^2 thanks to the carbon stored in the non-timber products. With timber carbon storage included, the intensity tipped to a "carbon positive" balance of 16 kg CO_2 of net storage in a cradle-to-gate analysis.

Trent University Forensics Building: Action Beyond Incrementalism

Material carbon emissions,
kg CO_2e, except where noted

Part of building	Base case	As-built	As-built including timber storage
Footings and slabs	29,516	13,503	13,503
Foundation walls	13,108	9,866	1,128
Exterior walls	123,900	-6,967	-18,043
Exterior cladding	11,327	6,263	2,861
Windows and doors	3,378	3,378	3,378
Interior walls	6,968	-4,900	-3,580
Floors	858	-15	-679
Ceilings	963	227	227
Roof system	21,138	4,130	-5,624
Net total	**211,156**	**25,484**	**-6,829**
MCE reduction		**88%**	**103%**
Net carbon intensity, $kgCO_2/m^2$	**498**	**60**	**-16.1**

Exhibit 3 | Trent University; https://www.trentu.ca/forensicscience/program/our-facilities-resources/forensics-crime-scene-facility; https://endeavourcentre.org/trent-university-forensic-crime-scene-building-is-a-zero-carbon-leader/

Glossary

CONSTRUCTION STAGE (A4–A5) | Covers the emissions associated with the transportation of materials to the construction site and on-site construction.

EMBODIED CARBON | The greenhouse gas emissions associated with the raw material extraction, manufacturing and processing, transportation, and installation of a building material.

EPD | Environmental product declarations are third-party-verified documents that report the environmental impacts of a product. EPDs typically only show A1–A3 emissions, which often represent a significant portion of the embodied carbon over a product's life cycle.

FF&E | Fittings, furniture, and equipment building components.

GWP | Global warming potential, a metric of greenhouse has emissions impact measured relative to the impact of one molecule of carbon dioxide, usually over a 100-year time-frame

LCA | Life-cycle assessment: a systematic set of procedures for compiling and examining the inputs and outputs of materials and energy, and the associated environmental impacts directly attributable to a building, infrastructure, product, or material throughout its life cycle.

MEP | Mechanical, electrical, and plumbing building equipment and operations.

OPERATIONAL CARBON | The emissions associated with energy used (life-cycle stage B6) to operate the building or in the operation of infrastructure.

PCR | Product category rules are a set of specific rules, requirements, and guidelines for developing type III environmental declarations for one or more product categories. Product category rules are reviewed and improved periodically over time.

PRODUCT STAGE (A1–A3) | Covers the emissions associated with the extraction and processing of materials, energy, and water consumption used by the factory or in constructing the product.

UP-FRONT CARBON | These emissions have already been released into the atmosphere before the building is occupied or begins operation.

WBLCA | Whole-building life-cycle assessment that covers all life-cycle stages of a building (product stage A1–A3, construction stage A4–A5, use stage B1–B7, and end-of-life stage C1–C4) and measures impacts across multiple major environmental indicators (not just carbon emissions).

WLCA | Whole-life carbon assessment to measure carbon emissions from all life-cycle stages, encompassing both embodied and operational carbon together.

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