Carbon-Storing Materials

Summary Report

February 2021

CLF Carbon Leadership Forum

About the Carbon Leadership Forum

Inspiring and spurring collective action to solve the embodied carbon challenge

The Carbon Leadership Forum is a non-profit industry-academic collaborative at the University of Washington. We are architects, engineers, contractors, material suppliers, building owners, and policymakers who work collaboratively, pioneering research, creating resources, and incubating member-led initiatives for greatest collective impact. Our goal is to accelerate transformation of the building sector to radically reduce and ultimately eliminate the embodied carbon in building materials and construction.

Authors

The Carbon Leadership Forum research team:

- Julie Kriegh, PhD, AIA, Research Scientist, Carbon Leadership Forum, Department of Architecture, College of Built Environments, University of Washington.
- Chris Magwood, Director, Endeavor Center, The Sustainable Building School, Peterborough, Ontario, Canada.
- Wil Srubar III, PhD, Associate Professor, University of Colorado Boulder, Civil, Environmental and Architectural Engineering, Materials Science and Engineering Program.

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Executive Summary

The Carbon Leadership Forum at the University of Washington has recently completed a four-month research project with a major US tech company to understand the potential of using low-carbon and carbon-storing materials in new construction. The project focused on carbon-intensive hotspot materials (e.g., concrete foundations and slab floors, insulated roof and wall panels, and structural framing) in light industrial buildings. The study found that a sizable reduction (~60%) in embodied carbon is possible in two to three years by bringing readily-available low-carbon materials into wider use. Furthermore, this work predicts that fostering a carbon-storing material supply system by investing in the development and manufacturing of nascent carbon-storing materials industries will make a carbon-positive future possible in three to five years (see Figure 1).

Why is this strategy important? The International Panel on Climate Change (IPCC) has established that reductions in carbon emissions alone are not enough to curtail climate disaster. Therefore, it is crucial that we systematically draw down and store carbon.[1] Over the next 30 years, embodied carbon, namely emissions associated with the procurement, manufacturing, construction use, and disposal of building materials, is predicted to account for almost 50% of all new construction-related carbon emissions (Architecture2030). Addressing these emissions ***now*** is critical since embodied carbon emissions are committed at a building's inception and remain constant throughout the life of a building.

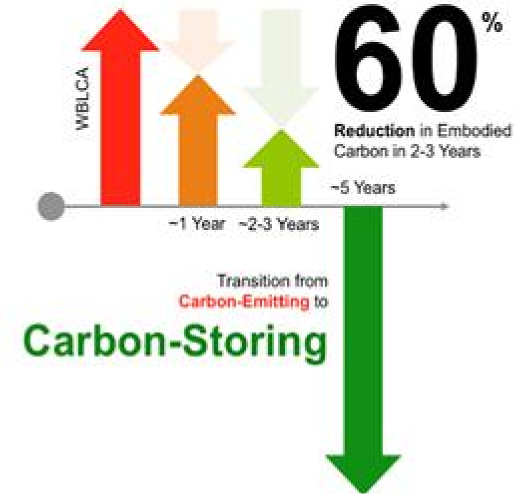

Figure 1. Potential carbon reductions (credit: Wil Srubar).

A key strategy. We can convert buildings from being an existential climate threat (emissions source) to a significant climate solution (emissions sink) by using biogenic materials that store carbon and reduce emissions during the production of construction materials. Emissions sinks are crucial to achieving decarbonization by 2030 because carbon has a time value; the impact of photosynthetic drawdown exerts the most impact at the beginning of the building process (see Figure 2).

Another key strategy can be found in the use of rapidly renewable biogenic carbon-storing building materials produced from biomass (e.g., annually harvested agricultural residues and purpose-grown fibers). Indeed, the use of biogenic materials renders possible not only upfront photosynthetic drawdown but also the potential for long-term carbon positivity. Both are crucial to achieving decarbonization by

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[1] The IPCC: "limiting warming to 1.5 degrees C will require removing carbon from the atmosphere in addition to reducing emissions"

2030 because achieving upfront photosynthetic drawdown in the early stages of the building process exerts the greatest impact on emissions and climate.

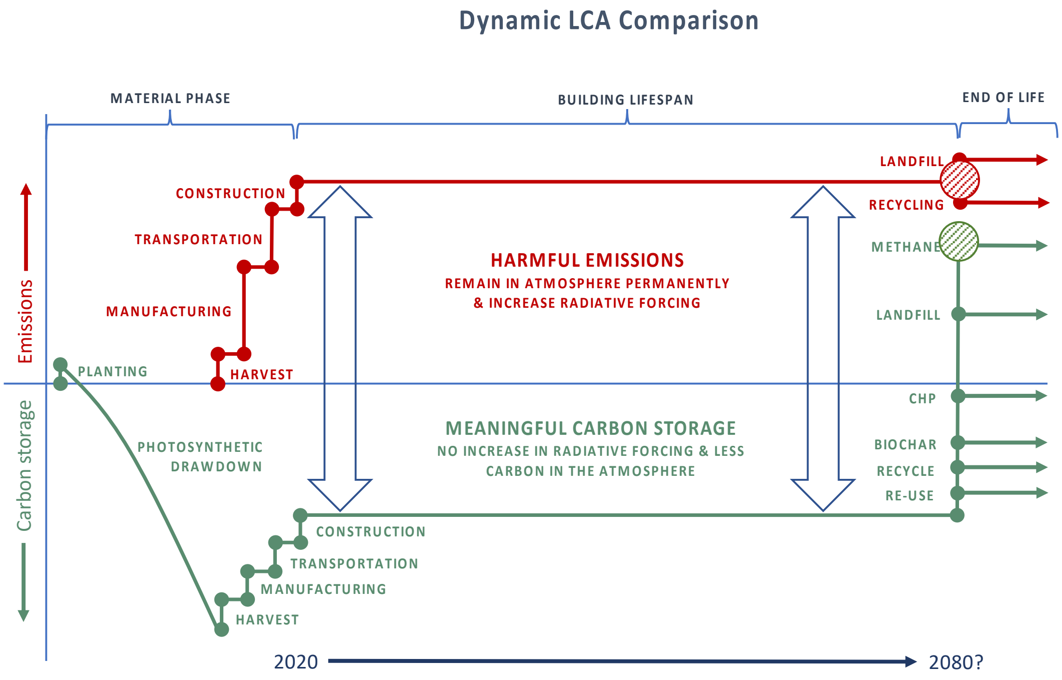

Figure 2. Photosynthetic drawdown (credit: Chris Magwood).

What are the broader impacts? It is possible to catalyze building decarbonization by establishing a new socio-techno-economic model that promotes building with biomass. Biogenic building materials made from biomass – underutilized agricultural residues (e.g., rice hulls, wheat straw, and bamboo leaf ash, sunflower stalks, sugar bagasse) and purpose-grown fibers (e.g., bamboo, cork, hemp, algae, and seaweed) – have the potential to create new building products (Cantor & Manea, 2015; Liuzzi, S., 2017; Maraveas, C., 2020). Building with these biogenic materials also has the promise to catalyze new manufacturing hubs, create jobs, provide training and education opportunities, and reduce the need for traditional, emissions-intensive disposal methods of waste fibers (e.g., incinerating, landfilling, composting). In addition, the carbon avoided and carbon stored in buildings represents a new asset class of carbon products for emerging carbon marketplaces. Taken together, these strategies are estimated to contribute to significant (> 1 gigatons of CO_2 per year) reductions of total carbon emissions globally (Churkina, G., et al. 2020; Habert, G., et al. 2020; Frank, S., et al, 2018). This work proposes that, by pairing communities where biogenic materials are harvested with companies (industry partners) where manufacturing and construction services occur, we can reduce upfront emissions in the building industry. We can also cut emissions associated with underutilized agricultural residues while catalyzing new carbon and building product markets and strong economies, producing multiple co-benefits.

1 Introduction

1.1 Context

Globally, the building and construction sectors account for nearly 40% of global energy-related carbon dioxide emissions through the construction and operation of buildings (including the impacts of upstream power generation).[2] Current building codes address operating energy but typically overlook the impacts "embodied" in building materials and construction products. In fact, when aggregated across industry sectors, more than half of all GHG emissions relate to materials management (including material extraction and manufacturing).[3] As building operations become more efficient, managing the embodied impacts related to producing and installing building materials becomes increasingly significant.

Meaningful embodied carbon reductions can be achieved using materials on the market today. Carbon-storing materials, both bio-based (such as mass timber) and mineral-based (e.g., emerging concrete products and concrete utilizing carbon capture and storage (CCS) technology), demonstrate the feasibility of using building materials to store carbon. Indeed, if the amount of carbon stored in a building exceeds the amount emitted during materials extraction, the building can be considered a "carbon sink" (Churkina et al., 2020). Though many carbon-storing materials are available on the market today, others are still in early development and deployment stages and require testing in order to gain market acceptance and scale in use.

Our research project focused on a light industrial building. This typology provides a unique testing ground for innovations in carbon-storing materials due to the unique performance requirements, high operating energy demands, and 15-year projected lifespan of these types of buildings. Given the industry's continuing plans to develop, build, and operate light industrial campuses, we believe our research question carries broad implications and merit:

> ***What is required to exceed carbon neutrality targets by storing enough carbon in building materials for the building to become a net carbon sink?***

By exploring both immediate and emerging strategies for embodied carbon reduction and storage, we tested our research question and developed a methodology and low-carbon and carbon-storing materials roadmap with potential for a broad impact.

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[2] UNEP and IEA, "Global Status Report 2017: Towards a Zero-Emission, Efficient, and Resilient Buildings and Construction Sector," 2017.

[3] OECD, "Global Material Resources Outlook to 2060: Economic Drivers and Environmental Consequences" (Paris, 2019), https://doi.org/https://doi.org/10.1787/9789264307452-en.

1.2 Project vision: Designing for carbon-storing materials systems

The Carbon Leadership Forum (CLF) was hired as a consultant in January of 2020 by a US technology company to identify opportunities for material substitutions to promote the decarbonization of their light industrial buildings in their new technology center building projects.

These technology centers, by virtue of their sheer size, rapid proliferation, and high use of resources, possess a unique ability to impact global, national, regional, and community building scales and manufacturing hubs. As such, the work of this project utilizes a “systems-of-system” (SoS) approach, based on our understanding that researchers, industry professionals, businesses, markets, and supply chains are components of numerous complex, integrated systems situated globally, regionally, and in local communities (see Section 1.5 for more SoS information). The measure of success for this carbon-storing project was our collective ability to help inform and guide decisions and actions in the design and building of these campuses, potentially inspiring thousands of individuals and companies in the industry to follow suit by reducing embodied carbon emissions in the most powerful and impactful ways.

Using an SoS approach to the design, construction, and operation, a technology center campus can serve as the nexus of a community of buildings, strategic innovation, and more. It can also weave a socio-techno-economic fabric that enables carbon reductions while catalyzing new regional manufacturing industries to join in the construction of a connected community of buildings beyond the technology center campus. Furthermore, increased use of new carbon-storing materials may encourage the development of new tools, databases and banking methodologies industry-wide.

1.3 Project values

Serving as imperatives for the project, the following values guided the project’s SoS approach:

- **Lead by example.** Set new and disruptive business-as-usual standards for a business impact with a global reach in embodied carbon in campus design.
- **Influence materials production.** Support manufacturing practices to foster industry adoption.
- **Take a holistic approach.** Design and build entire material supply systems, identifying mutual co-benefits in the local community, environment, and economy.
- **Be future-ready.** Consider the use of technologies and infrastructures responsive to the call for innovation and scalable solutions designed for an as-yet unknown technology future.

1.4 Project goals and recommendations

From this set of four underpinning values, the team created an index of low-carbon and carbon-storing materials to consider, vet, and evaluate. The materials index examined a range of products as a basis from which to evaluate opportunities and challenges for use in building design. This materials index (see Section 7) was honed over the course of the project into specific goals for recommendations in the following three time frames:

- **Immediate 1-to-1 substitutions (one-year time frame).** These recommendations are intended to provide *embodied carbon reductions* via material substitutions widely available, fulfilling the intent of the current building design without the need for a redesign.
- **Near-future use (two- to three-year timeframe).** These recommendations are intended to provide significant embodied carbon reductions via biogenic material substitutions and mineralized carbon products available on the market and may require component redesign without altering the basic geometry or form of the current light industrial building design.
- **Carbon-positive future (three- to five-year timeframe).** These recommendations include biogenic and mineralized material substitutions that are not yet widely available. Some of these materials would work with the current building design and require only component redesign, but others would require an overall redesign of the building. Included in the carbon-positive future are materials currently in small-scale production as well as those in various stages of research and development. These developmental opportunities are termed “quantum-leap” opportunities because they disrupt business-as-usual design practices. The carbon-positive future options present opportunities to progress beyond embodied carbon reductions at the material level toward the project goals as described in the system-of-systems approach outlined below.

1.5 System-of-systems approach

The CLF’s mission to inspire and spur collective action to solve the embodied carbon challenge comprises an important piece of the climate change puzzle that can be expanded through system-of-systems (SoS) thinking. When we consider the broader impacts of systems at multiple scales (e.g., community-wide, regionally, globally), an SoS mindset envisions our built and natural systems as composed of interwoven threads creating a fabric crucial to healthy systems for our planet, communities, and building industries. When we pull on various threads, an SoS approach reveals how low-carbon and carbon-storing materials, manufacturing, building, human, and natural environments are connected. The intersections of these threads offer spark points for innovative strategies.

For this study, the team envisioned the future technology campus as a “Hub” that will catalyze new regional product manufacturing industries to contribute to the construction of a connected community of buildings both within and beyond the boundaries of day-to-day technology operations.

Taking an incremental and sequential approach, the team first sought to map materials for immediate one-to-one replacement of carbon-intensive materials common across all regions and applicable to core technology center facilities globally. Next, the team identified opportunities to incorporate appropriate regional materials for replacement of existing materials with new carbon-storing materials according to local socio-techno-economic conditions of a selected region of North America. Then, recognizing that a technology campus project can affect socio-techno-economic conditions via investment in regional low-carbon and carbon-storage material manufacturing hubs, we sought to identify potential impacts on mature, emergent, and non-existent markets. For example, partnering with local agricultural businesses to include “agricultural residue” products in the manufacturing of materials like hempcrete could incorporate regionally appropriate fibers found in tobacco, sunflower, or rice plants into building materials.

Finally, the team sought to enhance opportunities for connecting low-carbon and carbon-storing materials research, design, manufacturing, and construction practices to local communities for housing, education, and employment.[4] Opportunities for connected communities include (see Figure 3):

- **Design for biophilia.** Enhance sustainable communities for humans and non-humans through design (e.g., grow low-carbon materials on site, foster distribution of carbon-storing materials).
- **Regenerative design.** Use of district renewable energy, energy storage, water collection, and renewable materials (e.g., use energy and water to support adjacent communities).
- **Design for circularity.** Ensure potential for modularity and reuse through prefabrication of components and building assemblies and reuse.
- **Beyond the boundaries of the campus.** Enhance technology, education, jobs, and housing in support of the local economy and workforce training.

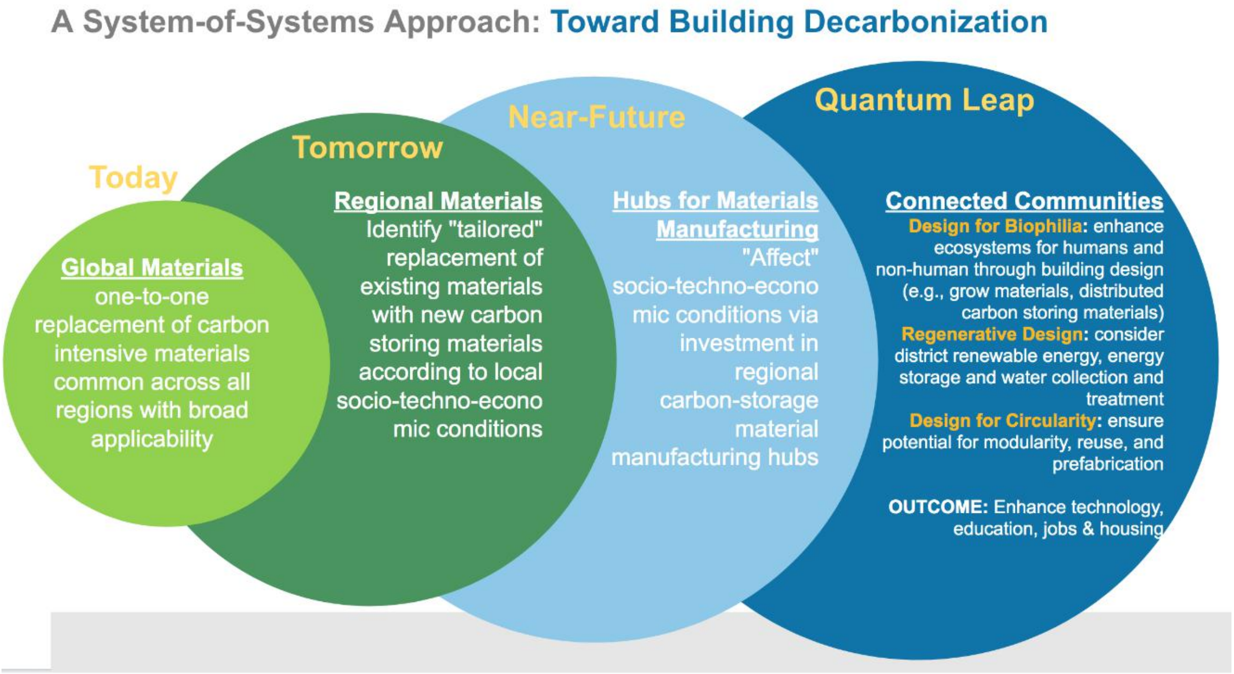

Figure 3. A system-of-systems approach: Toward Building Decarbonization (credit: Julie Kriegh).

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[4] See Section 4 for further information on these opportunities

2 Whole building life cycle assessment

2.1 WBLCA overview

A whole building life cycle assessment (WBLCA) of an existing light industrial building was conducted in order to establish a benchmark for a prototypical building. This single-story building is an approximately 287,602 square-foot facility. It is a steel-framed, pre-engineered metal building (PEMB) with a concrete foundation. This analysis was performed in 2020 by WSP Engineering using Tally, an LCA tool that is integrated with Revit (a building information modeling (BIM) software). Operational energy was not assessed.

The building scope of the WBLCA included:

- Structural elements, such as beams, columns, and slabs
- Enclosure elements, such as walls, roofs, finishes, waterproofing
- Interior walls

The building scope excluded:

- Elements or material systems that made up less than 5% of the total mass of the building
- Mechanical, electrical, and plumbing (MEP) systems
- Miscellaneous items such as equipment; landscape elements; fire detection and alarm systems; parking lots; site improvements; finishes on the interior floors and ceilings; railings; and non-structural partitions.

The following life cycle stages were assessed:

- A1: Raw material supply
- A2: Transport (from raw material supply site to manufacturing site)
- A3: Manufacturing
- A4: Transport (from manufacturing site to building site)
- B2: Maintenance
- B3: Repair
- B4: Replacement
- B5: Refurbishment
- C2: Transport (from building site to waste disposal site)
- C3: Waste processing
- C4: Disposal
- D: Benefits and loads beyond the system boundary (e.g., recycling, energy recovery)

2.2 WBLCA results

The embodied carbon footprint of the prototypical building was calculated to be approximately **380 kgCO_2e/m^2**. Table 1 presents a summary of the overall WBLCA results.

Table 1. Summary of WBLCA results, reflecting life cycle stages A1-A4, B2-B5, C2-C4, and D (credit: WSP Engineering).

Measure	Units	Result	Result normalized by gross floor area (units/m^2)
Global warming potential	kgCO_2eq	10,165,381	380
Acidification potential	kgSO_2eq	41,835	1.56
Eutrophication potential	kgNeq	2,457	0.09
Ozone depletion potential	kg CFC-11eq	0.26	9.59E-06
Smog formation potential	kgO_3eq	595,370	22
Primary energy demand	MJ	146,950,819	5497
Non-renewable energy demand	MJ	135,212,453	5058
Renewable energy demand	MJ	11,698,460	438
Mass total of materials	kg	32,368,779	1211

Figure 4 shows the contributions from different building categories to the overall global warming potential (GWP) or embodied carbon impact of the building. Figure 5 shows the contributions to total GWP by material division. This figure shows that concrete, metals, and insulation (a.k.a. "Thermal and Moisture Protection") make the greatest contributions to GWP.

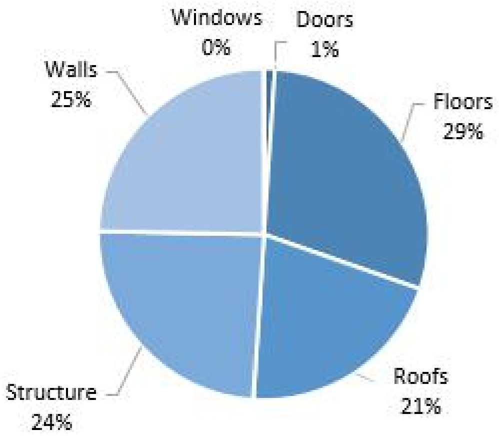

Figure 4. Contributions to total GWP by category (credit: WSP Engineering).

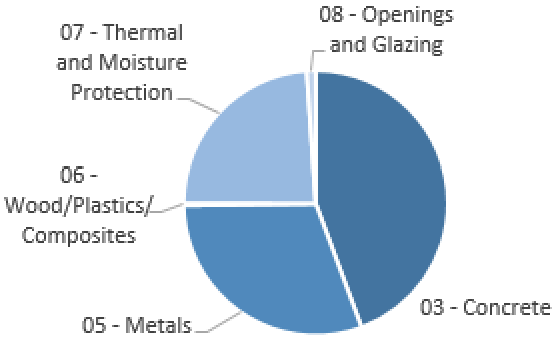

Figure 5. Contributions to total GWP by material division (credit: WSP Engineering).

Figure 6 shows the contributions to overall environmental impacts by life cycle stage. This figure shows how the Product stage made the biggest contribution to the embodied impacts of the building.

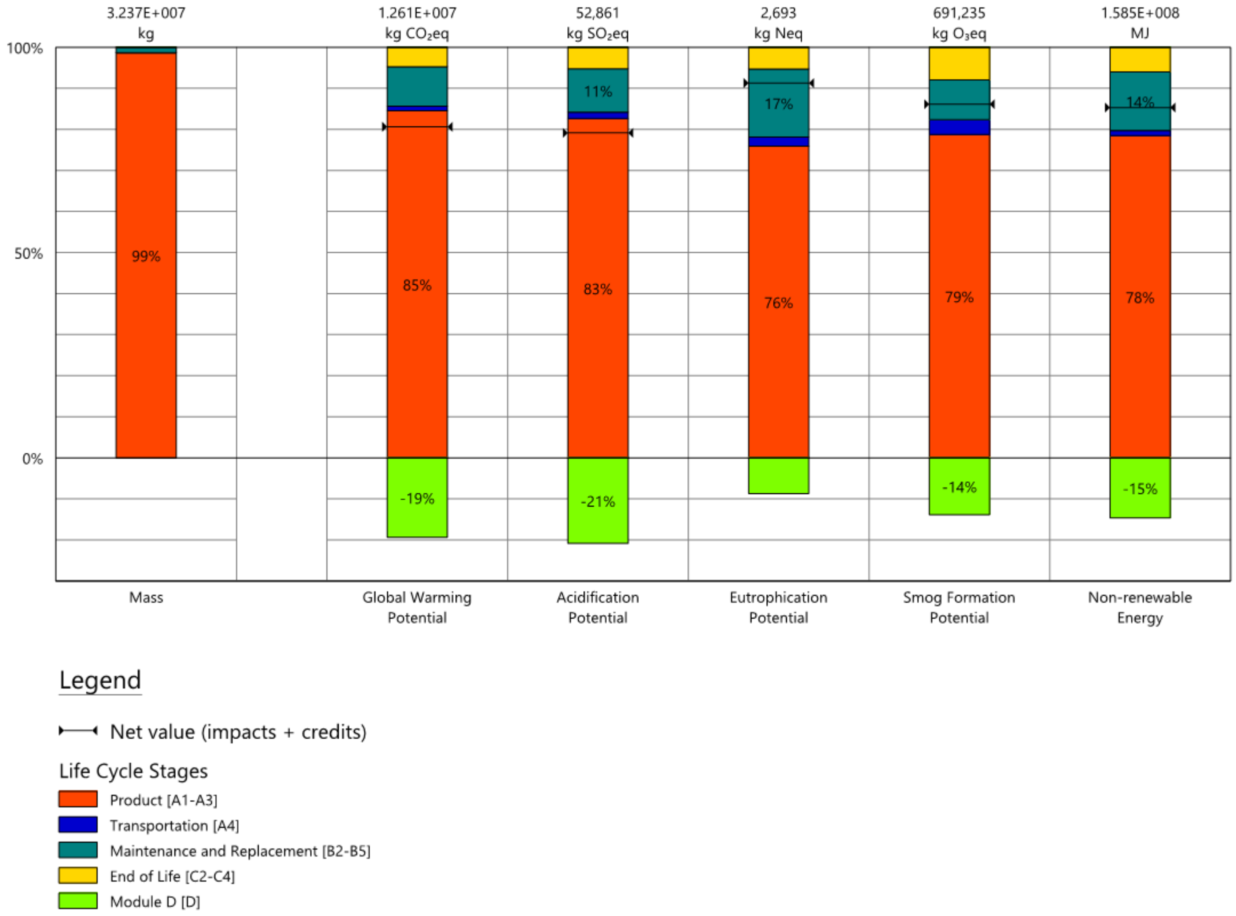

Figure 6. Contributions to overall environmental impacts by life cycle stage, results from Tally (credit: WSP Engineering).

2.3 Bay slice study

A bay slice refers to one structural bay with half a structural bay on each side is open on each side. A bay covers approximately 5000 square feet of area. A bay slice was used to model the following alternative designs:

1. Steel baseline case
2. Steel proposed case
3. Glulam proposed case

The key materials in the different bay slice models are shown in Table 2.

Table 2. Key materials in different bay slice models (credit: WSP Engineering).

Steel Baseline Case	Steel Proposed Case	Glulam Proposed Case
● Total Concrete Structure	● Total Concrete Structure	● Total Concrete Structure
● Total Steel Structure	● Total Steel Structure	● Total Steel Structure
		● Total Glulam Structure
● 6" Gravel Base	● 6" Gravel Base	● 6" Gravel Base
● Base-of-Wall Cladding	● MetlSpan C42 Wall	● Benson Wood Wall Panel
● MetlSpan C42 Wall	● MetlSpan CFR42 Roof	● Benson Wood Roof Panel
● MetlSpan CFR42 Roof	● IsoSpan	● IsoSpan
● Louver + Bird Screen	● Louver + Bird Screen	● Louver + Bird Screen
● XPS Rigid Insulation, excluding XPS at Base-of-Wall Cladding	● XPS Rigid Insulation - Footing Only	● XPS Rigid Insulation - Footing Only

The results from the bay slice study are shown in Table 3. The assessment was conducted by WSP Engineering in Tally and assumed a service life of 60 years for the building. Biogenic carbon was included in the results for modules A1-A4, B, C, and D (the treatment of biogenic carbon was taken on a 100-year timeline in alignment with GWP 100 standard). In this case it is assumed that the life of the building is less than 100 years and the full disposal and degradation cycle will occur. Results are reported with and without the benefits and loads of biogenic carbon. Results show that using glulam in place of steel can reduce the embodied carbon by at least 60% compared to the baseline case (see Table 3).[5]

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[5] WBLCA assessment and Bay Slice study were conducted by WSP Engineering in Tally and reported in a June 10, 2020 memo.

Table 3. Summary results from bay slice study, reflecting life cycle stages A1-A4, B2-B5, C2-C4, and D (credit: WSP Engineering).

Case	GWP (kgCO2eq)	Absolute GWP reduction from steel baseline case (kgCO2eq)	% GWP reduction
Steel Baseline	484,404.80	-	-
Steel Proposed with biogenic carbon	433,691.92	50,712.88	10.47%
Steel Proposed without biogenic carbon	434,243.11	50,161.69	10.36%
Glulam Proposed with biogenic carbon	142,284.93	342,119.87	70.63%
Glulam Proposed without biogenic carbon	167,670.02	266,021.90	65.39%

2.4 Discussion

Building components that had the potential to be replaced with low-carbon and carbon-storing alternatives were identified and organized in three implementation time horizons: 1-to-1 replacements (implementable within one year), near-future replacements (2-3 years), and innovative strategies enabling a carbon-positive future (3-5 years). Potential reductions in embodied carbon increase dramatically at each time horizon, with a net neutral or even carbon-storing balance achievable within a five-year time frame:

- 1-to-1 replacements → 20% reductions achievable immediately
- Near-future replacements → 60% reductions achievable within 2-3 years
- Carbon-positive approach → 100% reductions achievable within 3-5 years

The recommended carbon-storing materials and strategies fall into five distinct categories, addressing the current design's embodied carbon hotspots:

- **Concrete.** Minimization of concrete elements and improvements to concrete specifications are the single most important factors to achieve emission reductions in the immediate term. Sizable reductions are possible in the near term as developments in concrete formulation progress, with opportunities for leadership in adoption. Carbon-sequestering aggregate and biogenic cementitious materials offer the potential to reduce the carbon footprint of concrete to zero within five years.
- **Structural framing.** The embodied carbon of the current steel frame of the building design can be reduced by conscientious steel procurement (e.g., electric arc furnace steel or direct reuse). A switch to a glulam timber frame offers significant emission reductions and, with appropriate sourcing of the timber, could lend substantial carbon storage to the building.

- **Building enclosure.** The current metal-insulated panels (MIPs) with foam insulated cores can be improved only minimally by procurement decisions. However, a switch to wood-framed panels with cellulose insulation with appropriate detailing for fire protection achieves major reductions and carries the potential for a high amount of carbon storage. Panels currently available on the market with cellulose insulation offer suitable replacements for current MIPs in the near term. Wood-framed panels could be optimized within five years to be entirely carbon-storing, made from certified wood or bamboo and natural fiber insulation that is regionally-sourced, based on the panels currently being produced in limited quantities.
- **Louvers and bird screens.** Aluminum fabrications are currently used in the design, with limited opportunities for emission reduction via responsible sourcing. Bio-composite materials using agricultural fibers and bio-resins offer potential replacements within 3-5 years, a shift that would enable this portion of the building to achieve zero emissions or net carbon storage.
- **Purpose-grown fibers, earth, and waste.** Throughout the building, many opportunities can be found to use building materials based on regionally appropriate natural fibers, soils, and waste streams, including sheet goods, flooring, cladding, millwork, interior panels, and finishes. All of these choices would contribute to increased carbon storage capacity.

3 Findings and recommendations

3.1 1-to-1 replacements

Materials research demonstrated that simple material substitution made to general specifications and low-carbon material procurement strategies can yield a **20% reduction** in embodied carbon compared to the baseline WBLCA (see Table 3).

Key recommendations for short-term (immediate) implementation are as follows:

- **Concrete foundations (footings and slabs).** Minimize the use of concrete. Edit master specifications to specify design compressive strength of concrete @ 56 (or 90) days; remove limits of 30% maximum SCM content and specify 40% minimum SCM content where appropriate; specify limits in cement content (verifiable with concrete mix design submittal and batch ticket) and/or embodied carbon (verifiable with EPDs) per compressive strength category per region; and encourage use of Type IL cements, which are now widely available.
- **Foundations (perimeter wall).** Despite a relatively small impact on overall emissions, a move to using biogenic insulated concrete forms (e.g., IsoSpan, Nexcem IsoSpan) would enable a scenario in which use of more innovative concrete mixes requiring longer curing times would not slow the construction schedule because the formwork is permanent.
- **Structural systems.** Source all steel from electric arc furnace (EAF) facilities and/or encourage direct reuse where appropriate.
- **Wall and roof panels.** In the current design, wall and roof panels are constructed of metal insulated panels (MIPs) filled with extruded polystyrene (XPS) or expanded polystyrene (EPS) foam insulation cores. Analysis showed that no significant reduction in emissions could be demonstrated by substituting mineral wool for the current foam-based insulation in the MIPs.

However, manufacturers may be open to supplying cellulose insulation in lieu of extruded polystyrene (XPS) or expanded polystyrene (EPS) foam panels as an alternate.

3.2 Near-future replacement

Even with the 20% reductions achievable today through short-term changes, building systems will remain responsible for significant outputs of carbon. Material substitutions and low-carbon strategies implementable in the near-future (2-3 years) provide a roadmap to transform technology campuses from carbon-emitting building platforms to carbon sinks. For example, the near-future WBLCA does not incorporate a CLT floor/foundation (with appropriate detailing) or bio-based louvers, but these elements would further and significantly reduce the carbon footprint of the building (see Table 3).

Key recommendations for near-future (2-3-year implementation) are as follows:

- **Concrete foundations (footings and slabs).** Edit master specifications to mandate Type IL and/or LC3 cements; explore potential partnerships with alternative cement/concrete and carbon-storing aggregate and filler manufacturers; work with concrete suppliers to prompt their transition to natural, more sustainable SCMs; engage a CLT manufacturer/design firm for conceptual design and analysis of CLT foundations in place of concrete.
- **Structural systems.** Redesign the steel structural system to accommodate a glue-laminated (glulam) engineered wood structural system with appropriate fireproofing considerations.
- **Wall and roof panels.** Engage a manufacturer of wood-frame/cellulose wall and roof panels (e.g., prefabricated panels) to establish appropriate design parameters and finishing options; work with panel manufacturer to source sustainably harvested wood products for panels; work with design team and panel manufacturer to ensure panels are easily dismountable at the end of the building's lifespan; encourage panel manufacturer to produce an EPD for the panels.
- **Louvers.** Connect with a biofiber and bioresin fabricator to design an appropriate louver and bird screen system to replace the current aluminum version; encourage the fabricator to produce an EPD for the product to quantify emission reductions and storage potential.

3.3 Carbon-positive future

These strategies can reduce emissions by at least 60% (see Table 3), and potentially more, depending on the accounting for biogenic carbon.

Key strategies for a carbon-positive future (3-5 year implementation) are as follows:

- **Fiber-based materials.** In general, agricultural biofibers are regionally available and highly abundant. Biological fibers such as hemp, straw, and other agricultural residues, as well as seaweed, could be used as building blocks for strong, durable building materials. Proof-of-concept and small-scale technologies already exist to transform biofibers into building materials. These technologies can be scaled and replicated in other regions around the world.
- **Earth-based materials.** Similar to biofibers, earth-based materials abound, as does the knowledge and practical know-how to build strong, durable, insulative, fire-resistant earth

structures. Opportunities exist for (1) introducing compressed earth block technologies in regions where they do not yet exist and (2) combining earth blocks with biofiber reinforcements, panels, or insulation materials to create high-performance carbon-storing envelope assemblies.

- **Purpose-grown materials.** The power and potential of rapid photosynthesis and the unique abilities of photosynthetic organisms can be harnessed in the manufacturing and "growth" of carbon-storing materials. Algae, for example, can be used to create biofuels and biochar as well as a multitude of other functional bioproducts, such as inks, foods, carbon-storing mineral fillers for concrete, and other load-bearing carbon-storing building materials and finishes. Algae (and photosynthesis more broadly) could thus serve as a nexus for a carbon-storing community.
- **Waste stream materials.** Measures can be taken to prevent waste-stream biogenic materials from returning carbon to the atmosphere. Municipal recycling systems and regional industrial by-products can often furnish raw materials for a wide variety of building materials. Such materials are in production in many places today and could be encouraged near technology centers. Partnerships in research and development with companies exploring new recycled materials can be fostered.

4 Discussion and future directions

4.1 Paradigm shift toward a carbon-positive future

A transition to a carbon-positive future can be facilitated by a paradigm shift in perspectives of technology campuses as the center of carbon-storing communities. A pivot of this type will necessitate design changes that go beyond emission reductions and promote carbon-storing materials and strategies that contribute even further to meeting carbon-neutral goals by 2030. As increasing numbers of companies pivot to support global strategies exemplified by existing and emergent regional industries worldwide, a paradigm shift from carbon emission reductions to carbon-storage strategies will follow, meeting both the values and goals stated below:

- **Lead by example.** Set new and disruptive business-as-usual standards for an impact that has global reach with regard to carbon storage in design and construction practices, both on technology center campuses and in local communities and industries.
- **Influence materials production.** Support manufacturing practices to foster industry adoption with a focus on globally strategic plans to promote the production of new region-specific biogenic materials (e.g., fiber and purposefully-grown materials).
- **Take a holistic approach.** Foster carbon-storing communities that includes mutual co-benefits for the local people, environment, and economy. This model essentially focuses on the importance of photosynthetic (carbon) drawdown and fostering community-based co-benefits for the new biogenic materials industries. Existing examples include: energy-flexible buildings tied to a smart grid, district heating and cooling relationships with a local community, transit-oriented and development linking transportation to housing, economic opportunity zones pairing agriculture residue products with materials manufacturing, and education and workforce training

partnerships with local universities. This report suggests that a technology center could comprise the hub for carbon-storing communities.

- **Be future-ready.** Be a leader in the future carbon economy and a pioneer in the eco-ag-tech industry. Design for prefabrication, modularity, circularity, and reuse will enable future flexibility.

5 Limitations and future applications

Limitations. This study did not thoroughly investigate potential changes to: building codes, material assemblies with respect to moisture, humidity and temperature, architectural design, structural engineering, cost estimating, and construction schedules or specifications.

Future applications. We anticipate that there are several notable next steps in the development of carbon-storing materials including:

1) Code revisions
    - Identify code and standards barriers to adoption of new materials
    - Engage in standards and code development process to support revisions
    - Support testing and certification as needed to address concerns such as fire resistance/water
2) Pilot materials
    - Engage an architectural, engineering, and construction teams to evaluate materials with respect to cost, schedule, life safety, building codes, fire, humidity, and other performance specifications, and product availability
    - Investigate new and innovative biogenic materials in early stages of development
3) Prototype buildings
    - Build small but impactful prototype, not necessarily industrial campus
    - Consider demonstration projects for affordable housing and community center structures
4) Address opportunities and barriers
    - Promote EPDs for materials, LCAs, policies, tools, and methodologies
    - Provide corporate incentives for new materials/manufacturing and education/careers
    - Develop survey instruments addressing opportunities and barriers to market adoption including: environmental values, design, engineering, manufacturing, and construction practices
    - Evaluate opportunities to transform the avoided and stored carbon into carbon assets that can be sold on emerging carbon marketplaces for buildings
5) Advocate for environmental justice
    - Advocate for environmental justice with respect to climate impacts, materials and manufacturing, access to economic opportunities through business development, education, and job training
    - Endorse carbon-storing materials to promote healthy outcomes for people, prosperity and the planet

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7 Appendix: Carbon-Storing Materials Index

Carbon Leadership Forum Embodied Carbon Materials | Index

Kriegh, J., Magwood, C., Srubar, W. 2021

Time / Years	Strategy Prototype	Strategy Replacement Material	Recommendation + Example (Type of component/material)	Intervention type (see definitions in Reference Tables tab)	Alignment with Values 1-4 (Systems Tab)	Immediate 1-to-1 Substitutions (~1 year Timeframe)	Near-Future (~ 2-3 year Timeframe)	Carbon Positive Future. (~5 year Timeframe)	Timeline for Commercial Use	Identified challenges + opportunities	Regional availability/beneficiary (where is it currently available, any regional constraints (e.g. soil type)	Product / Company Links	EPD available?	Compliance testing?	Positive local impact (ecosystems, people, natural resources, carbon reductions?) (Y/N)	Carbon reduction potential	A1-A3 (kgCO2e/m3) % Reduction	Influencing industry ($ - market potential)	Biophilia & natural design (Y/N)	Social equity (Y/N)	Scalability (1 - 4 score)	Disruptive potential (Potential for Impacts beyond the boundary of the data center campus)	Risk mitigation (Y/N)	Feasibility (% - probability of commercial scale)	Circularity (prefabrication, modularity, re-construction)	Applicability to building scale	Regional availability
															Medium	High	Med	High	Medium	Med	High	High	Low	Med	High		
	Foundations/Slab																										
1-1	**Foundations-Concrete Structural Piers and Slab Floor**	**Low-Carbon Concrete (High SCM & 56- and 90-Day Design Compressive Strength)**	1. Edit Master Specifications to specify design compressive strength @ 56 (or 90) days 2. Remove limit of 30% maximum SCM content and specify 40% minimum SCM 3. Specify limits in cement content (verifiable with concrete mix design submittal and batch ticket) and/or (3) embodied carbon (verifiable with EPDs) per compressive strength category per region 4. Encourage use of Type IL cement, where available Example: Katerra has used 40% - 70% supplementary cementitious material (SCM); US Concrete consistently delivers high-volume slag concrete.	Off-the-shelf alternative (1:1 replacement)	1. Lead by example 2. Influence material production	Versions of high SCM mixes exist everywhere. This category includes many different admixtures, each of which has regional appropriateness. In general, high SCM specifications can achieve 15-30% emission reductions. This is an easy step to take in a high-impact category. Specifying compressive strengths at 56 or 90 days instead of 28 would enable utilization of a lower cementitious materials mixture for the same strength/application.	Investment/development in this area would have significant impact on global emissions. Development of new/improved SCMs (including biological ones like palm kernel ash) would be valuable.		Now.	Excellent opportunity to use best practices and achieve substantial carbon reductions. See Marin County code for carbon-reduced concrete for model specification language. 1) Encouraging high SCM concrete to become business-as-usual would be high impact; achievable by edits to master specifications. 2) Development of SCMs, and in particular less common ones, could be influential; there are opportunities to invest in companies producing natural pozzolans.	No constraints. The SCMs are likely to vary by regional availability, but this should already be well established for batching plants. Some more rural ready-mix plants may need investment in another silo.	https://www.marincounty.org/-/media/files/departments/cd/planning/sustainability/low-carbon-concrete/12172019-update/low-carbon-concrete-code.pdf?la=en	Yes	Yes	No	Medium	20%	Medium, industry moving this way already	No	NA	1	Product exists but not widely specified at present	Low	High	No. But potential for creative solutions	All scales	All
2-3	**Foundations-Concrete Structural Piers and Slab Floor**	**New concrete technologies (see also below biological aggregates and SCMs)**	1. Edit Master Specifications to specify preference for Type IL and/or LC3 Cement; the more they are asked, the quicker it will become mainstream in the US. 2. Maintain in contact with Blue Planet and Solidia for potential partnerships. 3. Work with concrete suppliers and request their transition to natural SCMs. Example: Solidia Technology, BLue Planet	Co-development: product scaling required	1. Lead by example 2. Influence material production 3. Take a holistic approach 4. Be future ready		Aggregates represent a grand opportunity for carbon-storage. Limestone, a common aggregate in concrete, is composed primarily of CaCO3, of which 44% (by mass) is, in effect, historically-sequestered CO2. Thus, more CO2 could be stored in concrete than is emitted during its production if limestone aggregates can be “grown” using waste CO2. Two primary technologies for producing carbon-storing aggregate exist. Both are based on CO2 mineralization technologies. One, Blue Planet Technology , is a chemical approach. The other is biological. Substitution of OPC for alkali-activated slag can reduce the carbon footprint of concrete mixtures >80%. Despite this advantage, the use of alkali-activated slag concrete is not without its challenges. Slag sources are less readily available in the US than OPC; however, there has been a recent increase in the import of slag sources.	The biological approach is considered a quantum-leap photosynthetic biological mineralization approach based on stromatolite formation that is being investigated at the University of Colorado and is described in more detail in the Carbon-positive Future section of this report.	2-5 years	**Strategy (1.1)** LC3 is technically considered a “blended portland cement” that includes the addition of metakaolin (calcined kaolinite clay) and limestone. LC3 is similar to Type IL cement in that it contains up to 15% ground limestone. The main components of LC3 include portland cement (50%), calcined clay (30%), limestone (15%), and gypsum (5%). The major innovation in LC3 is to combine the use of abundantly available low-grade kaolinite clay with a further 15% of limestone, with no reduction in mechanical performance. **Strategy (1.2)** Blue Planet produces carbonate rocks, or synthetic limestone, from sequestered carbon dioxide (CO2) (see Figure 6). Ideally, this synthetic limestone would be used as a replacement for natural limestone aggregate in concrete mixtures. Blue Planet utilizes a water-based method for capturing CO2 from flue gas. **Strategy (1.3)** AACs are portland-cement-free alternative cements. Fundamentally, AACs are a class of materials that are created through the combination of (1) an alkali source (e.g., sodium hydroxide) and (2) an aluminosilicate (e.g., fly ash, slag, metakaolin) to form a binder, in much the same way in which (1) water and (2) calcium silicates form the binder in OPC. Solidia claims two core technologies, including (1) a sustainable cement manufacturing technology which can be produced in a traditional cement kiln using less energy, resulting in ~40-50% reduction in carbon emissions and (2) a sustainable concrete curing technology, which utilizes CO2 instead of water for curing.	LC3 cements are most common in Europe. A limited supply exists in the US. Blue Planet is currently building its first large-scale production facility in Pittsburgh, CA. This pilot will showcase how Blue Planet technology can be applied to a variety of industrial facilities. For instance, CO2 used in production of Blue Planet aggregate can be sequestered from cement manufacturing facilities. A carbon-negative concrete can be produced by using blue planet aggregate and cement manufactured by a plant utilizing Blue Planet CO2 sequestration. Deep decarbonization will decrease the supply of fly ash. In fact, most (if not all) west coast slag comes from Asia. Thus, the cement and concrete industry is embracing a transition to natural and alternative SCMs. Current alternative SCMs that are being vetted include natural and industrial sources of minerals rich in aluminum and silicon.	https://www.solidiatech.com. http://www.blueplanet-ltd.com	Yes				60%	High		NA	HIgh	Yes	Med	High	No.	All Scales	Developed
2-3	**Foundations-Concrete Structural Piers and Slab Floor**	**Cross Laminated Timber (CLT) foundation**	1. Engage a CLT manufacturer/design firm for conceptual design and analysis of CLT foundations.	Concept investment	1. Lead by example 2. Influence material production 3. Take a holistic approach 4. Be future ready		While utilization of novel cementitious materials for foundation systems would indeed manifest into palpable savings in embodied carbon, the utilization of CLT as the primary structural systems for foundations would aid in transitioning the foundation from a carbon-emitting system to a carbon-storing system in the near-term. While only one publicly available design detail was available (see Figure 8)[1] [2] [3] , the concept of utilizing CLT panels on helical micropiles is an engineerable system, which would reduce the embodied carbon of the foundation system to approximately 100 kgCO2e/m3 without considering the biogenic carbon storage potential of CLT.	Requires Redesign of building and full scale testing	2-5 years	If biogenic carbon storage is considered, the carbon emissions of the CLT floor is estimated to be approximately -678 kgCO2e/m3 (see Table 6). Such a foundation system could: ● Offer substantially reduced embodied carbon emissions with the building in its current form ● Be part of a more intentional redesign for lower emissions that would reduce the size of the foundation and roof systems by creating a multi-story building. Each additional story would cut the foundation and roof size substantially. Even if the building retains a concrete foundation and floor, a move to a stacked design would reduce the overall impact of the concrete and allow for CLT floors to be used on all subsequent stories. ● Reduce embodied carbon but would also shrink the size of the required stormwater retention features, reducing site change impacts. It may also offer opportunities to capture and use the ground temperature under the CLT floor to aid in passive and/or active cooling of the building by creating a reservoir of naturally cooled air under the floor.	While utilization of novel cementitious materials for foundation systems would indeed manifest into palpable savings in embodied carbon, the utilization of CLT as the primary structural systems for foundations would aid in transitioning the foundation from a carbon-emitting system to a carbon-storing system in the near-term. While only one publicly available design detail was available (see Figure 8), the concept of utilizing CLT panels on helical micropiles is an engineerable system, which would reduce the embodied carbon of the foundation system to approximately 100 kgCO2e/m3 without considering the biogenic carbon storage potential of CLT.	CLT Handbook. (https://info.thinkwood.com/clt-handbook)	Yes	CLT production and design in North America is governed by the American National Standards Association approved ANSI/APA PRG 320-2012 Standard for Performance-Rated Cross-Laminated Timber	Yes		60%	High	Yes	NA	High	Yes	Low	High	Yes	All Scales	Developed
1-1	**Foundations - Perimeter Wall**	**IsoSpan and Nexcem**	1. Replace poured concrete perimeter wall foundation and foam insulation with IsoSpan 2. Encourage North American suppliers of wood-chip ICFs to offer wood fiber board inserts and consider the use of alternative cements in their block production to reduce emissions 3. Require suppliers of wood-chip ICFs to produce EPDs Example: Bio-based insulated concrete form	Off-the-shelf alternative (1:1 replacement)	1. Lead by example 2. Influence material production	This Insulated Concrete Form (ICF) would be a drop-in substitute for the current poured concrete foundation with rigid insulation and would be the only carbon-storing foundation option currently available. Needs to be imported from Europe now.			Now. Production in Europe	Insulated concrete form made from waste wood materials. Excellent opportunity to bring a leading product from Europe to NA. While this element of the building represents a relatively small percentage of the overall building composition, the existence of a carbon-storing alternative with a proven performance history suggested that we include this as part of the 1:1 replacement recommendations.	No constraints.	https://www.isospan.eu/en/ https://nexcembuild.com/	Yes	No	No	High	20%	High	No	NA	2	Yes	Low	High	No.	Admin	Developed
	Biological Aggregates & Biological SCMs																										
3-5	**Carbon-positive Future Materials**	**Purpose-Grown Materials**	1. Identify opportunities within building design for potential use of purpose-grown materials 2. Conduct analysis to understand opportunities for purpose-grown materials 3. Connect with researchers and start-ups to form network of expertise 4. Invest in research and development of innovation at all levels 5. Foster direct connections between all nodes of the system					Two primary technologies for producing carbon-storing aggregate exist. Both are based on CO2 mineralization technologies. 1. Blue Planet Technology is a chemical approach that was previously discussed as a near-term solution. 2. Photosynthetic mineralization is a biological approach based on stromatolite formation that is currently under investigation at the University of Colorado.		A new science of purpose-grown building materials is beginning to emerge, and includes options like microbe- and algae-based cement and mycelium insulation. These materials represent the far edge of the quantum-leap but we believe that the feasibility of these materials will develop quickly and progress could be monitored by the data center design team and considered for early adoption through demonstration projects.							100%										
3-5	**Carbon-positive Future Materials**	Carbon8 aggregates Blue Planet	Aggregates made from waste CO2 (typically from cement production facilities)	Co-development: product scaling required	1. Lead by example 2. Influence material production 3. Take a holistic approach 4. Be future ready	If it's possible to obtain Carbon8 or Blue Planet aggregate, it would be a precedent-setting use. Blue Planet is looking for up-front customers to help with their scale-up.	Investment in these companies or comparable technologies has large global potential. The most likely source for the CO2 is cement plant emissions, which could transform the net emissions of the cement industry.		Soon. Limited production in US and UK	Promising technology to turn waste CO2 into aggregate for construction and concrete. Could be a major breakthrough to offset cement production emissions. Needs support/development.	No constraints. Needs CO2 production (mainly cement factories) to co-produce	http://c8s.co.uk/ http://www.blueplanet-ltd.com/	No	Partial	Yes	Uncertain	100%	High	No		2	Yes	Low	High	No	Admin	Developed
3-5	**Carbon-positive Future Materials**	Photosynthetic microorganisms (algae)	Algae bricks, mortar, and tile	Concept investment	1. Lead by example 2. Influence material production 3. Take a holistic approach 4. Be future ready	Co-investment in R&D	Co-investment in R&D	Complete pilot for smaller scale inclusion in new build	Long-Term, Concept investment	Challenge: not yet commercially viable Opportunity: on-site cultivation; coupled system with food production, fuel/energy production; materials production.	Algae is an informal term for a large, diverse, and group of photosynthetic eukaryotic organisms. Algae may be cultivated for the purposes of biomass production for energy, wastewater treatment, or, of primary interest, CO2 fixation. Research shows that 1 kg of algae sequesters 1.7 kg of CO2. It follows that the cultivation, growth, and permanent storage of algae. On-site cultivation of algae could yield a multitude of co-products of direct benefit to data center design and construction, as well as ripple-out benefits to the broader community ecosystem. For example, on-site cultivation of algae could yield biomass for energy. The biochar ash could be used for other purposes, such as air scrubbers, personal hygiene products, or admixtures in concrete. Algae could be produced, packaged, and consumed as food products, or as biological inks for fully compostable, carbon-storing paper products. Algae can also be used as biocatalysts to “grow” and mineralize structural materials. It can also be encapsulated, preserved, and stored in tiles and other materials to prevent its decomposition back into CO2.					High	100%		Yes			Yes	Uncertain	Uncertain		Uncertain	Uncertain
3-5	**Carbon-positive Future Materials**	Zeobond (Alternative Cement Concrete)	Alternative Cement Concrete; structural concrete, foundations, tilt-up construction, etc.	Co-development: product scaling required	1. Lead by example 2. Influence material production 3. Take a holistic approach 4. Be future ready		Inquiry with ready-mix producers to gauge interest in alkali-activated cement concrete; Caltrans is no stranger to alternative cements - they poured a CSA cement concrete on portions of a highway in Southern CA. The technology is mature; the only question is cost, risk, and reliability upon scale-up.		Now. Limited/Regional Production.	Zeobond is a world leader in alternative cementitious materials (no portland cement).		http://zeobond.com			No	Medium	100%	Medium	No			Maybe	Low	High	No. But potential for creative solutions	Admin	All
3-5	**Carbon-positive Future Materials**	Foam glass/Glavel	Subgrade, structural insulation made from recycled glass. Replaces foam insulation.	Off-the-shelf alternative (1:1 replacement)	1. Lead by example 2. Influence material production 3. Take a holistic approach 4. Be future ready	There is no sub-slab insulation indicated on the drawings, so this product may have no role in the DCs. If subgrade insulation is required anywhere, this is an ideal replacement.	Vermont production facility will begin production in 2020. Could be manufactured anywhere glass recycling takes place. Affordable, relatively simple production with available technology.		Now. Limited production.	Replacing foam insulation with recycled, inert, very low carbon material	Glavel is currently setting up production in Vermont. Could be set up anywhere that has glass recycling collection	https://www.glavel.com/	Yes	Yes	Yes	Medium	100%	High	No		1	Yes	Low	High	Yes	All scales	All
3-5	**Carbon-positive Future Materials**	Palm kernel ash/palm kernel shell	Biological concrete using palm kernel shell aggregate and palm kernel ash cement	Co-development: product scaling required	1. Lead by example 2. Influence material production 3. Take a holistic approach 4. Be future ready		This has high potential to reduce carbon emissions from concrete. Along with rice hull ash, these are biological SCMs and as such provide vast emission reduction potential. Likely possible to produce in palm-growing regions and export globally (overall emissions reductions including transportation). Burning of shells also provides CHP opportunities in developing countries, reducing fossil fuel use as co-benefit	Research, development and testing required	R&D	Good research available on the potential for this all-biological concrete option. Research on shell as lightweight aggregate and ash as cement done separately and together.	Palm oil producing regions	https://www.researchgate.net/publication/279919872_The_Use_of_Palm_Kernel_Shell_and_Ash_for_Concrete_Production	No	No	No	High	100%	Low in US	No		2	Yes	Moderate	Moderate	No	Admin	Developing
3-5	**Carbon-positive Future Materials**	Biomason	Tile, Paving Material	Co-development: product scaling required	1. Lead by example 2. Influence material production 3. Take a holistic approach 4. Be future ready	Production of floor tiles and cladding tiles available now. Would make an excellent demonstration.	Potential for disruption of concrete industry is huge.		Now.	Cost, scale, lack of EPD, true carbon storage potential unknown.	Currently in North Carolina. Production could be located anywhere.	http://www.biomason.com	No	Yes	No	Low	100%	High	Maybe			Yes	Uncertain	Uncertain	No	Admin	Developed

	Structure																										
	Structural	**Framing Steel- Electric Arc Furnace Steelmaking**	1. Specify Electric Arc Furnace (EAF) steel only; 2. Mandate facility-specific EPDs for all structural steel members;	Off-the-shelf alternative (1:1 replacement)	1. Lead by example 2. Influence material production	Hot-rolled blast-furnace steel is used as the current structural framing system. Two broad strategies were recommended to minimize the embodied carbon of the structural framing system: 1. Sourcing steel from Electric Arc Furnace steelmaking facilities 2. Pivoting from a steel to a glue-laminated (glulam) engineered wood structural system Strategy (1) will aid in reducing total embodied carbon while Strategy (2) will aid in transforming the structural system from a carbon-emitting to a carbon-storing system. (see Mass Timber below)			Now. Materials for both Strategy (1) and Strategy (2) are currently available and in commercial use.	Steel is manufactured in two types of steelmaking facilities: Basic Oxygen Furnaces (BOFs) or Electric Arc Furnaces (EAFs). Large steel mills typically use BOFs. BOFs burn coal or natural gas to melt raw iron ore to extract the iron. The iron ore is mixed with scraps of iron and steel to make new steel. Since the majority of the material inputs for BOFs are mined (e.g., raw iron ore), the recycled content level for BOFs is ~25%-37%. Recycled steel can exhibit A1-A3 embodied carbon footprint five times lower than virgin steel. Smaller factories utilize electric arc furnaces (EAFs). The primary material inputs to EAFs include iron and steel scrap. EAFs do not process raw iron ore. Therefore, steel that is made using an EAF approach has recycled contents up to 100%. The average recycled content for hot-rolled steel made using EAFs is 93%. Structural steel does not suffer from downcycling. In other words, hot-rolled steel made from 100% recycled steel has the same structural performance characteristics of virgin steel made with BOFs. EAFs are typically powered by electricity rather than coal and/or natural gas combustion. Therefore, steel made with EAFs have the potential to exhibit ultra-low carbon footprints if 100% renewable energy sources provide 100% of the electricity generation. It follows that specifying steel solely from EAFs is a primary way to reduce the embodied carbon of steel.	In addition, product EPDs for steel members fabricated from billets, including rebar and hollow structural shape (HSS) sections, should include facility-, plant-, and/or mill-specific data for steel fabrication in addition to steelmaking. Steelmaking concerns the emissions associated with forming billets using BOF or EAF. A majority of carbon emissions, however, can be attributed to the steel fabrication process (i.e., the facility that converts billets to different shapes) as opposed to the steelmaking process, especially with respect to EAF steelmaking. Variation also exists within EAFs due to the variations in the energy mix of the electricity grid that services the EAF. EPDs that rely solely on industry average data should be supplanted with manufacturer-specific (and facility-specific) EPDs, if possible. Note that 70–75 percent of all steel in the world is produced by the BOF process and the remainder by the EAF route. The use of the EAF or BOF process varies between different regions. For example >90 percent of China's steel is produced by BOF, while the USA produces the majority of its steel by EAF.		Yes	Yes	No	High	20%	Improved Steel Specifications	No	Yes, when considering coal burning plants and the environmental impacts associated with large facilities.	1	Yes	Low	High	Yes	All Scales	Developed
1-2	**Structural**	**Mass timber (glulam, etc)**	3. Redesign of steel-frame superstructure to glulam columns and beams. 4. Investigate viable regional manufacturers of glulam and mass timber products. 5. Learn the nuances of embodied carbon accounting of wood products, sustainable forestry practices (SFI vs. FSC vs. Other), and transportation impacts. Example: Replace structural steel columns and beams	Off-the-shelf alternative (1:1 replacement)	1. Lead by example 2. Influence material production	These are 1D columns & beams made from timber products. Could be direct substitutes for steel frames. Spans shown in building plans are achievable. Currently, difficult to attribute meaningful storage, but emission reductions from steel frame will be substantial.	The use of mass timber will require redesign, though materials and compliance testing are available	Multi-story design is possible when taking a SoS approach to include future computing designs such as Quantum computing	Now with redesign	Excellent opportunity to use best conventional practice. Would help with plans for disassembly. The American Wood Council National Design Specification (NDS) and the NDS Supplement governs the design and analysis of dimensional lumber, timber, glulam, and cross-laminated timber (CLT) structural elements. The steel-to-glulam transition necessitates structural redesign and consideration of cost and regional availability. These aspects, along with carbon-storing characteristics of wood, are likely primary drivers for selecting a glulam framing system vs. EAF steel framing system. Due to its self-protective, self-insulative properties, glulam by nature is fire resistant. Multiple reports detailing the fireproof nature of glulam exist in the public domain.	Production in Pacific NW and Quebec. Some production in the US South. No constraints, but significant questions about whether or not the carbon storage in timber is meaningful	https://www.apawood.org/manufacturer-directory	Yes	Yes	Yes	High	60-100%	Medium, industry moving this way already	Yes		2	No, already established	Low	High	Yes	All scales	Developed
1-1	**Wall and Roof Panels**	**Cross laminated timber (CLT)**	Structural wall, floor and roof panels	Off-the-shelf alternative (1:1 replacement)	1. Lead by example 2. Influence material production 3. Take a holistic approach 4. Be future ready	These are 2D wall and roof panels made from timber. Would need to explore applicability for DCs, as panels would need insulation added and may not be cost effective. Engineering analysis would clarify opportunities, including possibility of a CLT floor system. Potential to partner with CLT design firms for scoping study. Currently, difficult (but not impossible) to attribute meaningful storage, but emission reductions from steel frame will be substantial.	The use of mass timber will require redesign, though materials and compliance testing are available	Multi-story design is possible when taking a SoS approach to include future computing designs such as Quantum computing	Now with redesign	Excellent opportunity to use best conventional practice. Would help with plans for disassembly.	Production in Pacific NW and Quebec. Some production in the US South. No constraints, but significant questions about whether or not the carbon storage in timber is meaningful	https://www.apawood.org/manufacturer-directory https://www.nationalobserver.com/2020/03/30/opinion/canadas-forests-become-carbon-bombs-ottawa-pushes-crisis-books	Yes	Yes	Yes	High	60-100%	Medium, industry moving this way already	Yes		2	No, already established	Low	High	Yes	All scales	Developed
	Thermal and Moisture																										
2-3	**Wall and Roof Panels**	**Bensonwood prefabricated wall and roof panels**	1. Explore the potential for a replacement enclosure system for the existing building design using wood/cellulose panels to replace MIPs with either a steel or timber frame 2. Explore the potential for a redesign that reduces the floor area ratio to increase the floor/enclosure ratio, which will amplify the embodied carbon impacts of the wood/cellulose panels 3. Examine the emerging life cycle analysis of timber products and ensure that best practices are used for sourcing sustainable timber Example: Prefabricated, insulated wall and roof panels such as Bensonwood.	Co-development: product scaling required	1. Lead by example 2. Influence material production 3. Take a holistic approach		The building design incorporates metal insulated panels (MIPs) to provide the above-grade building enclosure for the walls and roof. These panels are mounted to the steel frame and use a tongue-and-groove connection between panels. The panels use a petrochemical foam insulation core and the combination of the embodied emissions from the metal and the foam result in one of the major "hot spots" for emissions. It is worth noting that four different foam types are typical in MIPs and the embodied carbon impacts of each vary widely. It is feasible to replace the MIPs with wall and floor panels made with wood framing components and dense-packed cellulose insulation. These panels are manufactured by numerous companies in the USA, Canada and Europe and have an established performance record across a number of different building typologies.		Now. Production in US	Bensonwood was identified as a potential supplier of this type of wood and cellulose panel as they have a fully automated factory in the USA with the potential to provide panels at the scale of a data center. The initial investigation into the embodied carbon impacts of these panels showed a tremendous potential for embodied carbon reductions. As there are no product-specific EPDs in this category of materials, we performed an analysis of the components of the Bensonwood R-24 wall panel using EPDs for each of the component materials. These panels can be ordered in large sizes and volumes, and in a variety of R-values. Single best way to add carbon storage to conventional design	It would be possible to engage with Bensonwood or another supplier to customize the panels to ensure that R-values and interior and exterior finishes meet the safety and aesthetic standards for the data center. Typically the wood/cellulose panels offer higher-than-average R-values and it would be informative to develop an energy model for the data center in each climate zone and determine the cost benefit of increasing the R-values to improve long-term energy efficiency. A wood/cellulose panel contains far less toxic chemical content than a MIP and could practically be specified to contain no red list or questionable chemicals	https://bensonwood.com/building-systems/panelized-enclosures/	Yes, for panel components	Yes	Yes	High	60%	High	No		1	Yes	Low	High	Yes	All scales	All
1-1	**Wall and Roof Insulation**	**Cellulose insulation**	1. Replace all batt-style insulation with cellulose batts. 2. Encourage or assist manufacturers of other bio-based insulation batts to produce EPDs. Example: Spray-applied or cavity fill insulation made from recycled paper/cardboard fibers	Off-the-shelf alternative (1:1 replacement)	1. Lead by example 2. Influence material production	Current building plans specify cellulose products (3A). This would likely be the most cost effective opportunity for immediate carbon storage in the DC. Fire resistance must be achieved through design.			Now.	Excellent opportunity to use best conventional practice. The current building design incorporates batt-style insulation in the roof and in some interior walls, and specifies a mineral-based insulation (fiberglass or rock wool) for this purpose. The direct substitution of cellulose batt insulation, manufactured in the USA by EcoCell.	Widely produced across North America. In addition to cellulose batts, a number of other batt-style insulation products are available in North America but do not have an EPD by which their carbon reductions and storage potential can be accurately assessed. These include batts made from hemp fiber, cotton scraps and sheep's wool, all of which are commercially available but are lacking EPDs.	https://www.cellulose.org/index.php https://www.cmsgreen.com/insulation/ecocell-batts	Yes	Yes	Yes	High	20%	Medium	No		1	No	Low	Already exists	Yes	All scales	All
3-5	**Carbon-positive Future Materials**	**Cellulose foam**	Insulation boards made from cellulose	Research and development	1. Lead by example 2. Influence material production 3. Take a holistic approach 4. Be future ready		Y	Requires design and development in a given region to bring to scale	R&D taking place at Washington State University and in Asia	Promising technology to turn cellulose into lightweight foam insulation to replace petrochemical foam. Concern about potentially toxic ingredients and/or composite waste at end of life.	No constraints.	https://news.wsu.edu/2019/05/09/researchers-develop-viable-environmentally-friendly-alternative-styrofoam/	No	No	Uncertain	Uncertain	100%	High	No		?	Yes	High	Uncertain	?	Admin	Developed
3-5	**Carbon-positive Future Materials**	**Fiber-based Materials and Systems**	All of the systems in this category could be modified to work with a variety of regional fiber materials. The straw-based systems can work with any type of regional grain straw (wheat, rice, oat, barley, sorghum, spelt, etc.) and the hempcrete system can work hemp stalks or any pithy agricultural waste (sunflower, tobacco, collard greens, sunchoke, etc.). The Bamcore system uses bamboo as the skins of a SIP panel and this system lends itself to the easy integration of any kind of fiber waste as insulation fill (rice hulls, straw, hemp, tomato stalk, etc.).	Co-development: product scaling required	1. Lead by example 2. Influence material production 3. Take a holistic approach 4. Be future ready			The category of fiber-based materials include numerous options that are very close to being possible to implement at scale, and several are at a development stage where they could be integrated into the "admin" portion of the building or used at a demonstration scale. Most of these are panelized wall and roof systems that have been used in smaller scale construction but not yet proven at the scale of a data center. By demonstrating the use of these materials in a data center campus, a carbon-positive future could be accelerated by bringing these materials to scale in use and gaining market acceptance.		All of the systems listed could be modified to work with a variety of regional fiber materials. The straw-based systems can work with any type of regional grain straw (wheat, rice, oat, barley, sorghum, spelt, etc.) and the hempcrete system can work hemp stalks or any pithy agricultural waste (sunflower, tobacco, collard greens, sunchoke, etc.). The Bamcore system uses bamboo as the skins of a SIP panel and this system lends itself to the easy integration of any kind of fiber waste as insulation fill (rice hulls, straw, hemp, tomato stalk, etc.).	We used the phrase "Find the fiber/Grow the fiber" to indicate that ample fiber resources from farms, forests and oceans exist in every region of the world, and that the team designing and constructing a quantum-leap data center would understand the availability of regional fiber sources and have connections with manufacturers who are turning these fibers into suitable building materials. Regionally sourced fiber would not only provide carbon storage in the building but would support climate positive practices that result in additional carbon storage in soils and provide additional ecological benefits. Regional fibers can also be key ingredients in composite materials that include plant-based resins and bioplastics.						100%										
3-5	**Carbon-positive Future Materials**	Ecococon straw/timber	Prefabricated straw bale wall and roof panels. Example: Ecococon	Off-the-shelf alternative (1:1 replacement)	1. Lead by example 2. Influence material production 3. Take a holistic approach 4. Be future ready	Ecococon system in Europe is well developed and ripe for importation for a demonstration project. Ecococon is seeking North American production opportunities. This could be a drop-in replacement wall system for DCs, clad in gypsum.	This system is straightforward to reproduce with relatively low investment. Straw available in most regions globally, and NA has a wide range of regions with suitable straw harvest. Excellent candidate for small regional production facilities.	Requires development in a given region	Now. Production in Europe	One of the best options for mainstream innovation, with very high carbon storing potential. European systems are well developed and ripe for production in North America.	Straw production is high throughout North America. No production of panels on a commercial scale. Ecococon is looking for demonstration projects as a first step in bringing production to US	https://ecococon.eu/ca/	Yes	Yes	Yes	High	100%	High	Maybe		1	Yes	Low	High	Yes	Admin	All
3-5	**Carbon-positive Future Materials**	Bamcore wall system	Bamboo SIP, can be infilled with any biogenic insulation	Co-development: product scaling required	1. Lead by example 2. Influence material production 3. Take a holistic approach 4. Be future ready	Bamcore system ready for use at a scale suitable for admin building as a trial. Uncertain about cost. Allows for use of many types of carbon-storing insulation at varying R-values for different climates, making this a flexible system across many regions. Good fire resistance, but can be gypsum clad if additional resistance required.	This product could be a major advancement and may warrant support/investment to help bring to scale. US production happening at a small scale. Appropriate for many regions globally.	Requires development in a given region	Now. Limited production	Laminated bamboo structural wall system	Production in Florida. Bamboo grown in Central America. Another product ready for a breakthrough and potential to expand production to other regions.	http://bamcore.com/	Yes	Yes	No	High	100%	High	Yes		2	Yes	Low	High	Yes	Admin	All
3-5	**Carbon-positive Future Materials**	Modcell	Straw/timber system	Co-development: product scaling required	1. Lead by example 2. Influence material production 3. Take a holistic approach 4. Be future ready			Requires development in a given region				https://modcell.com/					100%										
3-5	**Carbon-positive Future Materials**	Stramit straw panels	Interior partition wall system and interior insulation board made from compressed wheat straw with kraft paper facings	Off-the-shelf alternative (1:1 replacement)	1. Lead by example 2. Influence material production 3. Take a holistic approach 4. Be future ready	Stramit has been used for over 70 years. US production has come and gone a few times. European production from Stramit and Ekopanely sufficient to use at a demonstration level now. Can be an exterior insulated panel and/or used as stand-alone interior partitions (particularly for admin building). Huge storage potential used to replace conventional dividing walls. Can be clad with gypsum.	This system is straightforward to reproduce with relatively low investment. Straw available in most regions globally, and NA has a wide range of regions with suitable straw harvest. Excellent candidate for small regional production facilities.	Requires design and development in a given region to bring to scale	Now. Production world wide except for NA	Stramit has been around for over 70 years, and is produced in Australia, Asia and Europe. It is a prime candidate for introduction into the NA market and has high carbon storage impacts, in particular when used as interior partition walls	No constraints. Used to be produced in Texas.	https://www.strawtec.com/ https://www.ekopanely.com/ http://isobioproject.com/partners/stramit-international-strawboard-ltd/	In house LCA	Yes	Yes	High	100%	High	No		1	Yes	Low	High	Yes	Admin	All
3-5	**Carbon-positive Future Materials**	Hempcrete (panels)	Insulation, blocks or loose fill	Co-development: product scaling required	1. Lead by example 2. Influence material production 3. Take a holistic approach 4. Be future ready	Just BioFibre in BC or Hembuild panels (Chicago-based) offers a wall panel that is a potential substitution for the metal insulated panels on the building drawings. Minus Materials (Denver) is launching production in 2021. Worth exploring for limited use on a regionally-focused project in 2020/2021.	Hembuild or similar precast panel system would be a major advancement in the industry. The high fire resistance and all-in-one enclosure system are advantages, and increased hemp production in NA and globally would support the growth of this type of product.	Requires design and development in a given region to bring to scale	Now. Limited production	Fire resistant biogenic insulation option. Uses the waste "hurd" of the hemp plant, by-product from fiber and/or seed production. Precast panels and blocks just starting to come to market. Opportunity to use plants other than hemp: sunflower stalk and other crops have the potential to be used as well	Small scale hemp production regionally in US and Canada. Excellent opportunities to grow with the developing industry.	http://americanlimetechnology.com/wp-content/uploads/2012/02/Hembuild_Hemclad_Brochure_20111.pdf	Yes	Some	Yes	Medium-High	100%	High	Yes		2-Jan	Yes	Low	High	Yes	Admin	All
3-5	**Carbon-positive Future Materials**	Just Biofiber blocks	Used as blocks with an integrated structural system or placed in-situ with forms	Co-development: product scaling required	1. Lead by example 2. Influence material production 3. Take a holistic approach 4. Be future ready	Just Biofiber offers a combined structure/insulation block that is carbon storing. Major advantage in combining structure and insulation. Not suitable for disassembly. Could be used in a limited way in a 2020 project. May make ideal fire-break wall within the DC.	This product could be a major advancement and may warrant support/investment to help bring to scale.	Requires design and development in a given region to bring to scale	Now. Limited production	Just Biofiber system is a leading example of precast, structural hempcrete. Hi	Just Biofiber blocks are a great example of a product that is nearing a break	http://justbiofiber.ca/	Yes	Yes	No	Medium-High	100%	High	No		3	Yes	Low	Moderate	No	Admin	All
3-5	**Carbon-positive Future Materials**	Agriboard	Structural insulated panels for walls and roof	Off-the-shelf alternative (1:1 replacement)	1. Lead by example 2. Influence material production 3. Take a holistic approach 4. Be future ready	This system has been around for almost 20 years, though the producer hasn't seemed able to scale the production. But this is an excellent opportunity for a drop-in replacement for metal insulated panels. If production is available, it would make an excellent substitution for a partial section initially.	This system is straightforward to reproduce with relatively low investment. Straw available in most regions globally, and NA has a wide range of regions with suitable straw harvest. Excellent candidate for small regional production facilities.	Requires design and development in a given region to bring to scale	Now. Limited production in US	Good potential to become mainstream. Potential partnership with Kingspan?	Agriboard has been producing for a few decades in Texas, but uncertain to the current status. This product is an excellent candidate for revitalizing current production or new partnerships	http://www.agriboard.com/	In house LCA	Yes	Yes	High	100%	High	No		1	Yes	Low	High	Yes	Admin	Developed
3-5	**Carbon-positive Future Materials**	**Fiber-based board and panel systems**	Fiber materials can also be pressed into board products that can be used throughout the building as structural sheathing, millwork, flooring and finishes		1. Lead by example 2. Influence material production 3. Take a holistic approach 4. Be future ready			One of the embodied carbon "hot spots" that was not addressed in the 1-to-1 or near-term presentations was the metal cladding and the aluminum louvers and bird screens in the building design. A number of fiber-based products are in small-scale production and could provide solutions for this final large source of embodied carbon	Now. Limited production	These board materials can be used within data centers as stand-alone products, however a more innovative use would be to encourage suppliers of fiber-based wall and floor panels to incorporate these types of products into their production, adding further beneficial carbon storage and local supply to the panels.							100%										
3-5	**Carbon-positive Future Materials**	Vesta Eco straw boards	Straw insulation panels	Co-development: product scaling required	1. Lead by example 2. Influence material production 3. Take a holistic approach 4. Be future ready	Range of products has potential for import for demonstration purposes. Exterior wall insulation and dividing walls.	VestaEco is keen to export their production machinery, which would be relevant for regional production in any straw-growing areas in NA and globally.	Requires design and development in a given region to bring to scale	Now. Production in Europe	Manufacture a range of different straw board insulation products. Also keen to export their manufacturing machinery.	No constraints.	http://www.vestaeco.com/Products,3.html	No	No	Yes	High	100%	High	No		1	Yes	Moderate	High	Maybe	Admin	All
3-5	**Carbon-positive Future Materials**	Kenaf/hemp/corn/bagasse/sorghum board	Structural and/or insulated panels of compressed ag fiber	Co-development: product scaling required	1. Lead by example 2. Influence material production 3. Take a holistic approach 4. Be future ready		Much R&D has been done, and production is occurring in Asia. Opportunities exist to develop production suited to different agricultural areas, tuning production to work with regional ag residues. Boards can be for SIPs, interior finishes, millwork, trim.	Requires design and development in a given region to bring to scale	Production largely in Asia	Replacing drywall and other interior cladding for ceilings and walls. Millwork and trim. Potential for structural sheathing. Most bulk ag fibers are turned into building panels somewhere in the world. Opportunities for US production (especially of sorghum and corn) is possible	Raw materials exist in large volumes across North America. No production currently in operation. One sorghum manufacturer has come and gone in the US (see link)	https://www.americansorghum.com/sorghums-eco-friendy-building-material/	No	No	No	High	100%	High	Maybe		1	Yes	Moderate	Moderate	Maybe	Admin	Developing

3-5	**Carbon-positive Future Materials**	Seaweed	Batt and Board Insulation	Co-development: product scaling required	1. Lead by example 2. Influence material production 3. Take a holistic approach 4. Be future ready			Requires design and development in a given region to bring to scale				Danish manufacturer https://convert.as/					100%										
3-5	**Carbon-positive Future Materials**	Hempwood	Structural Millwork/finish	Co-development: product scaling required	1. Lead by example 2. Influence material production 3. Take a holistic approach 4. Be future ready							Hempwood recent startup in Kentucky https://hempwood.com/					100%										
3-5	**Carbon-positive Future Materials**	Wheat straw MDF	Wall panels and millwork/trim	Off-the-shelf alternative (1:1 replacement)	1. Lead by example 2. Influence material production 3. Take a holistic approach 4. Be future ready		Production has occurred in NA, but no current facilities. Excellent opportunity to support regional production in a variety of straw-rich regions. Potential to be used in SIP production.	Requires design and development in a given region to bring to scale	Now. Production in Asia. Prior production in US/Canada	Several examples of wheat straw board have been produced in North America, though demand issues led to discontinuation. Current production in China is well developed (and being exported to Europe). Could be a great example of establishing building material production at the site of agricultural residue.	Production has occurred at several place in North America in the past. Could happen in most regions in NA.	https://www.novofibre.com/	No.	Yes	Yes	High	100%	High	Maybe		1	Yes	Low	High	Maybe	Admin	All
3-5	**Carbon-positive Future Materials**	Corn cob particle board	Sheathing and insulation panels made from corn cob particles	Co-development: product scaling required	1. Lead by example 2. Influence material production 3. Take a holistic approach 4. Be future ready		Much R&D has been done. Not aware of any production, but suitable for all corn growing regions globally. Boards can be for SIPs, interior finishes, millwork, trim	Requires design and development in a given region to bring to scale	R&D	Quite a bit of research has been conducted into using corn cob particles (an abundant waste in NA), sometimes in combination with other bio fibers, to create structural and insulation panels	No constraints. Could be produced in any corn growing region	https://www.jmaterenvironsci.com/Document/vol7/vol7_N4/138-JMES-1811-2015-Amenaghawon.pdf	No	Partial	Yes	High	100%	High	Maybe		1	Yes	Moderate	Moderate	Maybe	Admin	All
3-5	**Carbon-positive Future Materials**	Torzo boards	Panels and flooring from ag waste fibers	Off-the-shelf alternative (1:1 replacement)	1. Lead by example 2. Influence material production 3. Take a holistic approach 4. Be future ready	Torzo makes a wide range of board and plank products for walls, flooring and millwork, using different ag residues.	Torzo's range of fibers is a good model for production based in areas of concentration for different crops.	Requires design and development in a given region to bring to scale	Now.	High end, attractive panels and flooring made from a variety of waste stream and ag fibers	Torzo uses a variety of different ag and waste stream residues, each of which has regional centers of production	https://torzosurfaces.com/	No	Yes	No	Medium	100%	Low	Yes		3	No	Low	Already exists	Maybe	Admin	Developed
3-5	**Carbon-positive Future Materials**	**Fiber-based Materials and Systems**		Co-development: product scaling required	1. Lead by example 2. Influence material production 3. Take a holistic approach 4. Be future ready			The hemp fiber and bio resin composite material from Margent/Cecense has the potential to replace the louvers and bird screens as it can be fabricated to any specification. The remaining materials can be used as exterior cladding to replace the metal with carbon-storing options.									100%										
3-5	**Carbon-positive Future Materials**	Rice hull panels	Insulation and/or structural panels and decking/cladding boards	Co-development: product scaling required	1. Lead by example 2. Influence material production 3. Take a holistic approach 4. Be future ready		Much R&D has been done, and production is occurring in Asia. Boards can be for SIPs, interior finishes, millwork, trim.	Requires design and development in a given region to bring to scale	Production largely in Asia	Resysta is decking/cladding material available in US	Resysta cladding currently in production (uncertain where it's being made). See above for rice hull regions	https://hdgbuildingmaterials.com/products/resysta/	No	No	No	High	100%	High	Maybe		1	Yes	Moderate	Moderate	Maybe	Admin	All
3-5	**Carbon-positive Future Materials**	Resysta	Rice hull cladding	Off-the-shelf alternative (1:1 replacement)	1. Lead by example 2. Influence material production 3. Take a holistic approach 4. Be future ready	The only carbon-storing cladding option (besides wood) currently on the US market. Would make an excellent demonstration product, with potential to drive market expansion.	Development of sheet options would expand potential beyond residential and "accent" market.		Now. Limited US production	Plant-based exterior cladding options (other than wood) are limited. This could fill an important role.	Rice growing states	https://hdgbuildingmaterials.com/products/resysta/	No	Yes		Uncertain	100%	High	No		2	Yes	Moderate	Moderate	Yes	Admin	Developed
3-5	**Carbon-positive Future Materials**	Hemp corrugated siding	Corrugated cladding panels made from hemp fiber and hemp resin	Co-development: product scaling required	1. Lead by example 2. Influence material production 3. Take a holistic approach 4. Be future ready	Potential to import early production from UK. An exciting development that would be an excellent demonstration. Major composite manufacturer involved, working on fire resistance testing now.	Ripe for production in NA market. Company excited to explore opportunities to expand.		Now. Limited production in UK	A very promising cladding product, bringing a durable plant-based option to a field that doesn't have many plant-based options	Hemp growing states	http://product.margentfarm.com/					100%										
3-5	**Carbon-positive Future Materials**	Rice straw MDF	Wall panels and millwork/trim	Off-the-shelf alternative (1:1 replacement)	1. Lead by example 2. Influence material production 3. Take a holistic approach 4. Be future ready	CalPlant production beginning now. Excellent opportunity to support start-up. Boards can be used to replace gypsum on interior for visible finish. Millwork and trim.	Potential to be used in SIP production.		Now. Limited production in US	CalPlant1 is a leading example of establishing building material production at the site of agricultural residue. Production beginning in 2020.	Production currently in California. Could also happen in other rice growing states	https://calplant1.com/product/	In house LCA	Yes	No	High	100%	High	Maybe		1	Yes	Low	High	Maybe	Admin	All
1-5	**Carbon-positive Future Materials**	Cement bonded wood wool	Product could be developed for SIP production and/or for interior partition system. Interior wall insulation and sound attenuation	Off-the-shelf alternative (1:1 replacement)	1. Lead by example 2. Influence material production 3. Take a holistic approach 4. Be future ready	Product available now in the US from Armstrong. Long history, well proven. Particularly good for combination of fire resistance and sound attenuation. Excellent way to build in carbon storage capacity on interior elements. Carbon storing replacement for gypsum boards in many places.	Product could be developed for SIP production and/or for interior partition system. European "Heraklith" product https://www.heraklith.com/ used as exterior panel as well as interior uses. Production can occur in many regions of NA.		Now.	Replacing drywall and other interior cladding for ceilings and walls	Currently produced by Armstrong under the brand name Tectum.	https://www.armstrongceilings.com/commercial/en-us/articles/tectum-part-of-armstrong-portfolio.html	Yes	Yes	No	Medium	100%	Medium	Yes		1	No	Low	Already exists	Yes	All scales	Developed
1-5	**Carbon-positive Future Materials**	Mycofoam	Thermal insulation, board style. Also compressed into a high density panel for millwork & furniture	Co-development: product scaling required	1. Lead by example 2. Influence material production 3. Take a holistic approach 4. Be future ready	Ecovative is working with SIP manufacturer. Prototype panels could be available, and limited use on DC would be precedent setting. Partners eager for orders to establish business model.	This product range would be a major advancement, could replace petro-foam SIPs and bring high carbon storage to an industry that is currently a major emitter.		Could be now, with commitment to order in quantity	Full ASTM testing completed. Company capable of supply.	No constraints. Production currently in NY	https://ecovativedesign.com/	No	Yes	Maybe	Medium	100%	High	Yes		1	Yes	Moderate	High	Yes	Admin	Developed
1-5	**Carbon-positive Future Materials**	TTS panels and blocks	Biofiber based structural, sheathing and insulation panels and blocks	Research and development	1. Lead by example 2. Influence material production 3. Take a holistic approach 4. Be future ready		TTS is doing interesting work in a number of areas, including ICF blocks, panels and sheet goods. Nothing commercially available yet, but potential for growth.		Soon. Start-up in Alberta, Canada	TTS is doing promising work on biofiber composite panels and blocks that may soon be ready for implementation	No constraints. Currently in Alberta, Canada	http://ttsfpl.com/products/	No	Partial	Yes	Medium-High	100%	High	No		2	Yes	Moderate	Moderate	Maybe	Admin	All
1-5	**Carbon-positive Future Materials**	Wood fiber board	Insulation boards made from waste wood fiber. Some structural capacity	Off-the-shelf alternative (1:1 replacement)	1. Lead by example 2. Influence material production 3. Take a holistic approach 4. Be future ready	European products are well-developed and represent an excellent opportunity for carbon storage now. Fire rated products are available that meet all European standards for exterior cladding of large buildings.	US production can be encouraged and would be a major advancement. GoLab in Maine is currently working toward production in 2021. West coast production could also be encouraged. Products can be developed to replace foam SIP panels.		Now. Production mainly in Europe. Limited NA production. New facility planned for Maine	Excellent opportunity to use best conventional practice.	Go Lab is setting up production in Maine. Could be set up anywhere timber is produced.	https://golab.us/	Yes	Yes	No	High	100%	High	No		1	No	Low	High	Yes	All scales	Developed
1-5	**Carbon-positive Future Materials**	Hemp panels	Wall panels and millwork/trim	Off-the-shelf alternative (1:1 replacement)	1. Lead by example 2. Influence material production 3. Take a holistic approach 4. Be future ready	Limited production in US. Currently best suited for interior wall/ceili	Product would be well suited for SIP production, in combination with some of the biogenic insulation options noted here. Mycofoam, straw with hemp sheathing would be a major step forward.		Now. Limited production	Hempearth has limited production of product. Panels could be used in SIPs fo	US production happening at a small scale. Hemp growing regions would be	https://hempearth.ca/products/hempearth-hemp-board/	No	Yes	Yes	High	100%	High	Yes		1	Yes	Low	High	Yes	All scales	All
1-5	**Carbon-positive Future Materials**	Rice hull panels	Insulation and/or structural panels and decking/cladding boards	Co-development: product scaling required	1. Lead by example 2. Influence material production 3. Take a holistic approach 4. Be future ready		Much R&D has been done, and production is occurring in Asia. Boards can be for SIPs, interior finishes, millwork, trim.		Production largely in Asia	Resysta is decking/cladding material available in US	Resysta cladding currently in production (uncertain where it's being made).	https://hdgbuildingmaterials.com/products/resysta/	No	No	No	High	100%	High	Maybe		1	Yes	Moderate	Moderate	Maybe	Admin	All
1-5	**Carbon-positive Future Materials**	Cork	Wall and roof insulation. Combined insulation & cladding	Off-the-shelf alternative (1:1 replacement)	1. Lead by example 2. Influence material production 3. Take a holistic approach 4. Be future ready	Yes	Yes		Now.	Replacing exterior foam board and potential to replace metal cladding	Produced in Mediterranean. Several US distributors. Small Planet Workshop local supplier in Tumwater, WA. www.smallplanetsupply.com	https://www.thermacork.com/external-walls/	Yes	Yes	No	High	100%	Low	Yes		3	No	Low	Already exists	Yes	Admin	Developed
1-5	**Carbon-positive Future Materials**	Biochar	End product of pyrolysis (combustion without oxygen), turns biogenic carbon into carbon. Can be used as a lightweight aggregate.	Research and development	1. Lead by example 2. Influence material production 3. Take a holistic approach 4. Be future ready		Yes		Now. Limited production in US	Creation of biochar is a leading candidate for carbon sequestration. Adoption of biochar building materials would support the growth and development of biochar power/heat production		https://www.biochar-journal.org/en/ct/3	No	No	Yes	Uncertain	100%	Uncertain	No		?	Yes	Uncertain	Uncertain	?	Admin	All
1-5	**Carbon-positive Future Materials**	Rewall	Recycled drinking boxes as structural and decorative sheathing	Off-the-shelf alternative (1:1 replacement)	1. Lead by example 2. Influence material production 3. Take a holistic approach 4. Be future ready	Product available now from Continuus Materials in California. They have recently taken over production, and are only making roof sheathing boards for flat roofs. But earlier production included wall sheathing boards for exterior and interior walls, and provides excellent carbon storage at a low cost.	Product would be well suited for SIP production, in combination with some of the biogenic insulation options noted here. Mycofoam, straw with ReWall sheathing would be a major step forward.		Now. Limited production	Roof decking sheets are intended for large roofing projects. Excellent opportunity to confirm best conventional practice.	No constraints. Production currently in CA. This is an opportunity anywhere that drinking boxes are collected by recycling programs. Relatively easy to start new production. ReWall did a program with a school board where the students collected their drinking boxes and ReWall made wall panels for their school.	https://www.continuusmaterials.com/	No	Yes	Maybe	High	100%	High	No		1	Yes	Low	High	Yes	All scales	Developed
3-5	**Carbon-positive Future Materials**	**Earth- based Materials and Systems**	1. Identify opportunities within building design for potential use of earthen materials 2. Conduct regional soils analysis to understand opportunities for earthen building systems 3. Connect with regional soil scientists and earth building artisans to form network of expertise 4. Develop specifications for appropriate use of earthen materials to simplify inclusion when possible 5. Invest in research and development of innovation at all levels 6. Foster direct connections between all nodes of the system					Earthen materials can be used throughout the building in a variety of roles and these can be used independently or in conjunction.		The considerations for using earthen building materials would need to be incorporated into the early phase of the design process based on the assessment of regional soils and their suitability for inclusion in a particular data center.	No constraints.						100%										
3-5	**Carbon-positive Future Materials**	Watershed blocks	1) Rammed earth has significant potential to replace a lot of regular concrete, and leading in the use of precast rammed earth would have global reach 2) Production is in early days, significant potential to influence and foster industry adoption 3) Regional manufacturing in areas with poor soil for agriculture offers many co-benefits. Rammed earth is beautiful and biophilic. Example: Rammed earth block wall construction	Co-development: product scaling required	1. Lead by example 2. Influence material production 3. Take a holistic approach 4. Be future ready	Production exists in California, and is ripe for expansion. This could potentially replace the poured concrete foundation wall, but is likely not a time/cost effective measure. However, it would make a good fire break wall option and/or a visible wall in the admin portion of the building.	Watershed is working on precast rammed earth cladding panels, an idea that has vast potential globally.	Requires design and development in a given region to bring to scale	Now. Limited production	This California company is ripe for more mainstream adoption. Not carbon st	Production currently in California. Could be replicated elsewhere with appropriate soil composition	https://watershedmaterials.com/	In house LCA	Yes	Yes	Low-medium		High	Maybe		2	Yes	Low	Moderate	No.	Admin	All
3-5	**Carbon-positive Future Materials**	Clay panels	Drywall replacement made from clay	Co-development: product scaling required	1. Lead by example 2. Influence material production 3. Take a holistic approach 4. Be future ready		Limited production in Europe. Not carbon storing (but could be if ag fibers incorporated for tensile strength), but potential to dramatically reduce impacts from gypsum board.	Requires design and development in a given region to bring to scale	Now. Limited production in Europe	Clay based interior wall panels could replace gypsum board. Not carbon storing, but a very low carbon option to replace the higher emissions of gypsum board (drywall).	No production in North America. Some limited production in UK/Europe.	https://www.acoustix.be/produits/acoustix-pan-terre/ https://ecobuildingboards.weebly.com/uploads/5/0/7/3/5073481/ebb-overview_1.pdf	In house LCA	Yes	Yes	Low	100%	High	Yes		2	Yes	Low	Low	Maybe	Admin	All

3-5	**Carbon-positive Future Materials**	Earthen floors	Slabs, flooring	Co-development: product scaling required	1. Lead by example 2. Influence material production 3. Take a holistic approach 4. Be future ready							Claylin in Oregon http://claylin.com/					100%										
3-5	**Carbon-positive Future Materials**	In situ rammed earth	Structural walls and foundations	Co-development: product scaling required	1. Lead by example 2. Influence material production 3. Take a holistic approach 4. Be future ready							Numerous contractors throughout North America http://nareba.org/					100%										
3-5	**Carbon-positive Future Materials**	Compressed earth blocks	Structural walls and foundations	Co-development: product scaling required	1. Lead by example 2. Influence material production 3. Take a holistic approach 4. Be future ready							Numerous suppliers and installers throughout USA https://dwellearth.com/					100%										
3-5	**Carbon-positive Future Materials**	PISE sprayed earth	Structural walls and foundations	Co-development: product scaling required	1. Lead by example 2. Influence material production 3. Take a holistic approach 4. Be future ready							Numerous suppliers and installers throughout USA https://semmesco.com/our-methods/pise-rammed-earth/					100%										
3-5	**Carbon-positive Future Materials**	Clay-based paints	Finishes	Off-the-shelf alternative (1:1 replacement)	1. Lead by example 2. Influence material production 3. Take a holistic approach 4. Be future ready							Numerous suppliers and installers worldwide https://www.bioshieldpaint.com/index.php?main_page=index&cPath=144&zenid=6db917ee3a140079330148862346b53c					100%										
	Other Insulation Technologies																										
1	**Carbon-positive Future Materials**	**Cement bonded wood wool**	Interior wall insulation and sound attenuation	Off-the-shelf alternative (1:1 replacement)	1. Lead by example 2. Influence material production 3. Take a holistic approach 4. Be future ready	Product available now in the US from Armstrong. Long history, well proven. Particularly good for combination of fire resistance and sound attenuation. Excellent way to build in carbon storage capacity on interior elements. Carbon storing replacement for gypsum boards in many places.	Product could be developed for SIP production and/or for interior partition system. European "Heraklith" product https://www.heraklith.com/ used as exterior panel as well as interior uses. Production can occur in many regions of NA.	Requires design and development in a given region to bring to scale	Now.	Replacing drywall and other interior cladding for ceilings and walls	Currently produced by Armstrong under the brand name Tectum.	https://www.armstrongceilings.com/commercial/en-us/articles/tectum-part-of-armstrong-portfolio.html	Yes	Yes	No	Medium	20%	Medium	Yes		1	No	Low	Already exists	Yes	All scales	Developed
3-5	**Carbon-positive Future Materials**	**Rice hulls**	Loose fill insulation	Co-development: product scaling required	1. Lead by example 2. Influence material production 3. Take a holistic approach 4. Be future ready		One of the simplest biogenic insulation materials, as no additional processing required. High production volume in several US states. Can be used where any blown-in insulation is viable. Haven't seen batt products developed, but likely possible.	Requires design and development in a given region to bring to scale	High volume of production in US, not currently used for building purposes	Loose fill insulation for wall and roof cavities. Good opportunity to use a high volume waste material. Best properties of all ag fibers for insulation	Raw materials exist in large volumes in rice producing states: Arkansas, California, Louisiana, Mississippi, Missouri, Texas.		No	Yes	No	High	100%	High	No		1	Yes	Moderate	Moderate	Yes	Admin	All
3-5	**Carbon-positive Future Materials**	**Textile waste insulation**	Loose fill and batt insulation	Off-the-shelf alternative (1:1 replacement)	1. Lead by example 2. Influence material production 3. Take a holistic approach 4. Be future ready	UltraTouch batts from recycled denim (in Texas) a drop-in substitute for fiberglass or mineral wool batts. Fire resistance must be achieved through design.	Opportunities for other versions of recycled textile waste abound. Clothing industry seeking partners/opportunities. Regional production could happen in many parts of NA and globally. Blown-in versions are in R&D.	Requires design and development in a given region to bring to scale	Now. Production in US of denim batts. R&D for many other types of textile waste	Vast stocks of raw material. Fashion industry keen to appear less wasteful, good opportunities for R&D partnerships	No constraints.	https://www.researchgate.net/publication/235953688_Textile_waste_as_an_alternative_thermal_insulation_building_material_solution	No	Yes for UltraTouch. No for others	Yes	Medium	100%	High	No		1	Maybe	Low	High	Maybe	Admin	All
3-5	**Carbon-positive Future Materials**	**IsoStrau**	Loose fill insulation made from chopped straw	Off-the-shelf alternative (1:1 replacement)	1. Lead by example 2. Influence material production 3. Take a holistic approach 4. Be future ready	Product available from Austria now. Good demonstration potential in Admin building.	Extremely simple production, could be produced all across NA.	Requires design and development in a given region to bring to scale	Now. Production in Europe	A great example of how easy it can be to incorporate waste ag fibers in buildings. This could be done in NA very easily.	No constraints.	https://www.isostroh.com/iso-straw/	Yes	No	Yes	High	100%	High	No		1	Yes	Moderate	High	Yes	Admin	All
3-5	**Carbon-positive Future Materials**	**Wool**	Loose fill and batt insulation	Off-the-shelf alternative (1:1 replacement)	1. Lead by example 2. Influence material production 3. Take a holistic approach 4. Be future ready	Product available in NA now from Havelock Wool. A drop-in substitute for fiberglass and mineral wool batts. Higher cost, but excellent for indoor environment qualities, perhaps well suited for admin building.	Yes	Requires design and development in a given region to bring to scale	Now.	Produced in US, NZ	Requires regional wool production	https://havelockwool.com/	No, but in process	Yes	No	High	100%	Low	No		3	No	Low	Moderate	Yes	Admin	All
3-5	**Carbon-positive Future Materials**	**Bagasse**	Sugar cane stalk by-product. Used as loose insulation and pressed into batts and boards	Co-development: product scaling required	1. Lead by example 2. Influence material production 3. Take a holistic approach 4. Be future ready		Much R&D has been done. Not aware of any production, but suitable for all sugar growing regions globally. Boards can be for SIPs, interior finishes, millwork, trim	Requires design and development in a given region to bring to scale	Soon. Limited production and continued R&D in Asia and Brazil	Adaptable, abundant biofiber with potential to be used in many ways, including loose fill insulation, batt insulation and insulated and/or structural panels	Sugar growing regions	https://www.sciencedirect.com/science/article/abs/pii/S092134491300058X	No	No	No	High	100%	Low in US	Maybe		2	Yes	Moderate	Moderate	Maybe	Admin	Developing
3-5	**Carbon-positive Future Materials**	**Solomit straw panels**	Wire-tied ceiling panels	Co-development: product scaling required	1. Lead by example 2. Influence material production 3. Take a holistic approach 4. Be future ready	Yes	Yes	Requires design and development in a given region to bring to scale	Now. Production in Australia and Asia	Exposed straw panels that are wire tied. Great way to make straw visible for effect	No constraints.	https://solomit.com.au/acoustic-strawboard-ceilings/	In house LCA	Yes	Yes	High	100%	High	Yes		3	Yes	Moderate	Low	Yes	Admin	All
	Other Construction Technologies																										
	Carbon-positive Future Materials	**Lichen**	Indoor green walls	Research and development	1. Lead by example 2. Influence material production 3. Take a holistic approach 4. Be future ready		Co-investment in R&D	Requires design and development in a given region to bring to scale								High	100%		Yes			Yes	Uncertain	Uncertain		Uncertain	Uncertain
3-5	**Carbon-positive Future Materials**	**Green roof**	Membrane protection system for roof- regional product e.g., Live Roof in Pacific Northwest	Off-the-shelf alternative (1:1 replacement)	1. Lead by example 2. Influence material production 3. Take a holistic approach 4. Be future ready	Yes	Yes	Requires design and development in a given region to bring to scale	Now	Adds weight to roof. Can dramatically reduce stormwater runoff. Can we grow materials for future buildings? Use wastewater for irrigation? Might need a support structural frame independent of roof to eliminate water penetration, this might work well with heat plenum and cooling response above server racks	No constraints. Hot, dry climates can be difficult for green roof survival unless an extensive (deep soil) system	https://liveroof.com			Yes		100%		Yes		1	No, already e	Low	Already exists	No	All scales	All
	SoS Strategies																										
1-5 yr		**Systems of Systems approach to Grow a Greener Campus and connect to surrounding communities**	Building as demonstration project and proof of concept for new applications of carbon storing materials.	Co-development: product scaling required	1. Lead by example 2. Influence material production 3. Take a holistic approach 4. Be future ready	Yes	Yes		Now- can be implemented on many levels	See "Systems" sheet matrix for applications of SoS	Use waste heat and water from datacenter operations to grow algae in adjacent facility, Carbon storing materials used in local community buildings, Demonstration Centers/Education for underrepresented communities (indigenous populations), Design for circularity, Improve habitat/site conditions, improve local economy/manufacturing hub							Yes	Maybe	Yes	1	Yes	Moderate	High	Yes	All scales	All
1-5 yr		**Prefabricated modular systems**	Modular electrical rooms and more	Off-the-shelf alternative (1:1 replacement)	1. Lead by example 2. Influence material production 3. Take a holistic approach 4. Be future ready	Yes	Yes		Now	MS is doing this now.					Yes			Yes	Maybe	Yes	1	Yes	Low	High	Yes	All scales	All
1-5 yr		**Prefabricated modular components**	Wall and roof components built offsite or in a warehouse on site	Co-development: product scaling required	1. Lead by example 2. Influence material production 3. Take a holistic approach 4. Be future ready	Yes	Yes		Now. Regional production	Can reduce on-site construction time. Can be made with carbon-storing materials	No constraints. Distance from factory site is a relatively minor factor.	https://bensonwood.com/building-systems/			Yes			Yes	Maybe	Yes	1	Yes	Low	High	Yes	All scales	All
1-5 yr		**Circularity / design for deconstruction and reuse**	Building systems, Prefabrication/panels and Reconstruction potential as well as multi-story building design	Co-development: product scaling required	1. Lead by example 2. Influence material production 3. Take a holistic approach 4. Be future ready	Yes	Yes		Now. R&D needed to scale	Bring to scale leveraging multiple phases/types of construction & reuse. Many of the materials in this matrix can be combined into modular components for deconstruction and reuse.	No constraints				Yes			Yes	Maybe	Yes	1	Yes	Moderate	High		All scales	All