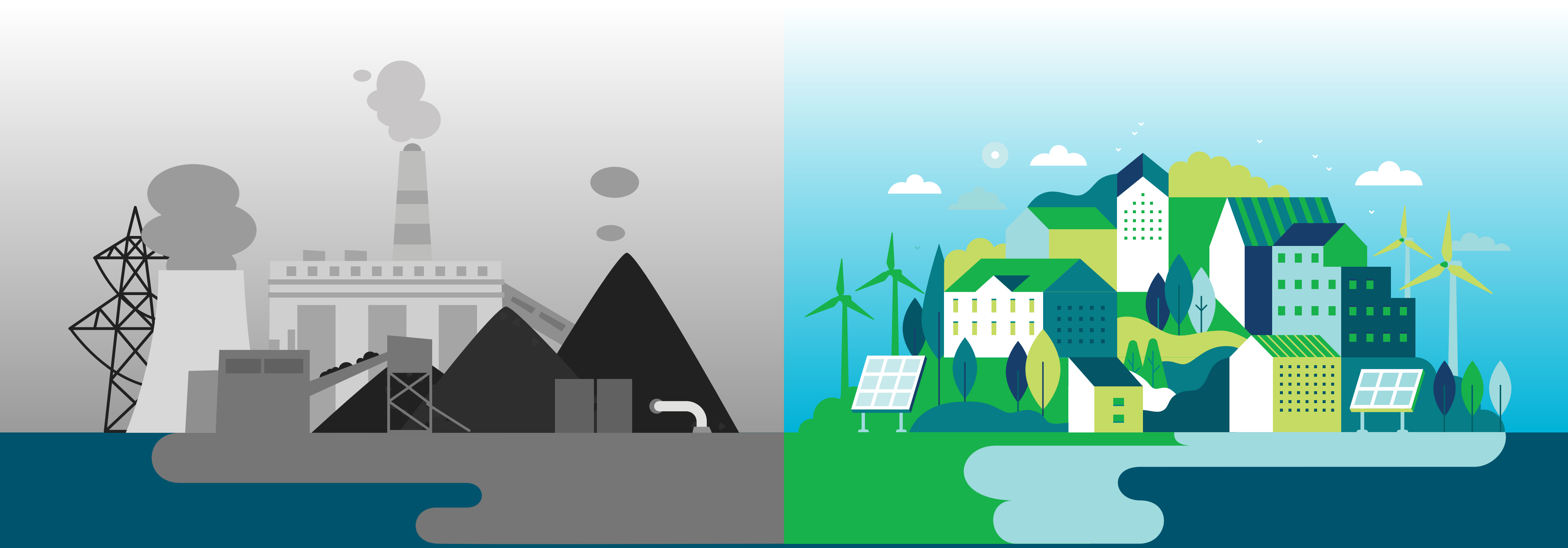

THE BUILDING DECARBONIZATION PRACTICE GUIDE

A Zero Carbon Future for the Built Environment

Google · Microsoft · Energy Foundation · UL · AIA California · WRNS Studio · Building Decarbonization Coalition · Guttmann & Blaevoet · Urban Fabrick · William J Worthen Foundation

VOLUME 6:
Embodied Carbon

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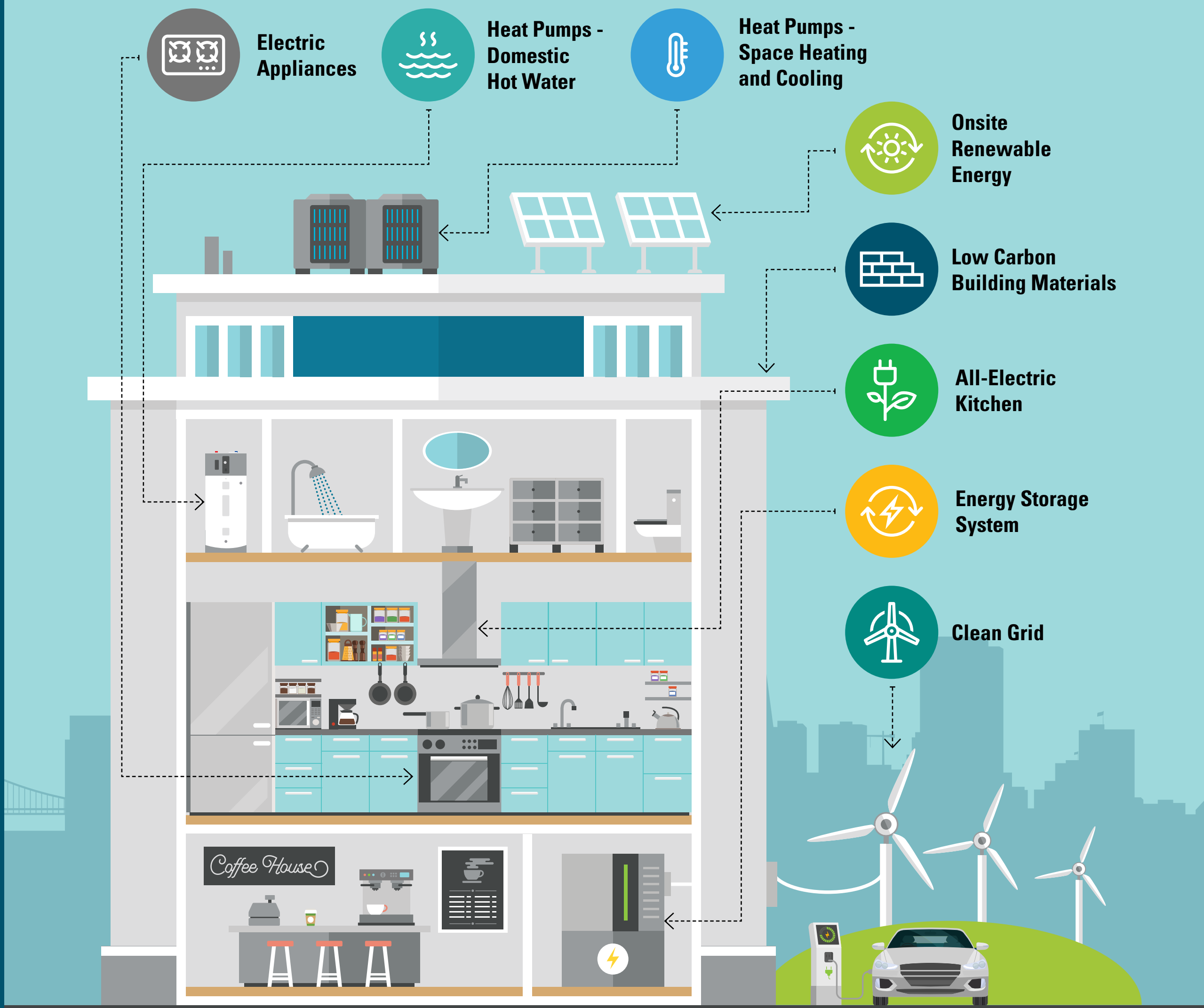

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VOLUME 6

Embodied Carbon

6.1_Introducing Embodied Carbon

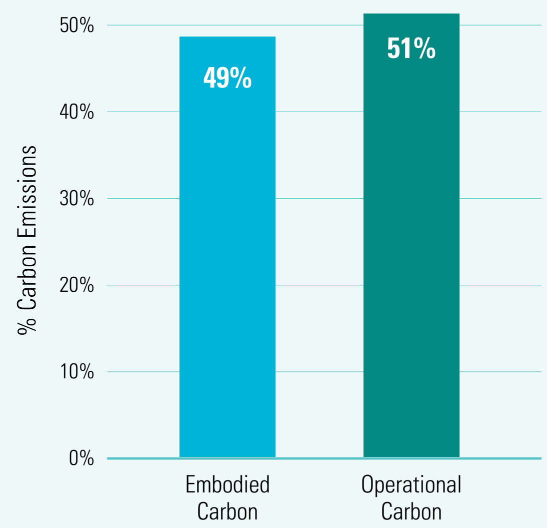
When trying to reduce a building's carbon footprint, the building industry has historically focused on operational carbon — the greenhouse gas emissions (expressed in terms of an equivalent amount of carbon dioxide) that result from the building's operations. However, the true impact of a building includes many carbon emissions that occur during other points in the project's life-cycle and that occur outside the immediate project boundary.

The term "Embodied Carbon" refers to the sum of all the greenhouse gas emissions across a building or product's lifecycle, which includes those associated with the mining, harvesting, processing, and manufacturing of materials as well as transportation, installation, maintenance and replacement, and disposal. Embodied carbon includes emissions of all greenhouse gasses, many of which have a more potent warming effect than carbon dioxide despite often being emitted in smaller quantities.

As buildings are increasingly designed to consume less energy, and that energy is, itself, less carbon intensive, neglecting lifecycle carbon emissions becomes increasingly problematic. Considering both embodied and operational carbon offers a much more complete understanding of a project's total carbon emissions and, importantly, helps identify areas where carbon reductions may be achievable.

While operational carbon is emitted over the life of a building, the majority of embodied carbon emissions occur during manufacturing and construction — prior to building occupancy. A much smaller proportion of the emissions is associated with maintenance activities during the life of the project and end-of-life deconstruction/disposal. Therefore, reducing embodied carbon becomes a way to drastically cut carbon emissions in the near term, which is also essential to a successful — and rapid — response to climate change. Figure 6.1 demonstrates the opportunity that embodied carbon represents globally (almost the same amount of carbon emissions between 2020 and 2050 as from operational energy use). In fact, as operational carbon emissions continue to decline, embodied carbon represents almost 75% of all construction-related emissions over the next ten years (see Volume 1, Figure 1.5).

FIGURE 6.1: TOTAL CARBON EMISSIONS OF GLOBAL NEW CONSTRUCTION FROM 2020-2050 (Business as Usual Projection)



Source: UN Environment Global Status Report 2017; EIA International Energy Outlook 2017

When addressing the problem of embodied carbon, it's important to make an initial assessment to identify what materials in a given project make the largest contribution to its embodied carbon content. This will vary based on project-specific details, but it is generally agreed that the majority of embodied carbon occurs in the structural systems of the building while the second largest percentage occurs in the facade. As with operational energy, which was initially addressed through efficiency improvements, we can think of the core and shell of a building as the low hanging fruit of embodied carbon. As we learn more about the embodied carbon associated with mechanical, electrical, and plumbing (MEP) systems, as well as periodic tenant improvements, we see that these are also large sources of embodied carbon that add up over the life of a building.

Embodied carbon should be addressed throughout project design, with continuous refinement throughout the design phases. During the conceptual phase, designers can start evaluating the embodied carbon of design choices utilizing industry average data with a focus on high level schematic comparisons. Site selection and design decisions (e.g., whether to reuse buildings or materials, building massing, and which structural and envelope system to choose) are made early in design and have a large impact on a project's total embodied carbon. Early comparisons can be refined as the selected design approach is optimized.

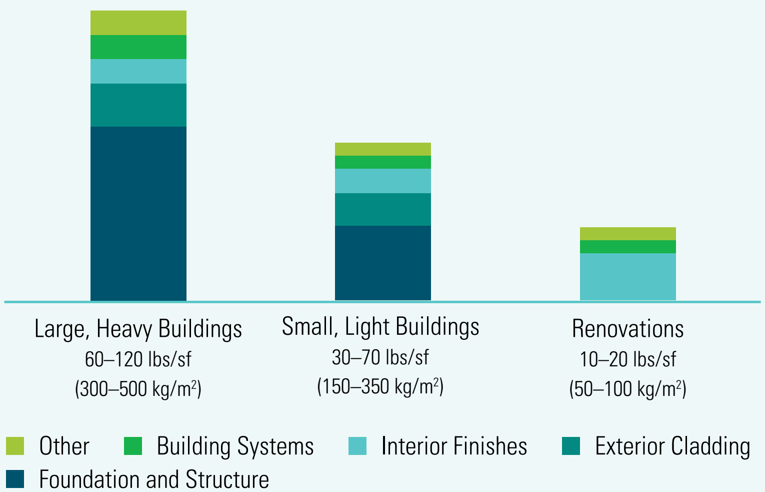
During the procurement phase, designers and builders should work together to source materials and products from suppliers that are manufacturing products with low carbon impacts. Suppliers may achieve reductions by using product ingredients with low carbon content, increasing production efficiencies, using clean energy sources, and manufacturing the product(s) in closer proximity to the project site, among other approaches. While it is possible to achieve reductions in embodied carbon through focusing efforts on procurement only, it is recommended that teams begin with a design focus to first achieve the optimal system and then use procurement as a means to reduce the embodied carbon even further.

6.1.1_WHERE IS A PROJECT'S EMBODIED CARBON?

When assessing the embodied carbon of a given project, it is important to clearly establish what assemblies and other aspects of the project, and what life-cycle stages (e.g., use and end-of-life), are included in the assessment. As the AEC community's awareness of the importance of embodied carbon grows, the scope and rigor of such assessments are developing in tandem. When making any comparisons, it is important to ensure that the assemblies, systems, and life-cycle stages meet the same functional requirements. This functional equivalence across the system must include trade-offs between embodied and operational carbon; when comparing assemblies with different performance characteristics (such as windows), one must ensure that embodied carbon reductions are not more than offset by operational carbon increases. For example, when comparing enclosure assemblies, the enclosure must either provide the same performance (U-factor, Solar Heat Gain Factor, etc.) or the operational carbon changes must be considered in combination with the assessment of embodied carbon.

Many available studies of carbon emissions are limited to structural and envelope materials, and these materials were among the first to have widely available industry-wide carbon impact data. They are now some of the first to have supply-chain-specific carbon data as well. This is a result of both the desire to focus on the materials that make up a significant portion of the initial emissions associated with creating a building (see Figure 6.2) and the fact that data for these assemblies is more accessible since they include a comparatively small number of materials.

FIGURE 6.2: CARBON EMISSIONS BY TYPE OF BUILDING STRUCTURE AND BUILDING ELEMENT



Source: "Time Value of Carbon", Carbon Leadership Forum, 2017

There are many other assemblies and life-cycle phases, however, that contribute to the embodied carbon of a project, such as site materials, emissions from construction equipment on site, interior materials, HVAC systems, and refrigerants. All of these elements are increasingly included in embodied carbon assessments. As the various assemblies, including their refreshment and refurbishment cycles are better understood, the full picture of their impact over the building's life-cycle is becoming clearer. As such, it is essential to understand the data gaps in past embodied carbon assessments and the new data needed to broaden the scope of future assessments.

As part of these more granular evaluations, it is important to consider the life-span and post-use pathways for materials such as interior finishes that may be highly impacted by renovations and maintenance.

6.2_Estimating Embodied Carbon

6.2.1 _OVERVIEW

There are various methods and procedures that can be used to measure embodied carbon. The method chosen for a particular project may depend on which life-cycle stages are being considered. Figure 6.3 illustrates and classifies the different stages, from product stage to end-of-life stage.

To measure the carbon impact of a project or product, a life-cycle assessment (LCA) can be performed.[1] This process aims to take stock of all carbon emissions of that material or product through its full life-cycle. The most common methods to measure embodied carbon either consider the entire life-cycle of the building or project (i.e. cradle-to-grave) or focus only on the Product Stage (i.e. cradle-to-gate). Figure 6.3 also illustrates how several aspects of a project life cycle can impact operational and embodied carbon emissions.

When an LCA is performed at the building or project scale, a whole-building life-cycle assessment (WBLCA) is done. This combines the individual LCAs of the different components that make up a project and provides an overall sum of carbon impacts for that project. The methodology for the WBLCA has been standardized through British Standard EN 15978:2011.

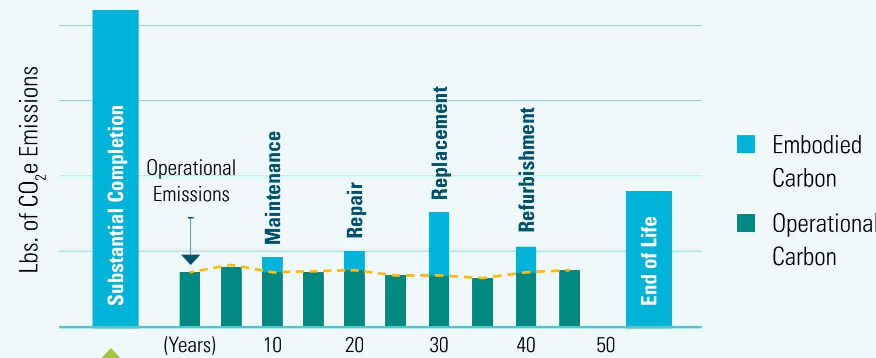
1 Reference ISO 14040, "Environmental management — Life cycle assessment — Principles and framework" and ISO 14044, "Environmental management — Life cycle assessment — Requirements and guidelines".

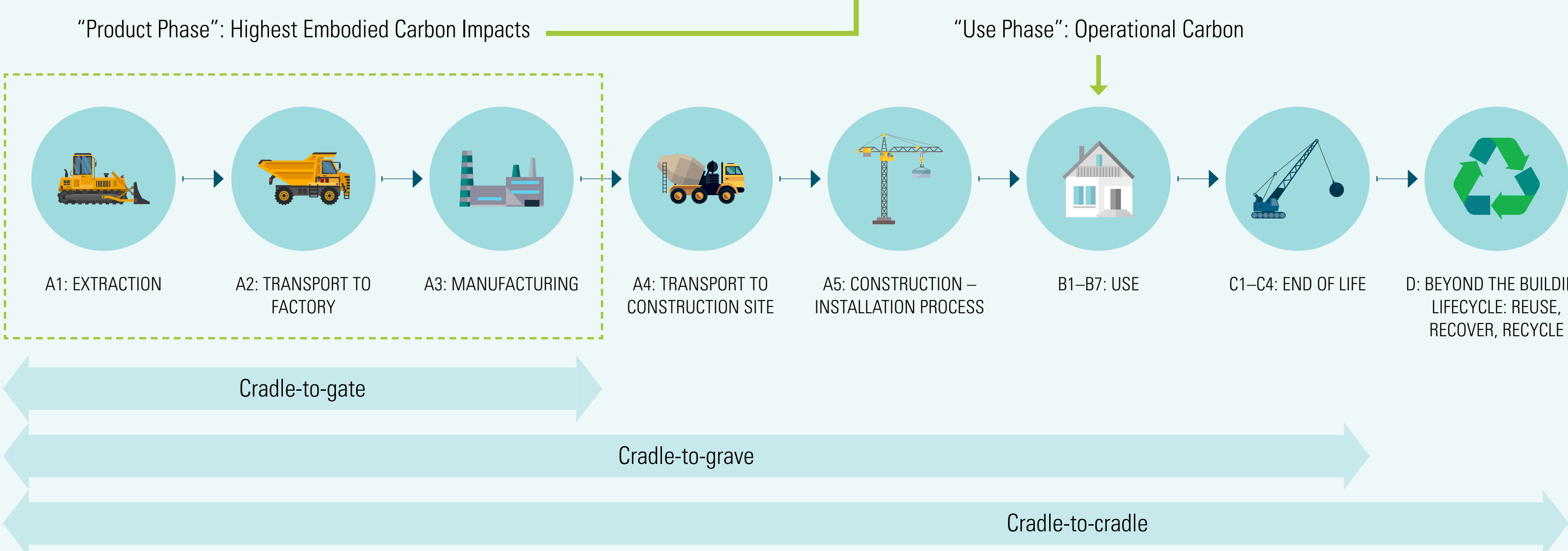
FIGURE 6.3: BUILDING LIFE-CYCLE ASSESSMENT (LCA)

Cradle-to-gate (A1 to A3): refers to the time frame from when a component's life starts to when it leaves the manufacturing facility ("gate"), before it is transported to the project site. This includes the entire "Product Stage."

Cradle-to-grave (A1 to C4): refers to the time frame from when a component's life starts ("cradle") to when it ends ("grave"). It includes all stages from "Product Stage" to "End-of-Life Stage."

Cradle-to-cradle (A1 to D): refers to the time frame from when a component's life starts to when it starts again. This includes all stages from the "Product Stage" to the "Benefits & Loads Beyond the System Boundary."





Source: Adapted from https://www.leti.london/ecp

6.2.3_ENVIRONMENTAL PRODUCT DECLARATIONS (EPDs)

Many manufacturers have chosen to quantify and disclose the embodied carbon of their products through an Environmental Product Declaration (EPD). An EPD is a report that discloses the environmental impacts of a material or product. It is created by performing an LCA at the component level, taking stock of materials that make up the item and the processes used to assemble it. Currently, EPDs are primarily based on a cradle-to-gate LCA, covering the early stages of a product's life from extraction through manufacturing.

EPDs are analogous to a nutrition label for food, which reports a food item's nutritional content, along with the ingredients that make it up. In a similar way, an EPD report tells the life cycle story of a product in a single, comprehensive report. The EPD provides information about a product's impact upon the environment, such as global warming potential, smog creation, ozone depletion, and water pollution. In the same way that a person might focus on the calories reported by a nutrition label, designers often focus on the Global Warming Potential (GWP) reported by an EPD.

EPDs are generally categorized as industry-average or product-specific. Industry-average EPDs are typically created by a trade organization, such as the National Ready Mixed Concrete Association (NRMCA) for concrete, and are not specific to a certain manufacturer. Conversely, a single manufacturer would produce a product-specific EPD.

Of the various types of EPDs, the most desirable is a product-specific Type III EPD (see Figure 6.4). This type follows a set of rigorous processes, which makes it the most relevant and reliable data for the project in which it is used. The Type III label also indicates that it has gone through third-party audit and verification.

FIGURE 6.4: THE THREE TYPES OF ENVIRONMENTAL PRODUCT DECLARATIONS (EPDs)

	PCR* is third-party reviewed?	EPD is third-party reviewed?	Specific to a single product from a single supplier	Standard followed
Product-Specific Declaration (Self-Declared)	–	–	✓	ISO 14044
Product-Specific TYpe III (Preferred)	✓	✓	✓	ISO 14025 ISO 14040 ISO 14044 ISO 21930/EN 15804
Industry-Wide	✓	✓	–	ISO 14025 ISO 14040 ISO 14044 ISO 21930/EN 15804

* Product Category Rule. A PCR enables different practitioners using the PCR to generate consistent results when assessing products of the same product category.

6.2.4_TOOLS TO ESTIMATE EMBODIED CARBON

Measuring embodied carbon can be a simple or complex process depending on the scope and methodology used. To aid designers, consultants, and contractors, a variety of tools are currently available to quantify embodied carbon. These tools offer quick, early estimates or deeper dives. There are also ever-expanding databases of EPDs that contain product-specific and industry-average product data. A brief overview of these tools follows.

6.2.4.1_Early Design Tools

The purpose of early design tools is to give project members a starting point for embodied carbon estimation. These are meant to be approachable to users of all experience levels, from the interested owner to the experienced design consultant, and they do not typically require in-depth project-specific inputs.

These tools offer only a rough estimate and should not be considered highly accurate. They are best used at the earliest stages of a project to give teams a sense of what project components contribute the largest carbon impact in relative terms. These initial estimates should be confirmed in later design phases by other, more accurate tools.

Early Design Tools:[2]

» ECOM, by SE2050 (See Figure 6.5 for a sample of the output)

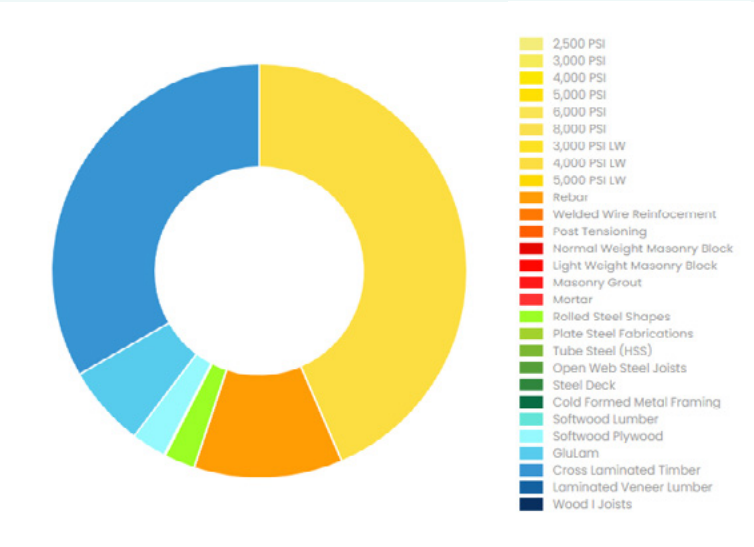
» EcoCalculator, by ASMI

6.2.4.2 _Life-Cycle Assessment Tools & Datasets

LCA tools and datasets allow project members to delve deeper into embodied carbon accounting. Although many are user-friendly, they are best suited for more experienced users, such as sustainability consultants, architects, and engineers. Users should have a robust knowledge of project inputs to increase the accuracy of a given tool's results.

These tools and datasets can be used from early design through to final design. Since they are typically used to identify embodied carbon reduction targets, they are most useful during the design phase, when design decisions are still being made. Once in construction, it is less likely that an impactful design reduction strategy can be implemented.

FIGURE 6.5: EXAMPLE OF OUTPUT FROM ECOM



Source: https://se2050.org/ecom-tool/

2 For additional tools, see https://carbonleadershipforum.org/clf-architect-toolkit/

WBLCA Tools:

- » Tally*, by KT Innovations, thinkstep, Autodesk
  (See Figure 6.6 for example output)
- » Athena Impact Estimator*, by ASMI
- » One Click LCA*, by Bionova Ltd.
- » Carbon Planning Tool, by the Environment Agency
- » eTool

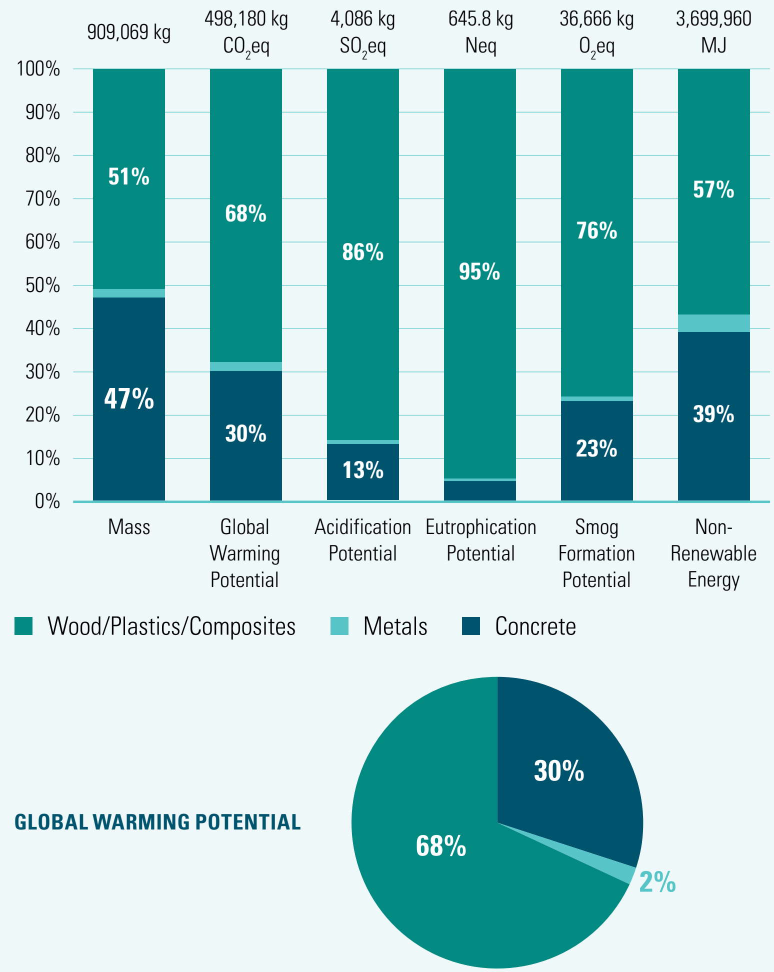
* Denotes tools widely used in the U.S. market

LCA / Embodied Carbon Tools and Datasets:

- » openLCA, by GreenDelta
- » ICE Database, by Circular Ecology
- » GaBi Database, by sphera
- » ecoinvent Database

For additional tools, see the tools listed in the AIA-CLF Embodied Carbon Toolkit for Architects, Part II, Measuring Embodied Carbon (see section 6.5).

FIGURE 6.6: EXAMPLE OUTPUT FROM TALLY (EXCLUDING BIOGENIC CARBON)



6.2.4.3_EPD Databases

Since EPDs are currently the best source of Product Stage data, EPD databases are an important tool for project participants. Different from LCA tools, the goal of these databases is to provide users with direct access to Product Stage data from a single source. These databases can be queried for industry-average or product-specific EPDs, often by region or manufacturer.

Because EPD data is product-specific, these databases are best used in the later stages of design and when component procurement strategies are formulated. Designers may use these databases to determine more accurate embodied carbon estimates for their materials during design or to choose which products to specify. Once material take-offs are available, the design team or contractor may use these databases to compare carbon information from two prospective suppliers.

EPD Databases:

- EC3, by BuildingTransparency (See Figure 6.7 for sample output)
- International EPD System, by EPD International AB

6.2.4.4_Comparability of Estimation Tools

The various tools available to estimate embodied carbon may derive results from different embodied carbon or LCA datasets. Because the underlying data is not the same, results from various tools should not be compared to each other. Instead, the same tool should be used when results are compared at different phases of design.

6.3_Reducing Embodied Carbon

Reducing embodied carbon takes an entire team, and every member can have an impact. Figure 6.8 includes high-impact reduction strategies and the parties — policy maker, owner, design professional, contractor — best positioned to influence their implementation. This is, however, only a partial list of available strategies; others may be found in the references. Recent studies present strong arguments that reducing embodied carbon emissions by 20% to 30% is feasible now, using readily available materials and current technologies.[3]

Policy makers are among the most important drivers of change. Many project teams would not address embodied carbon reductions without policy-driven incentives and mandates. More information about the growing embodied carbon policy landscape may be found at the Carbon Leadership Forum's website.[4]

Of course, reducing the embodied carbon through the strategies discussed below should always be done in consideration of possible trade-offs in environmental impacts (e.g., water use and operational carbon impacts that may offset embodied carbon reduction benefits).

Each of the nine strategies listed in Figure 6.8 are elaborated on below.

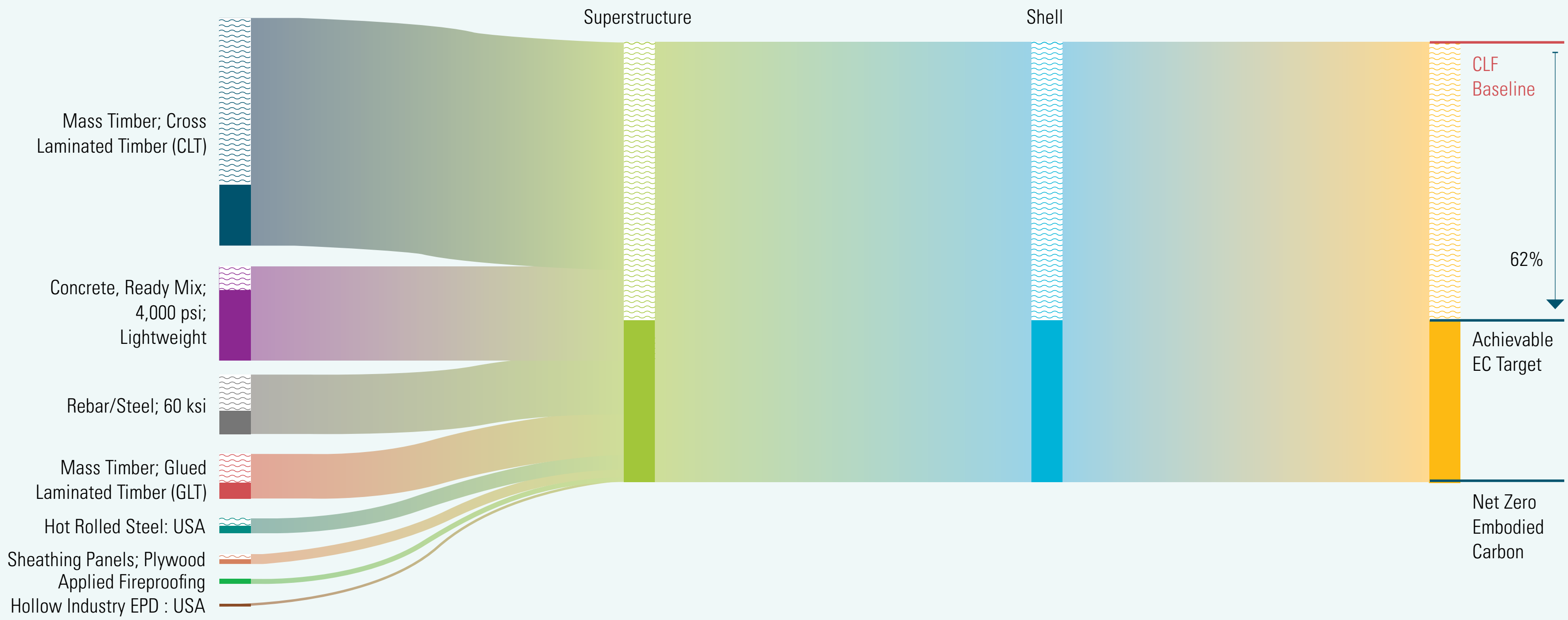
6.3.1_REUSE BUILDINGS

Always consider reuse and retrofit before designing a new building. Reuse and renovation with system upgrades typically generates 50% to 75% less embodied carbon emissions than new construction. For this reason, reuse is almost always the most effective strategy to reduce embodied carbon.

3 For example, see the London Energy Transformation Initiative's Embodied Carbon Primer, January 2020 edition, or the Embodied Carbon Stewardship Report, published by Walter P. Moore

4 https://carbonleadershipforum.org/clf-policy-toolkit/

FIGURE 6.7: EXAMPLE OUTPUT FROM EC3



Note: This graphic shows a project, evaluated in May of 2021, that has achieved a 62% embodied carbon reduction compared to the CLF Baseline and how reductions in each superstructure and shell component contribute to this reduction.

FIGURE 6.8: EMBODIED CARBON REDUCTION STRATEGIES AND DECISION INFLUENCERS

	Influencers			
Strategy	**Policy Maker**	**Owner**	**Design Professional**	**Contractor**
Reuse Buildings	X	X	X	
Reuse Materials	X		X	X
Measure and Identify Project "Hot Spots"			X	
Focus on High-GWP Materials and Systems	X	X	X	X
Use Less Portland Cement	X		X	X
"Right-Size" the Project		X	X	
Use Biobased and Other Carbon-Storing Materials in Place of High-Embodied Carbon Materials	X	X	X	
Optimize Use of Materials			X	X
Source from Lower-GWP Manufacturers			X	X

In some cases, the project team may choose to perform an LCA to measure the carbon impacts of design options (reuse, retrofit, or build new), accounting for both embodied and operational carbon emissions. Project teams should also consider including energy performance upgrades to reduce emissions from operations when renovating existing buildings. Even if the energy efficiency of the upgraded building is not as good as the new building option, the lower overall carbon solution is often the upgraded option due to the high embodied carbon content of new construction and the short term benefits of embodied carbon reduction. We recommend evaluation time frames that align with the goal to achieve carbon neutrality in the building sector by 2050.

When reusing existing buildings, project teams should evaluate the potential for converting existing mixed-fuel buildings into all-electric buildings. Deep energy upgrades and electrification are effective ways for projects to reduce total emissions from the built environment. When full electrification cannot be accomplished, an all-electric ready approach should be the goal; this will prepare renovated buildings for a true carbon neutral future as utility grids become powered by 100% renewable energy.

6.3.2_REUSE MATERIALS

Salvaged materials have a much lower embodied carbon footprint than newly manufactured materials because the extraction and manufacturing life-cycle stages are eliminated. As such, wherever possible, we recommend reusing materials such as brick, metals, broken concrete, wood, furniture, casework, and doors. The environmental impacts of reuse are due solely to extraction from the previous building, transportation (generally from the previous building to a storage facility then to the current building), and refabrication, if needed. Reuse also reduces embodied carbon more than recycling by avoiding the emissions from processing, manufacturing, and transporting recyclables. In addition, reuse keeps wood out of landfills where it decays and releases methane, a powerful greenhouse gas.

The U.S. General Services Administration's Green Building Advisory Committee made this recommendation on quantifying the embodied carbon benefits of reuse for federal buildings:

"Where possible, product reuse (salvaged products) is highly encouraged, as these products do not create new emissions (low/zero additional Global Warming Potential) and can be considered zero embodied carbon for this analysis. This does not include new materials with recycled content. EPDs are not required for salvaged or reused materials/products…"[5]

Most code officials will permit the use of salvaged structural materials if approved by the structural engineer under the "alternative materials" provisions of building codes (e.g. the International Building Code, section 104.11). Timber and steel framing are the best candidates for reuse. Structural engineers can evaluate the properties of existing timber and steel structural members using assorted tools, including tests and inspections. If needed, wood specialists can recommend species and grades of structural members. If the age of steel is known, engineers can make an educated assumption as to its strength based on the specifications in use at that time. Steel samples can also be removed for strength testing and to evaluate weldability.

Concrete framing is not usually salvageable for many reasons. Cast-in-place concrete members, for example, often rely on continuity with other members, which is lost if the pieces are separated. They are also heavy and the reinforcement is hidden; this makes it harder to determine its strength. Even precast concrete members are often interconnected with each other using toppings, grouted joints, and welded embedments. Recycled aggregate for concrete, however, can be made by crushing demolished concrete elements.

Source: U.S. Army Corps of Engineers Headquarters building utilizing 300,000 board feet of structural and non-structural lumber from an adjacent warehouse deconstruction. | https://www.gsa.gov/cdnstatic/GSA_FCS_Press_Book_email.pdf

5 U.S. GSA, Green Building Advisory Committee Advice Letter: Policy Recommendations for Procurement of Low Embodied Energy and Carbon Materials by Federal Agencies, Feb. 2021 https://www.gsa.gov/cdnstatic/GSA%20GBAC%20Low%20EC%20Procurement%20Policy%20Advice%20Letter-2-17-21.pdf

Embodied carbon can also be dramatically reduced through design for disassembly or reversible building design and deconstruction. Oregon and Washington have adopted state building codes that allow the use of reclaimed lumber for structural purposes without regrading,[6] and Portland, Oregon, and Palo Alto, California have adopted mandatory deconstruction ordinances.[7] As the City of Portland's construction waste specialist, Sean Wood, reported at the January 2021 Urban Land Institute's Resilience Summit, Portland's ordinance over the previous five years resulted in the recovery of an average of five tons of material, primarily clean lumber, from the deconstruction of a typical single-family home. A deconstruction case study, from New Orleans, can be found in section 6.4.4.

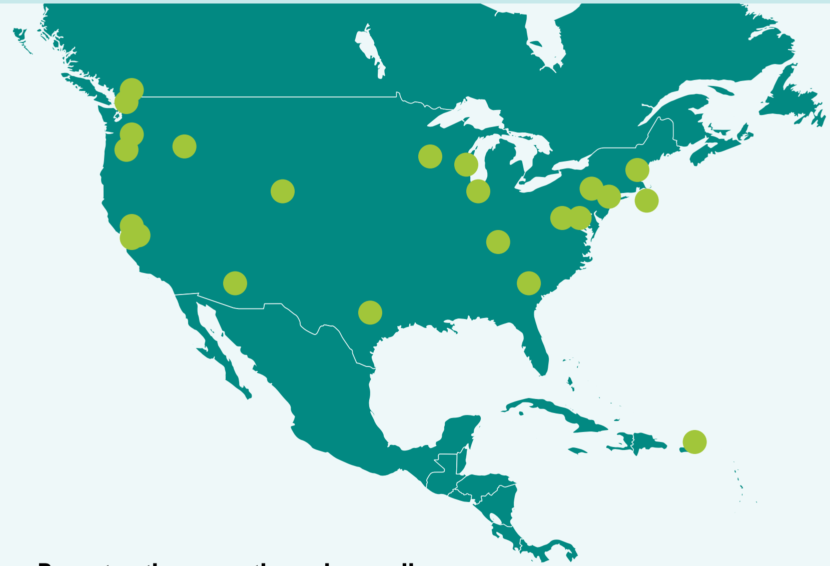
6.3.3 _MEASURE AND IDENTIFY PROJECT "HOT SPOTS"

Measurement is fundamental to any budgeting or optimization exercise, and it is no different with embodied carbon. Prescriptive guidance — such as requiring a minimum percentage of cement replacement in concrete or excluding steel without an EPD (steel is discussed in more detail in Section 6.3.9) — can provide general approaches to reducing embodied carbon. However, it is still beneficial to develop project-specific estimates of a building's embodied carbon, even if it contains some level of uncertainty. Appropriate LCA or other tools can help project teams identify "hot spots" — those assemblies or phases responsible for the largest contribution to the overall embodied carbon. It is often most efficient to make changes to those few materials responsible for the biggest impacts instead of smaller reductions across many assemblies. As a project progresses, users may choose to increase the sophistication of their tools to get a better handle on the carbon-intensive "hot spots" and to confirm that they are being

6 Oregon Residential Specialty Code, Chapter 1, Section R104.9.1, 2017, https://codes.iccsafe.org/content/ORRSC2017; Washington Administrative Code, R602.1.1.1 Used sawn lumber, 2018, https://apps.leg.wa.gov/wac/default.aspx?cite=51-51-0602

7 Portland Deconstruction Mandatory Residential Requirements, 2016, https://www.portland.gov/bps/climate-action/decon; Palo Alto Deconstruction and Construction Materials Management Residential and Commercial Building Requirements, 2020, https://www.cityofpaloalto.org/Departments/Public-Works/Zero-Waste/Zero-Waste-Requirements-Guidelines/Deconstruction-Construction-Materials-Management

FIGURE 6.9: EXAMPLES OF DECONSTRUCTION POLICIES ACROSS THE U.S. AND CANADA



Decontruction executive orders, ordinances, incentives, plans, or Deconstruction Advisory Groups

- Atlanta, GA
- Baltimore, MD
- Boise, ID
- Chicago/Cook County, IL
- Connecticut (State of)
- Denver, CO
- Ithaca/Cornell, NY
- Milwaukee, WI
- Nantucket, MA
- Nashville, TN
- Oakland, CA
- Palo Alto, CA
- Phoenix, AZ
- Pittsburgh, PA
- Puerto Rico
- San Antonio, TX
- San Francisco, CA
- San Mateo County, CA
- Seattle/King County, WA
- Somerville, MA
- Vancouver, BC
- Victoria, BC

Source: Shawn Wood, Construction Waste Specialist, City of Portland, OR, as presented at the ULI Resilience Summit, January 26, 2021.

addressed. Remember that all embodied carbon evaluations are estimates, even those from more sophisticated tools, so we recommend focusing on the big contributors to avoid getting bogged down in the small ones.

6.3.4_FOCUS ON MATERIALS AND SYSTEMS WITH THE LOWEST AMOUNTS OF EMBODIED CARBON

Generally, the structural system has the highest proportion of embodied carbon, followed by the building enclosure. Interior and MEP systems, especially if subject to high churn rates, can also have high embodied carbon. Look to these systems for embodied carbon reduction opportunities.

Materials such as aluminum, certain types of foam insulation, and products with a high cement content can pack a lot of embodied carbon into a small quantity of materials. Be familiar with such materials and on the lookout when selecting and specifying products. Sometimes materials with high carbon content are incorporated into products such as facade components, which may not be obvious at first glance. Ask manufacturers for EPDs and, if they do not have one, inquire about the materials that are used in their products (e.g., the type of insulation in a facade component).

6.3.4.1_Tenant Improvements

How often spaces are remodeled can have a large impact on the lifetime embodied carbon of a building. A Carbon Leadership Forum study found that the embodied carbon of the tenant improvements in five case study buildings ranged from 45 to 135 kg CO_2e/m^2.[8] If these impacts occur every 10 to 20 years over the life of a building, total life-cycle tenant improvement impacts could range from 130 to 810 kg CO_2e/m^2, which is comparable to the total initial construction carbon impacts. High impact items from the study included cubicles, furniture, doors, carpet, glazing, acoustical and metal ceiling panels, ceiling panel suspension systems, and partition walls.

8 “Life Cycle Assessment of Tenant Improvements in Commercial Office Buildings”, Carbon Leadership Forum, April, 2019, https://carbonleadershipforum.org/lca-of-mep-systems-and-tenant-improvements/.

9 https://www.buildingproductecosystems.org/closed-loop-wallboard

HIGH CARBON INTENSITY MATERIAL ANALYSIS: GYPSUM WALLBOARD AS AN EXAMPLE FOR DEVELOPING STRATEGIES TO REDUCE EMBODIED CARBON

Gypsum board (aka Sheetrock, drywall, wallboard, etc.) presents unique challenges due to the amount of product that ends up in the waste stream. The following discussion focuses on this one aspect of tenant improvements.

- Gypsum board is a challenge because once it is painted it is nearly impossible to recycle, or at least it isn't cost effective to recycle. One alternative is to use modular partition systems that can be disassembled and reused. However, they typically have high embodied carbon content.
- 10% of new gypsum board typically ends up as scrap on the job site.[9] While new, unpainted gypsum board is the easiest to recycle, most scrap ends up in a landfill. Although high recycled content is generally available, there are also limits to how much recycled content gypsum panels can contain due to issues with fire ratings. Clean, unpainted gypsum board can also be ground up and used as a soil amendment.
- Gypsum board sheets typically come in 4’ x 8’ and 4’ x 10' sizes. To minimize waste, wall studs should be designed to a 2' framing module. Alternatively, for light duty construction, joints can "float" between framing with the gypsum board screwed to a backing that bridges the joint.
- **Lower Carbon Alternatives:**
  - Lightweight gypsum board can reduce embodied carbon by up to 25%.
  - An industrial waste product — sulfur dioxide from power plant emissions (flue gas desulfurization, or FGD) — can be used to produce synthetic gypsum. While it is also a lower carbon alternative, some concerns have been raised about the potential presence of heavy metals, including mercury.
- **Very Low Carbon Alternatives:**
  - Where fire rating is not a concern, eliminate gypsum board altogether and use biobased alternatives, such as salvaged and FSC-certified wood or straw-based MDF and HDF panels. These products sequester as much, if not more, carbon as it takes to produce them.

6.3.5 _USE LESS PORTLAND CEMENT

Concrete accounts for more carbon emissions than any other building material and is often the largest single source of embodied carbon in a building project. Portland cement is the primary source of embodied carbon in concrete, and it accounts for somewhere in the range of 5 to 8 percent of total global carbon emissions from the built environment. A majority of projects use concrete, if not in the structural frames and envelopes then in the foundations and floor slabs.

Increasingly, there are other options. Cement may be replaced with supplementary cementitious materials (SCMs) such as fly ash, slag, ground post-consumer glass, and other pozzolans. The replacement rate depends upon the project requirements, the type of SCM, and the concrete application. SCMs can slow the rate of strength gain, which can limit the replacement rates for concrete elements that require higher early strength, such as post-tensioned elements and suspended slabs where the formwork must be removed at a rapid pace. However, in many applications, such as footings, foundation walls, and insulated concrete forms (ICFs), the rate of strength gain may not be as critical. In such cases, higher replacement rates should be considered. SCMs improve many properties of concrete, including density and durability, so they can offer additional benefits beyond embodied carbon reduction.

Blended cements, which include a mix of portland cement and fly ash, slag, or ground limestone, are also becoming more readily available. Blended cements provide similar performance to unblended portland cement but deliver a smaller carbon footprint.

Other strategies to consider are using larger aggregate sizes or better blended aggregates. Both these approaches reduce the paste volume, which is the cementitious matrix that fills the spaces between the aggregates and holds the concrete together. Larger aggregates displace more of the paste volume, and with well-graded aggregates, the smaller stones fill more of the voids between the larger ones.

An easy solution to reducing embodied carbon is to simply use less concrete. This strategy works as long as the concrete is not replaced with other materials, like structural steel, that have a similar amount of embodied carbon (an LCA can help the team evaluate such options). Ways to reduce concrete quantity include:

» Casting concrete with voids either hidden within slabs (such as BubbleDeck) or with joists or waffle slabs in place of flat slabs;

» Eliminating basements and below-grade spaces if they are not required;

» Using frost-protected shallow foundations instead of deeper footings in cold climates;

» Using light structural systems that can reduce the size of foundations.

We recommend working with the project's structural engineer to implement these strategies where feasible.

6.3.6_RIGHT-SIZE THE PROJECT

When focusing on embodied carbon, constructing a building that is larger than absolutely necessary is counterproductive. Once the project scope and program are known, it is essential to avoid over-sizing the project.

In general, making rooms smaller is not the most effective way to accomplish "right sizing." The best way to "right size" is to design spaces that can be adaptable and do double, if not triple, duty. Flexible and expandable rooms, which can accommodate multiple uses, will keep the overall project footprint smaller. Adding systems to facilitate the scheduling of space use and providing adequate storage space are key to making this strategy work. Project teams should design efficient circulation paths, and, above all, avoid superfluous spaces. Careful planning and layout will reduce both material consumption and heating and cooling demands.

In residential construction, LEED has created incentives for reducing the size as well as increasing the density of single-family and multi-family buildings in order to promote the benefits of "right-sizing."

6.3.7_BIO-BASED AND OTHER CARBON-STORING MATERIALS

The term "bio-based materials" typically refers to products that mainly consist of a substance (or substances) derived from living matter (biomass) and either occur naturally or are synthesized. It may also refer to products made by processes that use biomass. New options for bio-based materials that compete with conventional materials are becoming more ubiquitous. The great thing about carbon storing/capturing materials is that the more you use the more carbon you store.

Wherever possible, use bio-based and other carbon-storing materials in place of high embodied carbon materials. For both structure and finishes, wood structural systems (as opposed to steel and concrete) and wood siding (rather than vinyl) offer lower embodied carbon alternatives. For products of the same material — carpet for example — compare the EPDs of different suppliers prior to selection.

Bio-based materials are perceived as potentially "greener" alternatives than their counterparts; however, this claim should always be scrutinized closely. For example, wood is often a lower carbon choice than steel or concrete, but its carbon footprint is determined by forestry practices at its source, as well as harvesting and manufacturing methods. Be mindful of industry claims concerning wood; use wood that is certified by a third-party certification organization such as the Forest Stewardship Council (FSC) where possible. One study by Ecotrust showed that FSC certified forests sequestered 20% to 60% more carbon than traditionally managed forests.[10] This study is representative of a particular region (the Pacific Northwest) and did not compare the FSC forests to those certified under other programs such as the Sustainable Forestry Initiative (SFI) or Program for the Endorsement of Forest Certification (PEFC), which are also preferable to uncertified forests since they assure a baseline of good forestry practices.

The impact of forestry management practices on embodied carbon is complex and continues to be studied. For designers seeking guidance on the sourcing of "climate friendly" wood products, the whitepaper "Forestry Embodied Carbon Methodology" offers some helpful guidance.[11]

Cross laminated timber (CLT) can be a viable alternative to concrete and steel for taller buildings. Because the floors and often the walls are solid wood, designers will need to rethink insulation and MEP systems. CLT buildings can use up to five times as much wood as a light frame building, so it is even more important to choose sustainably-sourced wood from well-managed sources that actually store carbon.

For smaller-scale, low-rise projects and single family homes, there are an increasing array of bio-based materials. There is still considerable uncertainty in the data on embodied carbon in many of these materials, and investigating embodied carbon reduction claims — as with most materials used in construction — should be thoroughly evaluated. Also, their structural and other performance characteristics need to be considered carefully. In addition, there are limitations on the use of many bio-based products where fire-resistive construction is a requirement.

Where appropriate, the use of alternate agricultural products, like straw, hemp, cork, bamboo, and cellulose, as well as traditional building materials, like rammed earth and cob construction, can be considered. Short-cycle agricultural crops can sequester carbon more effectively than forests.

» Hemp stalks are used in hemp-based thermal insulation and hempcrete. Straw, the non-edible stock of cereal grains, is used in straw bale construction, insulation panels and fiberboard products. Stacked straw bales, plastered in lime are a great carbon storing material. Strawbale walls can be load bearing but typically rely on posts and beams to support the roof. The bales are pinned or tied together between reinforcing bars and then plastered. They perform well seismically and thermally, and they offer excellent fire resistance.[12] People are also experimenting with prefabricated straw bale wall panels that can be used as infill in CLT structures. Water needs to be kept away from straw bale walls; effective strategies include deep overhangs and raised footings.

10 https://ecotrust.org/wp-content/uploads/Forests_Tradeoffs-in-Timber-Carbon-Cash-Flow_2018-2.pdf

11 https://www.arup.com/perspectives/publications/research/section/forestry-embodied-carbon-methodology

12 See https://www.architecturaldigest.com/story/strawbale-construction and https://www.researchgate.net/publication/316463900_Fire_Resistance_of_the_Straw_Bale_Walls

» Using earth as a structural, load bearing system can be a low carbon alternative, but only if the earth doesn't require a lot of cement or asphalt as a binder/stabilizer. Some rammed earth applications call for the addition of up to 3% to 8% cement content.[13] Traditional, non-stabilized adobe blocks reinforced with straw and rammed earth can work well in dry climates in low seismic zones. There are also compressed, low-cement content blocks available. Look to local sources for what is appropriate and understood by local builders as well as what is code-compliant.

Finally, be on the look-out for new carbon-storing technology. This industry is expanding rapidly and new technologies are emerging at varying levels of availability. Look for new materials that are under development, including concrete aggregates. One such product entering production, a lightweight aggregate for use in concrete, can potentially compensate for all the emissions associated with the cement in the concrete mix.

6.3.8_OPTIMIZE THE USE OF MATERIALS

In any given project, use the most efficient structural solutions that local building codes allow and which save on the quantities of materials used. Optimization works best when started early in the design process. The flexibility to re-think structural layout and design diminishes as a design progresses. Since many of the larger embodied carbon elements are in the structure of the building, optimization of these elements must happen at the beginning of the project, and poor decisions made early are difficult to remediate. The following layout tips are recommended for efficient material use:

» Use moderate spans (longer spans usually require more material).

  - In flat slab concrete construction, the longest bay can sometimes dictate the thickness of the full floor system due to formwork construction.

» Avoid load transfers at floor levels where columns above and below the floor level do not align.

  - Where possible, run columns and walls down to the foundation without offsets.

» Minimize story heights while balancing other project objectives such as daylighting and natural ventilation.

Source: Camp Arroyo, Livermore, CA. Dining Hall. Straw bale construction. Photos courtesy of Siegel & Strain Architects and JD Peterson.

Source: Camp Arroyo, Livermore, CA. Bath House. Stabilized earth construction. Photos courtesy of Siegel & Strain Architects and JD Peterson.

13 "Materials for Sustainable Sites: A Complete Guide to the Evaluation, Selection, and Use of Sustainable Construction Materials", Meg Calkins, October 2008.

It is also important to eliminate unnecessary materials. Where possible, use structural materials as finishes, and eliminate the other finish materials (for example, use exposed concrete floors and ceilings, or exposed wood structures).

Finally, design in standard modules to minimize waste, taking advantage of standard size sheets for common materials such as 4x8 plywood and gypsum board. Another option is to use prefabricated modular construction since shop-built components generally have less waste, and shops often do a better job recycling/reusing waste. Keep in mind that sometimes transportation and lifting requirements can add materials and carbon emissions; these impacts can be mitigated by using onsite factories for prefabrication.

6.3.9_SOURCE FROM MANUFACTURERS THAT HAVE REDUCED THEIR GHG EMISSIONS

Wherever possible, source materials from manufacturers that use low-carbon energy sources and have efficient practices that reduce their products' embodied carbon compared to their competitors. When comparing products, use product-specific EPDs that have been evaluated using the same Product Category Rules, and compare product-specific EPDs to industry-average EPDs when available.

Usually, recycled-content materials have a lower embodied carbon than equivalent virgin materials, but not always. Processes required for recovery and recycling, as well as transportation and energy-source impacts, will influence this comparison. Review product-specific EPDs where available to confirm climate performance.

GHG impacts from the fabrication of **architectural aluminum** can vary greatly, and emissions from virgin ore can be more than six times higher than recycled aluminum. However, it can be difficult to find high recycled content material for architectural grade aluminum. As a result, either consider using aluminum sparingly and efficiently, or help move the market towards better recycled content material by demanding transparency from suppliers so that appropriate decisions on alternatives can be made.

Steel products such as structural steel, rebar, and cold-formed steel can be sourced from electric arc furnaces (EAFs) or basic oxygen furnaces (BOFs). As discussed in Volume 2, section 2.5.2, EAF steel has a higher recycled content and generally lower embodied carbon, especially if the electricity is from renewable sources. Most of the steel consumed in the U.S. is produced domestically, but significant quantities are also imported.[14] Whereas nearly all domestically produced structural rolled shapes and rebar are produced in EAFs, many foreign producers rely more heavily on BOFs. Therefore imported sources are more likely to have a higher embodied carbon, especially with the added transportation impacts. Specifying domestically-produced steel can be a good strategy, especially if producer-specific EPDs are available that show good climate performance. As manufacturing practices are always evolving, it is good practice to evaluate foreign products when EPDs are available.

Plastics and foam insulation have a high carbon footprint compared to the alternatives, and spray foams currently use expanding agents with very high global warming potential. Use these materials sparingly and only when there are no alternatives. Many foam insulation materials (e.g., polystyrene and polyisocyanurate) are petroleum-based products that require significant energy to manufacture, resulting in a high-embodied carbon footprint. For thermal insulation, consider alternatives such as cellulose-based products (primarily made from recycled newspaper) and even sheep's wool and cork. As always, transparency from manufacturers helps facilitate the analysis of alternatives.

14 According to a White Paper produced by the American Institute of Steel Construction in August of 2018, production of hot-rolled structural shapes in the United States in 2017 exceeded 6.1 million tons, of which 8% was exported. Also in 2017, 14% of the structural steel erected in the United States was fabricated outside the U.S.

6.4 Embodied Carbon Case Studies

Source: Dror Baldinger©

6.4.1_HOUSTON ADVANCED RESEARCH CENTER

Project Location: The Woodlands, TX

Completion Year: 2017

Project Size: 20,000 SF

What:

The Houston Advanced Research Center (HARC) is an ILFI Certified NZE research facility that successfully implemented a whole-building life-cycle assessment to reduce embodied emissions and push toward a "zero-carbon" building.[15] As an organization, HARC is a "not-for-profit research hub providing independent analysis on energy, air, and water issues."[16] In 2014, HARC's original campus no longer supported its mission, and they sought to build a new headquarters that directly reflected its mission and served as a living example for regionally appropriate sustainable design in the Gulf Coast region. It was also essential that the design respect the financial realities of a not-for-profit research institution.

15 https://dashboard.harcresearch.org/ and https://www.aisc.org/globalassets/modern-steel/archives/2018/11/redefiningnetzero.pdf

16 https://harcresearch.org/about/building/

How:

The project took a holistic approach to carbon, considering both operational and embodied carbon. Both operational and embodied carbon were considered as measures of performance from the early programming charrettes, and the full design team was engaged in the early meetings. This led to the inclusion of Whole Building LCA early in the process to inform the structural system as well as the bay spacing. Multiple schemes were considered, as were the interaction and total embodied carbon of the structure and enclosure. The WBLCA determined that a steel-framed system, and not the more common exterior concrete bearing wall, resulted in the lowest embodied carbon. This system, which also included continuity of the exterior cold form wall framing, allowed for reductions in both the embodied carbon of the super structure and the volume of concrete required in the foundation. In 2016 concrete suppliers in Houston did not have mix-specific EPDs; however, the team required that the supplier have participated in the NRMCA Industry Average EPD and also used cement content as a proxy for the GWP of the concrete mixes.

Structural System	Steel framed with concentrically braced frames
Embodied Carbon Reduction from Business as Usual	Approximately 20%
Owner	Houston Advanced Research Center (HARC)
Architect	Gensler
General Contractor	Brookstone
Structural Engineer	Walter P Moore

6.4.2._LCA OF THE CATALYST BUILDING

Project Location: Spokane, WA

Completion Year: 2020

Project Size: 168,800 SF

Source: Benjamin Benschneider

What:

During the design phase of this five-story office building, Katerra commissioned the Carbon Leadership Forum (CLF) and Center for International Trade in Forest Products (CINTRAFOR) at the University of Washington to analyze the environmental impacts of its Cross Laminated Timber (CLT) as a structural and design element. The Catalyst Building's life-cycle assessment offers a better understanding of the life-cycle environmental impacts of mass timber buildings and identifies opportunities to optimize the environmental performance of mid-rise CLT structures.[17]

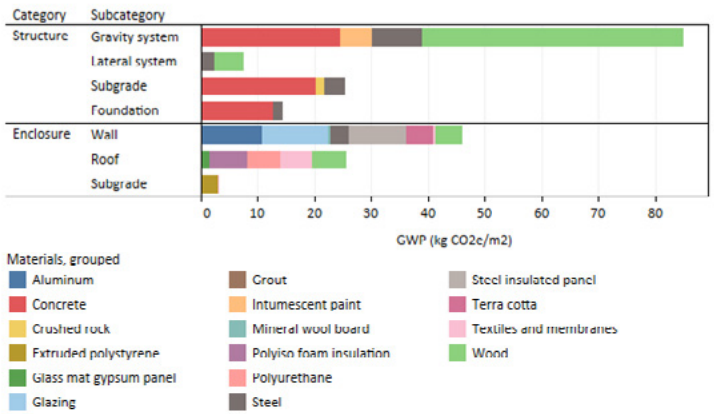
The life-cycle assessment of the core and shell estimated the building's upfront embodied carbon to be 207 kg CO_2e/m^2 (see Figure 6.10). This result is similar to other mass timber buildings and is lower than most other office buildings per unit of floor area, according to the Carbon Leadership Forum's Embodied Carbon Benchmark Study.[18] Additionally, the Catalyst Building stores approximately 204 kg CO_2/m^2 of biogenic carbon, which nearly offsets its upfront embodied carbon. However, a more comprehensive analysis, including end-of-life considerations, should have been performed in order to draw more definitive conclusions about the total carbon footprint of the building.

How:

Structural System	Gravity System: Glu-lam beams and columns, CLT slabs Lateral System: Buckling-Restrained Braces (BRB) and CLT shear walls
Embodied Carbon Reduction from Business as Usual	No business-as-usual case presented in this case study.

Owner	South Landing Investors, LCC
Architects	MGA/Michael Green Architecture, Katerra
General Contractor	Katerra
Structural Engineer	KPFF

FIGURE 6.10: GLOBAL WARMING POTENTIAL RESULTS (EMBODIED CARBON) FOR LIFE-CYCLE STAGE A (CRADLE-TO-GATE)



Source: "Life Cycle Assessment of Katerra's Cross-Laminated Timber (CLT) and Catalyst Building: Final Report", Carbon Leadership Forum and University of Washington Center for International Trade in Forest Products, November, 2019.

17 Note: this description is adapted from the case study write-up on the Carbon Leadership Forum's website: https://carbonleadershipforum.org/katerra/

18 https://carbonleadershipforum.org/embodied-carbon-benchmark-study-1/

6.4.3_OPENHOME WHOLE BUILDING LCA[19]

Project Location: Prototype (one completed project in New Hampshire, and currently under construction at sites in Colorado and New York)

Completion Year: N/A

Project Size: 3,653 SF

OpenHome is a system for constructing customizable prefab homes created in collaboration with Bensonwood, a builder of timber-frame houses and high-performance architectural components. The project is KieranTimberlake's first to identify a pathway to net-zero embodied carbon. The system also meets the requirements of the Passive House Standard, making it low- to zero operational carbon. The baseline prototype includes three bedrooms, three and a half bathrooms, a home studio space, kitchen, media room, living room, and dining room. KieranTimberlake's OpenHome system can be customized according to the climate, landscape of the site, and preferences of the owner.

The scope of the WBLCA model includes the substructure, superstructure, enclosure, and interior partitions and finishes. Without the purchase of carbon offsets, the final embodied carbon intensity of the buildings is 84 kg CO_2/m^2 (as shown in Figure 6.11) — a remarkable improvement over the baseline for single-family residential buildings of 315 kg CO_2/m^2 (developed based on the database in the Carbon Leadership Forum's 2017 benchmark study).[18]

Key steps in this optimization included:

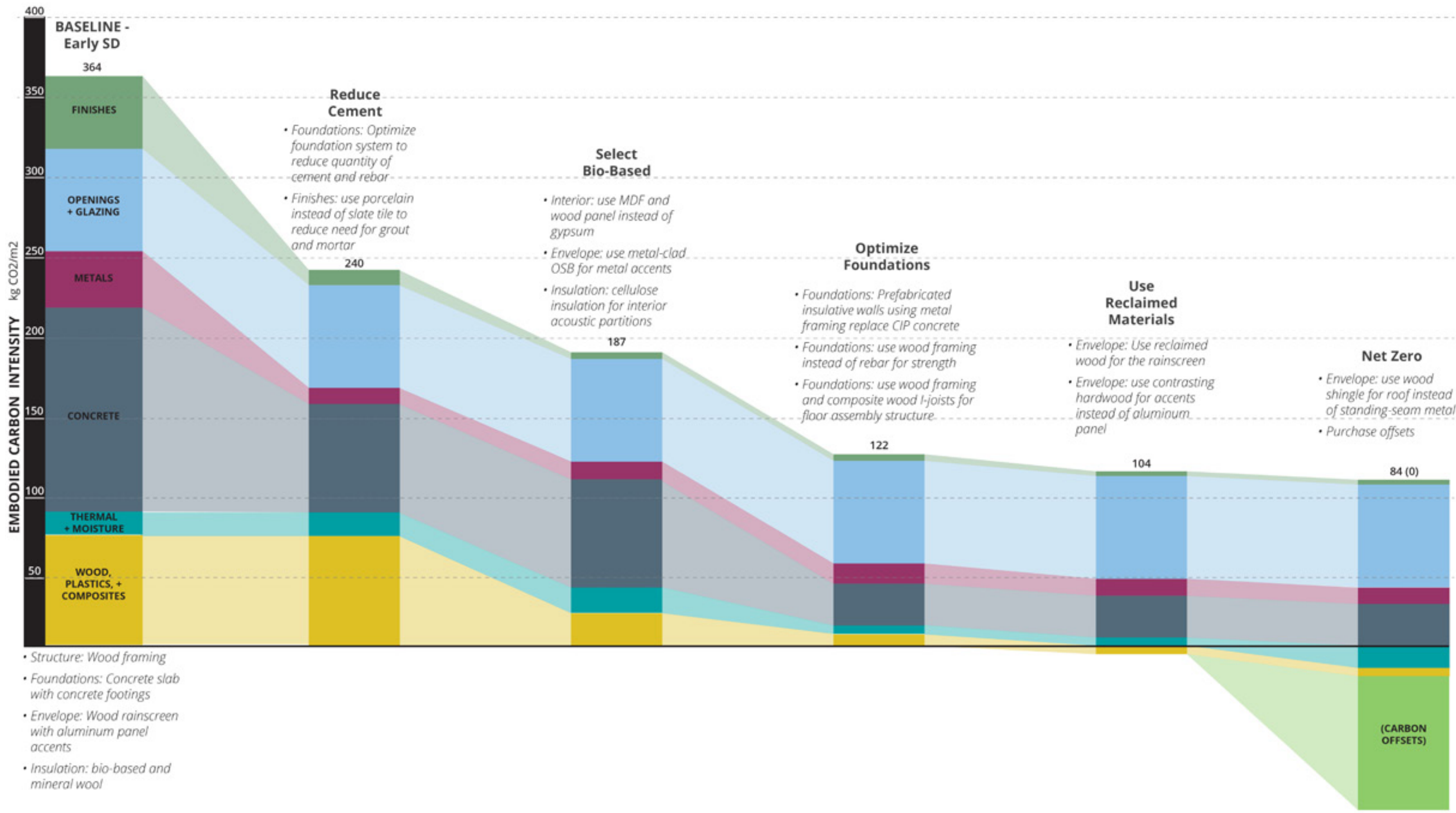
» reducing cement content, including in the concrete for the foundations (removal of footings and modifications to foundation walls) and in the mortar for the interior tiled areas;

» adding more bio-based materials to act as "carbon sinks" to sequester carbon; and

» using reclaimed materials when possible for any wood that is not carbon-negative over its lifecycle.

19 Simonen, K., Rodriguez, B., Barrera, S., Huang, M., "Embodied Carbon Benchmark Study, LCA for Low Carbon Construction, Part One", available at http://hdl.handle.net/1773/38017.

FIG. 6.11: ““OPEN HOME” WHOLE BUILDING LIFE CYCLE ASSESSMENT



Source: Case Study, KieranTimberlake, February, 2021.

6.4.4 DECONSTRUCTION AND REBUILDING PILOT AFTER HURRICANE KATRINA

Project Location: New Orleans, LA

Post-Katrina Mercy Corps deconstruction projects involved a range of materials and home types, from historic to contemporary. Photos: Brad Guy

What:

Within weeks of the 2005 hurricanes, Katrina and Rita, which hit the Gulf region of the United States, the non-profit Mercy Corps implemented a deconstruction program to reclaim building material from 60 of the approximately 275,000 destroyed and abandoned homes. In contrast to machine demolition, where entire buildings are crushed into waste and directed into landfills, deconstruction diverts materials away from landfills by redirecting them into reuse or recycling.

A detailed study was conducted on four homes deconstructed by Mercy Corps.[20] A total of 44 tons of material was redirected back into the local building material stream — enough to build three new homes out of the four that were deconstructed.

Architect and building materials reuse expert, Brad Guy, who worked on the New Orleans deconstruction, estimated that as many as 30,000 homes were demolished. If just 2,000 of those homes had been deconstructed, they would have yielded 6 million to 10 million feet of high-quality lumber and other usable materials. Meanwhile demolishing them generated landfill debris *equivalent to a 10-story building covering an entire Manhattan block*.

20 Hazel Denhart, "Deconstructing disaster: Economic and environmental impacts of deconstruction in post-Katrina New Orleans," January 2010 https://www.sciencedirect.com/science/article/abs/pii/S0921344909001712

How:

Organization	Mercy Corps (four home study findings)
Tons of Material Recovered	44 (11 tons/home average)
Wood Recovered	32,342 board feet of lumber
Salvage Rate	38-75% of the buildings by weight
Value of Building Material Recovered	$60,000
Cost	Deconstruction: $3.80 net cost to $1.53 net profit/square foot Demolition: $5.50 net cost/square foot

Images of an undamaged 1970s Florida floodplain buyout home being deconstructed. The lumber was used, under existing building codes, to rebuild HUD Section 8 Affordable Housing inland. Photos: Brad Guy

Trade-offs and Challenges:

Homeowners whose buildings were damaged beyond 51% of the fair market value received free demolition through federal funding provided by FEMA, but no funding was provided for deconstruction.

Deconstruction significantly reduces hazardous dust and associated pollution and health impacts. Lead-based paint dust from demolition projects has been shown to travel 400-600 feet — further than a block, or about twenty houses, from the site of the demolition. The lead dust contaminates more than just the soil; it can also enter windows of other homes in the area, and it directly impacts the health of demolition and debris transportation crew members.[21] When disaster debris waste is improperly disposed of, often in unlined construction and demolition or emergency landfills, it can generate methane and cause further community contamination.

Lessons Learned:

In addition to embodied carbon savings and other environmental benefits, deconstruction can provide meaningful local jobs and job training opportunities to help those impacted by disasters recover economically and socially.[22]

While not all disaster-damaged buildings can be safely deconstructed and reused, many more buildings can be, with large quantities of clean lumber, brick, and other building materials safely recovered for use.

21 Oregon Health Authority, Best Practices for the Demolition of Residences with Lead-Based Paint, 2018 https://www.oregon.gov/oha/PH/HEALTHYENVIRONMENTS/HEALTHYNEIGHBORHOODS/LEADPOISONING/Documents/Best-Practices-Demolition-of-Residences.pdf

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- Structural Engineering Institute's SE 2050 Commitment: https://se2050.org/
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BUILDING DECARBONIZATION COALITION

The Building Decarbonization Coalition unites building industry stakeholders with energy providers, environmental organizations and local governments to help electrify California's homes and work spaces with clean energy. Through research, policy development, and consumer inspiration, the BDC is pursuing fast, fair action to accelerate the development of zero-emission homes and buildings that will help California cut one of its largest sources of climate pollution, while creating safe, healthy and affordable communities. The Project Team gives special thanks to the BDC for its leadership in this endeavor and for the generous support of its Membership.

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CONNECTING POLICY AND PRACTICE WITH DESIGN URBAN FABRICK

WILLIAM J WORTHEN FOUNDATION

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