Transformative Carbon-Storing Materials: Accelerating an Ecosystem

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Carbon Leadership Forum

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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.

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ABSTRACT

Recent recognition of the severity of the climate crisis and the need for major, impactful interventions has accelerated interest in low-carbon and carbon-storing materials that can redress the significant upfront emissions associated with conventional building materials.[1] Decades of previous work to develop, improve, and implement these materials now provide a strong base of research, product development, and case studies that can support the drive to bring these materials to market quickly and help meet global climate targets.

Past experience with low-carbon and carbon-storing building materials has shown that specification and use of materials are indeed feasible and can match conventional alternatives in terms of cost, code compliance, and construction schedules.[2] However, the significant investments required to scale many of these materials has largely impaired their shift into the mainstream. The potential for meaningful climate impact through materials that serve as carbon sinks now gives such materials a clear advantage, with the potential to reverse the climate profile of buildings from a leading driver of carbon emissions to carbon reservoirs that can help reverse it.

Findings from this study highlight six materials for use in building foundations, structures, and/or enclosure systems. These materials—earthen slabs, non-portland cement concrete slabs, algae-grown bricks/panels, mycelium structural tubes, purpose-grown fiber, and agricultural waste panels—warrant in-depth examination because they offer novel material technologies or novel material uses with high carbon-storing potential, and they are worthy of investment to accelerate their scaling, manufacturing, and marketable use in the building industry supply chain. Furthermore this study outlines a methodology for establishing evaluation criteria to assess a given material's potential for impact in a carbon-positive architecture.

Keywords: carbon-storing materials, biogenic materials, algae, mycelium, soil, purpose-grown fibers, and agricultural residues, design for disassembly, 3-D printing, multi-story architecture, low-carbon materials, embodied carbon.

1 For more information on the climate challenge and the building sector see https://architecture2030.org/

2 https://www.worldgbc.org/sites/default/files/Business_Case_For_Green_Building_Report_WEB_2013-04-11-2.pdf

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1 INTRODUCTION

The construction industry in general—and Microsoft specifically—is increasingly interested in opportunities to create buildings that offer net carbon storage rather than generating greenhouse gas (GHG) emissions in the production of the building materials. A range of carbon-storing materials offers a viable potential to replace existing materials that are GHG "hotspots'' in current building designs, including foundations, structures, and enclosures.[3] This study explores novel low-carbon and carbon-storing materials that integrate algae, mycelium, soil, purpose-grown fibers, and agricultural residues, identifying nascent construction materials and technologies that present "high risk/ high reward" opportunities to contribute to carbon-storing buildings in a condensed time frame—accelerating product development, manufacturing, and construction use. The background and context through which the materials evaluated in this report were chosen are described herein (see Section 2).

More specifically, this research seeks to identify early-stage low-carbon and carbon-storing earth, living, and agricultural material technologies and evaluate their market readiness for regional manufacturing and use in the construction industry as well as consider their implications for architectural design and construction (see Section 3).

The research methodology includes an exploration of the existing literature and early-stage material development in labs and small-scale production startups to identify a range of materials that show promise. After characterizing and ranking these materials according to a comprehensive criteria materials index (see Appendix 1), the research team chose materials for foundation, structure, and enclosure use building on prior carbon-storing materials research.[4] An explanation of the criteria used to evaluate each material is given in Section 4. Key issues for each material under consideration are highlighted in the report, including material characteristics, potential uses, and further research and development required for each material to scale for use in the marketplace (see Section 4).

In general, characteristics considered in the process of developing early-stage laboratory materials for deployment in various fully functioning building materials include the following: durability, structural capacity, humidity, thermal conductivity, and fire performance. Though each material will have a specific testing, manufacturing, and marketing process, a proof-of-concept plan is outlined and key steps on the pathway for early-stage materials to achieve market readiness are identified (see Section 5).

Why is this investigation important to Microsoft now? Investing in a proof-of-concept plan to bring new carbon storing technologies to market aligns with Microsoft's environmental values and pledge to become carbon negative in present day operations by 2030 and to remove from the environment all carbon emitted by the company historically by 2050.[5] To overcome the lag typical of bringing early-stage material development research, testing, and product manufacturing to market and having those products be understood and accepted by design, engineering, and construction industries, the pathway must be accelerated. By taking responsibility for reducing its own carbon footprint, Microsoft is elevating the importance of innovation and promotion

3 Kriegh, Magwood, & Srubar, 2021. Carbon-Storing Materials. https://carbonleadershipforum.org/carbon-storing-materials/
4 Ibid.
5 https://blogs.microsoft.com/blog/2020/01/16/microsoft-will-be-carbon-negative-by-2030/ (accessed April 22, 2021)

of novel, carbon-storing materials to drive the market. Along with investing in new carbon-storing technologies, Microsoft's ambition is to accelerate the process globally by developing nascent technologies for suppliers worldwide.

Furthermore, Microsoft pledges to champion carbon-related public policy by supporting initiatives to hasten carbon reduction while considering implications for environmental justice. A brief discussion of these issues, recommendations, and opportunities appears in Section 6 of this report.

This study concludes with a proposal delineating additional steps to aggressively pursue and meet Microsoft's decarbonization goals. Informing and educating students, tradespeople, and professionals in architecture, engineering, and construction (AEC) is essential to inspiring innovation and removing actual and perceived barriers that inhibit much-needed evolution in AEC fields. In Section 7, a roadmap is proposed for an Integrated Design, Engineering, and Architecture (IDEA) program[6] that could be realized via a long-term alliance with academic institutions and developed through Microsoft's Climate Innovation Fund. The IDEA project proposes to continue the exploration and analysis of bringing novel carbon-storing materials to market as well as implications for education and social good to be achieved by embedding research apprenticeships into the research, design, and construction work necessary to accelerate nascent technologies. Fundamental to this work is an understanding of the values inherent in a holistic social-technological-economic drive to decarbonization. Materials mapping to climate, regional availability, policy initiatives, and market/industry values is one example of a project that could be developed in conjunction with Microsoft AI for Earth and the IDEA program.

6 The IDEA Center is adapted from proposals by Drs. Lee, Kriegh, and Dossick (UW College of Built Environments); Dr. Srubar (UC Boulder); and Executive Director Magwood (Endeavour Centre) that were initiated in early 2021.

2 CONTEXT

2.1 Carbon-storing materials: Background

With each new building and constructed landscape, carbon emissions are released into the atmosphere from both materials production and construction activities. Building construction accounts for more than 11% of global carbon emissions,[7] much of which is generated during the production and processing of construction materials. The building sector, as a primary consumer of materials, has the potential to drive the market for innovative material solutions that can both reduce impact of conventional materials and store carbon in long-life building products.

Materials and methods already on the market – especially carbon-intensive applications (hotspots) such as foundations/slabs, structures, and roof/wall enclosure assemblies – can bring about meaningful embodied carbon reductions. In 2020 and 2021, Microsoft engaged the University of Washington Carbon Leadership Forum (UW CLF) in a research project to identify carbon-storing materials and methods that were ready for the following: a) immediate 1:1 substitution, b) scaling for broader market deployment in 2 to 3 years with minimal design revisions, c) laboratory testing and/or piloting on a small scale, and d) exploring as novel materials for potential market deployment in 5 years.[8] The research indicated that bio-based building materials offer key benefits globally (reducing emissions and storing carbon in long-life material products) and regionally (supporting small farmers and businesses, and improving human health).

Available carbon-storing, bio-based materials (such as mass timber, engineered bamboo, and straw-based panels) demonstrate the feasibility of using building materials to store carbon—thus establishing buildings and landscapes as potentially significant reducers to carbon emissions. Such projects offer potential ripple effects, including support for emergent carbon-storing building material industries, namely, jobs in manufacturing hubs, career training and educational centers, and policy initiatives. By recognizing the importance of these vital socio-technical-economic relationships, Microsoft is underscoring the importance of innovation and bringing novel carbon-storing materials forward. Along with investing in new carbon-storing technologies, Microsoft's ambition is to accelerate the process globally by developing nascent technologies for suppliers worldwide. This combined effort of promoting novel materials development at the lab scale and materials testing and design education is, to our knowledge, the first of its kind.

In 2021, Microsoft commissioned the current study, ***Transformative Carbon-Storing Materials: Accelerating an Ecosystem***, to explore opportunities for promising early-stage, novel carbon-storing technologies to move decarbonization of the building sector forward. To demonstrate the potential of successfully implementing new, original, fresh, and unique materials into built projects, several exemplars and their uses are highlighted below.

2.2 Case studies that demonstrate potential for novel materials

2.2.1 Bio-based panels

Bio-based materials can be assembled as prefabricated panels for use in wall and roof

7 For more information on the climate challenge and the building sector see https://architecture2030.org/
8 Kriegh, Magwood, & Srubar, 2021. Carbon-Storing Materials. https://carbonleadershipforum.org/carbon-storing-materials/

enclosure systems. These panels can be configured as structural or non-structural elements—framing, insulation, and sheathing. The benefits of building with bio-based panels include an easy integration into current design and construction practices, a high capacity for carbon storage, a non-toxic material option, use of locally available fiber residues, and low-tech manufacturing processes. Some, such as clay plaster/ panels and algae cement, also offer fire-resistance. Though numerous examples can be found in small-scale use globally, further research and development (R&D) as well as manufacturing support are needed to scale bio-based products and bring them quickly to market.

The Louise Michel School (Figure 1) demonstrates the potential of using prefabricated straw bale panels in a multi-story institutional building.[9] This school building uses a mass timber frame enclosed by prefabricated straw bale panels. Unique in its material selection, the building was also used to establish new standards in France for the fire resistance of bio-based materials, which now benefit from a testing protocol that will make similar projects easier to undertake. The design uses the straw bale enclosure to meet the highest standards of energy efficiency and air tightness. The straw bale enclosure's ability to be air tight yet vapor permeable comprises a major step forward in building science for large structures.[10]

Figure 1. Louise Michel School at Issy-les-Moulineaux, France; Sonia Cortesse, Architect.

2.2.2 Hempcrete (and other "cretes")

Hempcrete is an insulation material made from chipped hurd (core) of hemp and other pithy agricultural stalks bound together with a mineral-based binder. The characteristics of this insulation material include the following: high fire resistance due to properties of the mineral binder, excellent moisture-handling capabilities, good carbon storage capacity, non-toxicity, and use of locally available fiber residues, including sunflower, tobacco, and sunchoke.

Hempcrete is currently produced worldwide at a small scale for both block units and precast panel applications. Expanded R&D is necessary for improved binders and material specifications to accelerate manufacturing and bring this product to scale. The Marks & Spenser Cheshire Oaks Center flagship store is a sustainable commercial complex built with prefabricated hempcrete enclosure panels (Figure 2). Their largest store outside of London at 195,000 square feet and over two floors, is a project that demonstrates the potential for hempcrete use in large floor plate, multi-level structures.

With its timber frame and prefabricated hempcrete enclosure panels, the building achieved a BREEAM "Excellent" rating for environmental performance, the hempcrete walls lending it high thermal and moisture-handling performance. Upon completion, it won both National and Regional RIBA Awards, the RIBA Sustainability Award, and the BCSC Gold Award for Sustainability.[11]

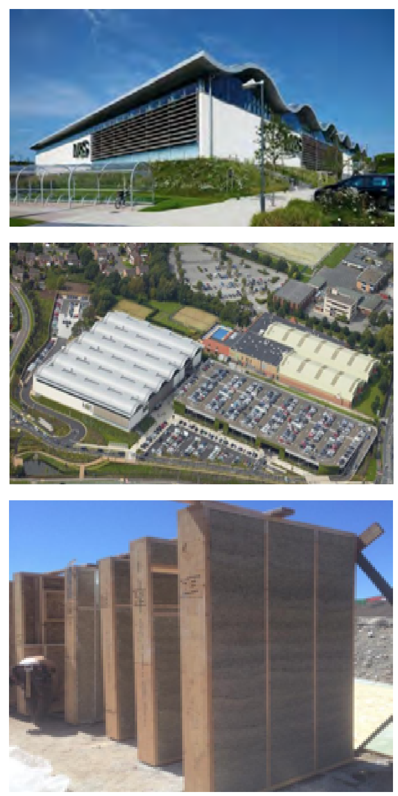

Figure 2. The Marks & Spencer Cheshire Oaks Centre: elevations (left), aerial (center), and a detail of hempcrete construction (right); Cheshire, England; Aukett Swanke Architects.

2.2.3 Prefabricated thatch cladding

Prefabricated thatch cladding is a wall cladding system (i.e. a visible surface layered over a structural one) using traditional reed thatching that has been adapted to mechanized and panelized fabrication. Using a widely available, low-value, low-cost biomaterial as

9 https://www.forum-holzbau.com/pdf/22_FBC_2014_Pagnoux.pdf
10 http://bet-gaujard.com/wp/wp-content/uploads/2014/01/proc7_corrAMD3.pdf
11 http://www.aukettswanke.com/projects/Marks

cladding for large buildings offers not only a durable and affordable system, but also one transformative in its biophilic appearance. The material offers substantial carbon storage value due to its simple and efficient manufacturing.

Already widely used to upkeep and replace traditional roofing throughout Europe, Africa, and Asia, thatch products could be brought to market quickly for global application with the support of R&D.

Since its opening in June 2015, the Enterprise Centre (Figure 3) has been a thriving and supportive hub for start-ups and small-to-medium sized enterprises. It has won multiple awards and is widely recognized as among the greenest buildings in Europe, meeting the Passive House energy efficiency standard and achieving a BREEAM “Outstanding” rating. This 120,000-square-foot building incorporates far more than thatch panels attached to the outside. Bio-based materials in this building includes mass timber framing, walls, and floors; straw interior wall and ceiling panels; clay- and lime-based panels and plaster; and a creative approach to incorporating these materials into an inspiring aesthetic.[12] It achieves multiple goals in building performance such as meeting BREEAM and Passive House standards while also earning recognition from RIBA and BCSC Gold Awards for Sustainability.

Figure 3. The Enterprise Centre at University of East Anglia (left), bio-based materials (right); Architype Architects.

12 https://www.architype.co.uk/project/the-enterprise-centre-uea/

3 EVALUATION: METHODS AND CRITERIA FOR MATERIALS SELECTION

For this study, a broad range of novel materials was carefully evaluated, taking into account multiple goals set forth by Microsoft and the research team for the selection process. The methods and criteria for evaluation and materials selection are elucidated below.

3.1 Transformative Materials Index[13]

Based on the research team's literature review and Microsoft's values, a two-way matrix was created to characterize the potential of each novel material investigated (see Appendix 1). Prospective material candidates are listed in the vertical axis and organized by construction use for foundations, structures, and enclosure (roof and wall). Listed on the horizontal axis are twelve key criteria on which to evaluate the initial range of materials selected for analysis. These twelve criteria and a weighted prioritization factor (5, 3, or 1) are outlined in brief below:

- **Criteria 1, Development Stage:**
    - 5 - Early-stage R&D with lab testing is currently underway, with a 24-to-36-month period predicted for manufacturing readiness
    - 3 - R&D with small scale deployment is currently underway; further code compliance testing and Environmental Product Declarations (EPDs) are recommended with a 12-to-24-month period anticipated for manufacturing scaling
    - 1 - Product(s) are currently deployed in the market, though manufacturing scaling is needed and/or code compliance and regional standards are not fully approved, with a 6-to-12-month period estimated for completion of the code approval process
- **Criteria 2, Mockup and Prototype Potential:**
    - 5 - A prototype of the material and/or assembly has yet to be created and would be revolutionary
    - 3 - A prototype of the material and/or assembly has been created and development for a building/structure would be precedent-setting
    - 1 - A prototype of the material and/or assembly has been created and deployment in a building/structure would confirm viability
- **Criteria 3, State of Compliance Testing: (in all cases, a testing budget would have major impact toward market readiness)**
    - 5 - Testing requirements and protocols are nonexistent, minimal, or lacking for the materials in the suggested configuration
    - 3 - Testing requirements and protocols are established to some but not all code

13 The Transformative Materials Index was developed by the CLF research team (Kriegh, J., Magwood, C., Srubar, W., Lewis, M., Simonen, K. (6.30.2021)) with input from WSP engineers and Microsoft.

standards; individual products or assemblies will likely require testing

- 1 - Testing requirements and protocols are well established for most/all code standards and underway/complete in the United States (US) and/or European Union (EU).

- **Criteria 4, Construction Assemblies and Prefabrication/Modularization Potential:**
    - 5 – Though no assembly or prefabrication has been attempted, the material qualifies as a candidate and shows a high potential for use in construction as a prefabricated panel or modular component
    - 3 - Assemblies are well established and have an unproven yet high potential for use in construction as a prefabricated panel or modular component
    - 1 - Details and assemblies are well established for this material
- **Criteria 5, Carbon-Storing Potential:**
    - 5 - The material has a high net storage >1kgCO_2/kg capacity, i.e. the highest level of carbon-storage capacity. Materials derived predominantly from photosynthetic biogenic material fall within this category.
    - 3 - The material has a moderate storage of 0.5 – 1 kgCO_2/kg capacity. Composite materials composed of some biogenic fiber mixed with other non-carbon-storing materials (e.g., straw-reinforced adobe) and materials derived predominantly from carbonate mineralization fall within this category.
    - 1 - The material has a low storage of <0.5 kgCO_2/kg capacity, i.e. net-zero emission (or even moderate net-positive emission) embodied carbon benefits. The storage capacity of the material is limited (e.g., earthen floor slabs).
- **Criteria 6, Data on Carbon-Storing Capacity:**
    - 5 - No verified documentation exists for the material's carbon-storing capacity (either no LCA or EPD)
    - 3 - The material has an LCA study; however, an EPD may be lacking
    - 1 - The material has an EPD
- **Criteria 7, Potential Locations and Availability for Raw Materials:**
    - 5 - The material is readily available globally
    - 3 - The material is available in most geographies
    - 1 - The material is readily available in some geographies
- **Criteria 8, Potential for Community Impact: (e.g., economic development, job creation, educational and training opportunities, reduces pollution burden, increases resilience)**
    - 5 - The material has a high potential for new or shared benefit in the communities where they are developed

- 3 - The material has a moderate potential for modest benefit in the communities where they are developed
- 1 - The material has a low potential for new or shared benefits in the communities where they are developed

- **Criteria 9, High Impact Reward: (materials that are at the very early stages of development and have the potential to excel in all criteria categories, e.g., extremely low embodied carbon, can be made carbon-storing, zero waste, long-lasting, material available globally, potential to drive supply chain and manufacturing with innovative materials, especially in developing economies, potential for building for disassembly)**
    - 5 - The material has multiple high reward attributes (listed above) and may be market-ready but lacks investment to scale
    - 3 - The material has a moderate reward with some distribution markets established, potential to be manufactured in many locations globally, and is ripe for major uptake
    - 1 - The material has a low reward because it is well developed and in use
- **Criteria 10, High Risk: (e.g., skepticism from designers, builders, and code officials; requires testing to establish parameters for material; perceptions of negative impacts to project schedule and/or cost, lack of familiarity to procure, lack of knowledge on construction methods and warranty)**
    - 5 - The material has a high risk due to early development stage
    - 3 - The material has a moderate risk as the material may exist but not for the new intended use
    - 1 - The material has a low risk because the sector is well developed or meshes with current engineering standards
- **Criteria 11, Reference Paper and/or Case Study Exists:**
    - 5 - The material has few large-scale built examples or published research papers
    - 3 - The material is still in early exploration with small-scale building projects and a few publications
    - 1 - The material is well documented and has been published in peer-reviewed journals
- **Criteria 12, Potential Development Partners:**
    - 5 - No known development partners or a small number of potential partners
    - 3 - Early phase and start-up companies exist but are not widespread to all regions

- 1 - Established companies exist, with some/many that distribute manufactured goods globally

3.2 Materials Impact Comparison Tool (MIC)[14]

From prior research, seventeen materials were explored with respect to three hotspot building systems –foundations, structures, and enclosures.[15] In addition, three construction methods – 3D printing, design for disassembly (DfD), and vertical or multi-story architectural design – were considered. The potential for these materials and construction methods to exert an impact based on the twelve criteria is summarized below (see Figure 4 and Figure 5).

3.3 Key criteria

The twelve key criteria on which the initial range of materials selected for analysis (see above) were evaluated include criteria typical of an exploration of feasibility. However, several categories look beyond matters of practicality and incorporate broader concerns, such as the potential to bring a highly positive impact to surrounding communities

14 The Materials Impact Comparison Tool (MIC) was used with permission by ZGF Architects (tool developer, 2021).
15 Kriegh, Magwood, & Srubar, 2021. Carbon-Storing Materials. https://carbonleadershipforum.org/carbon-storing-materials/

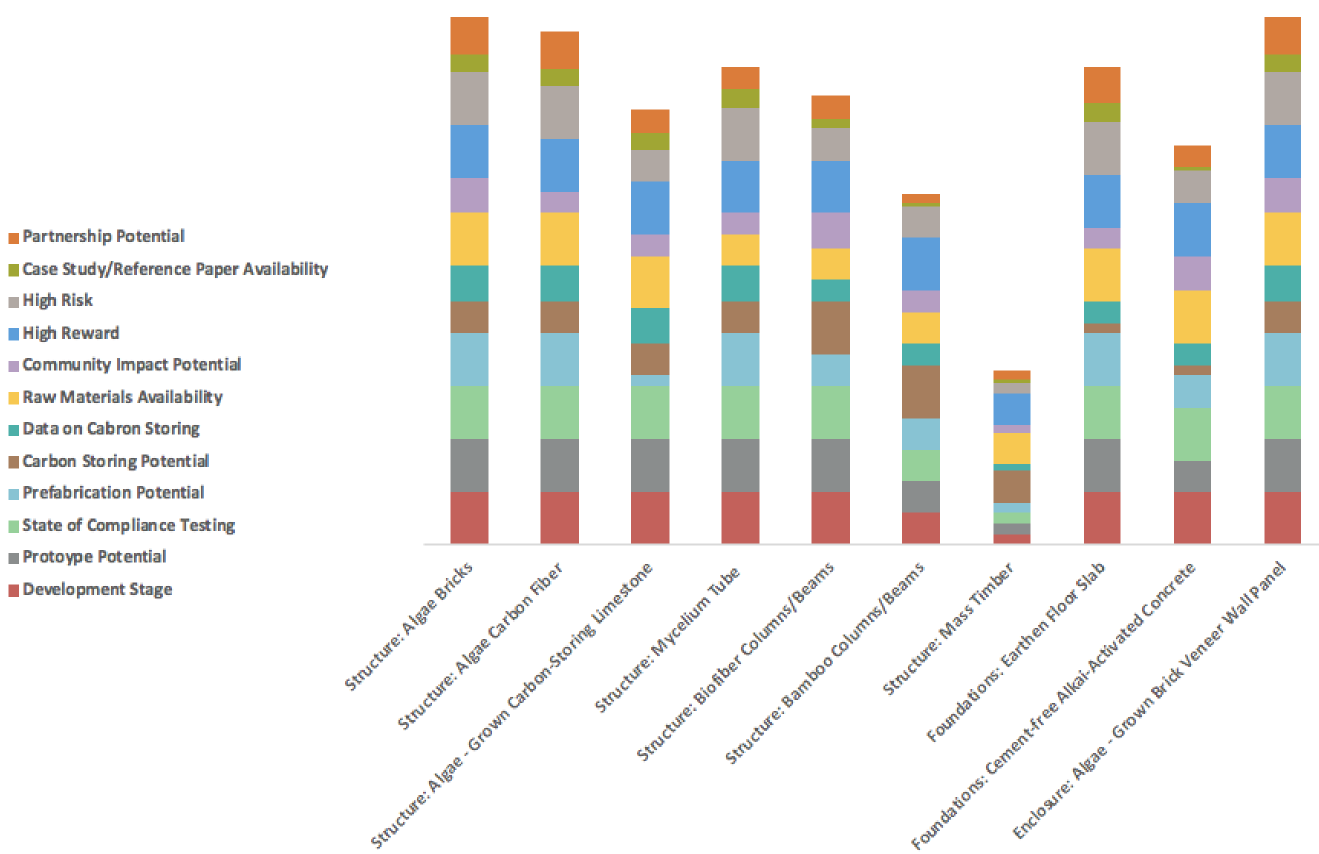

Figure 4. MIC for 10 out of 17 materials explored.

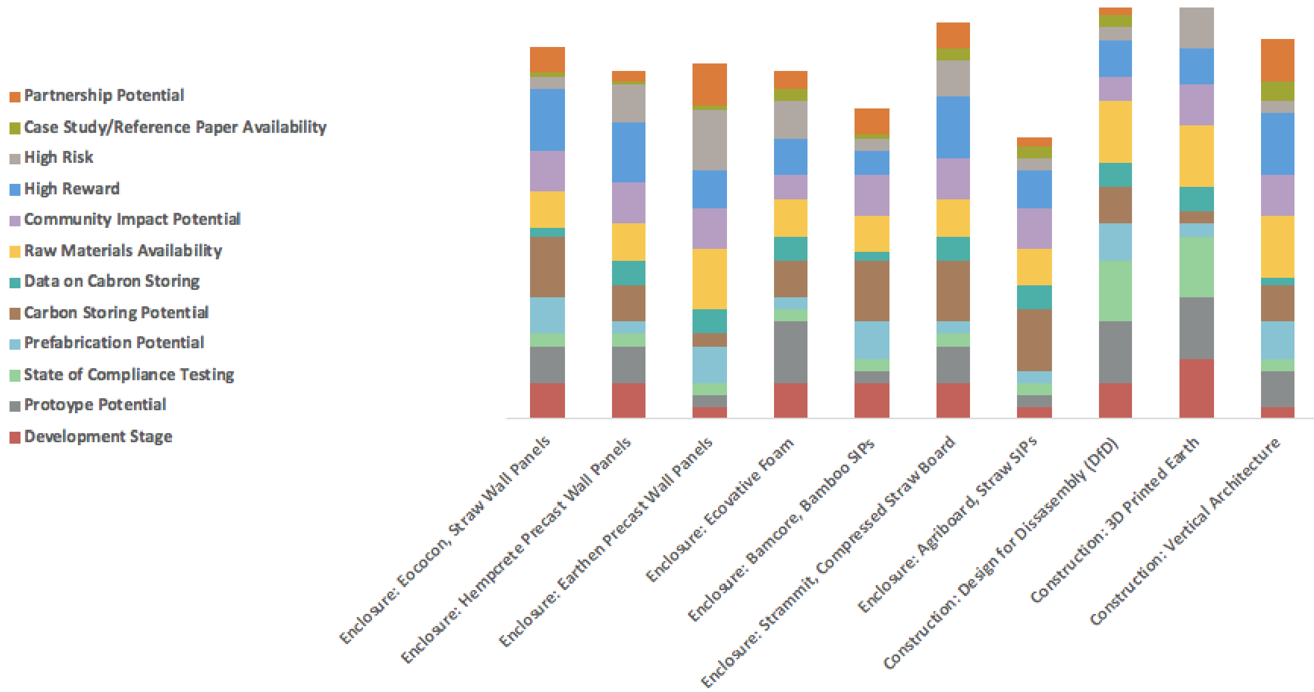

Figure 5. MIC for 7 out of 17 materials and 3 construction considerations explored.

and a high impact on decarbonizing the environment, hence the title of the this report—"Transformative Carbon-Storing Materials: Accelerating an Ecosystem." These considerations include the following: opportunities for economic development are increased through job creation, education, and training; pollution burdens are reduced; the material has extremely low embodied carbon, can be made carbon-storing, has zero waste, and is long-lasting; the material has the potential to drive supply chain and manufacturing with innovative products deployment (especially in developing economies); and the material's components have the potential to be designed for disassembly (DfD) and reused.

Construction methods were also considered in the evaluation, including the potential for prototyping, prefabrication, 3-D printing, DfD, and vertical (multi-story) design.

The approach to scoring the materials on each of these criteria reflected Microsoft's desire to place maximum value on materials that offer high reward potential even at high risk. In order to receive a high score of 5 in any category, the material under consideration had to demonstrate not only a high degree of reward value but also the lowest degree of proof-of-concept across all criteria. This approach to scoring penalized materials already well on the way to being market-ready in favor of those still at the earliest phases of research and development.

3.4 Material performance, properties, and carbon-storing capabilities

The list of materials under consideration in this study was carried forward from an earlier project,[16] during which they were reviewed to ensure properties that could reasonably

16 Kriegh, Magwood, & Srubar, 2021. Carbon-Storing Materials. https://carbonleadershipforum.org/carbon-storing-materials/

be expected to meet the performance requirements for inclusion in a building. After examining literature reviews, prototypes, and case studies, the research team considers the materials in this study appropriate for building use or promising enough that further exploration is warranted.

Wherever possible, life cycle assessments and/or environmental product declarations were considered to gauge the potential GHG emission impact of the materials. Carbon storage is relatively easy to ascertain as it is based on the chemistry of the material, so the amount of carbon contained in the material can be accurately determined without directly studying/sampling it. Emissions were calculated from harvesting, production, and later life cycle impacts based on reviews of documentation that provided accurate accounts of the materials' emissions profiles. In cases where no relevant studies were available, GHG impacts from similar or related materials were extrapolated.

For the purpose of this study, materials with the least amount of available data were scored high for the lack of existing studies or documentation. This weighting of preference means that the actual GHG profile of some materials may turn out to be greater or less than the initial characterization. The value in the scores reflects the value of definitively learning this information, even if a selected material turns out to be more or less impactful than the initial assessment might indicate.

3.5 Materials assemblies enclosure/construction systems

Most building materials function as one component in an assembly, meaning that the assessment of a particular material requires an understanding of how it might interact within a relevant construction assembly such as that found in a wall, floor, or roof system. New and transformative materials often require adaptation within assemblies to account for unique characteristics or construction procedures. The research team attempted to ascertain the level of ease or difficulty with which each material might be incorporated into existing assembly types, recognizing that some materials entail minimal requirements for combining with other assembly components (e.g., earthen floor slab) while others work only as an integrated component of an assembly (e.g., loose fiber insulation). A high score indicates our finding that the material can be used in a relevant assembly in a straightforward way.

3.6 Prototyping and piloting potential

A prototype building constitutes a desired next stage of this work, each material was considered for its ability to be incorporated into a new demonstration project. A high score indicates that demonstrating the use of the material would be precedent-setting. Materials already used in buildings were scored lowest. As none of the materials in this study has been used in a widespread way, the variation in scores indicates the relative novelty for each material. Note, however, that prototype buildings incorporating any of these materials – especially combining some or all – would be impactful.

4 TRANSFORMATIVE MATERIALS

Each of the materials under consideration and ultimately selected for further investigation was assessed using the Materials Impact Comparison (MIC) tool. The results of the MIC analysis are given below.

4.1 Analysis

The MIC tool was used to analyze and visually demonstrate the ranking of the seventeen materials and three construction methods according to the twelve key criteria (see Section 3). From this analysis, six materials were selected for further investigation, including Earthen Materials (earthen floor slabs and calcined clay-based alkali-activated cement concrete), Living Materials (algae grown bricks/panels and mycelium structures), and Agricultural Products (residue biomass and purpose grown fibers).

The MIC radar charts for each of the six materials are provided on the next page (Figure 6). The colors blue, yellow and red correspond with the numeric scoring 5, 3, and 1 priority ratings respectively. The following sections describes these materials, their characteristics, and stage of development. Note that not all of the materials have a high priority rating (shown in blue) in every criteria category. In the Earthen Floor Slab example (Figure 7), the material is rated with a low (shown in red) score with respect to carbon-storing potential. In this case, the material itself is not carbon-storing; however, the impact of using this material in place of conventional concrete is highly beneficial because conventional concrete manufacturing and use incurs a relatively large carbon footprint multiplied on a vast scale.

4.2 Earthen materials

4.2.1 Earthen floors

The use of concrete slab floor/foundation systems contributes significantly to GHG emissions from buildings. Much work is being done to address the emissions from concrete, but one option that has received too little attention is the replacement of concrete with earth for slab floors. Despite centuries of historical precedent, surprisingly little research has been devoted to the idea in a modern context. Contemporary earthen floor makers have incorporated important lessons from the concrete industry about aggregate size distribution, and from the linoleum industry about the use of durable, naturally polymerizing oils. On a small scale, earthen floors have been proven durable, waterproof, and biophilic (Figure 8).

Though earthen floors are not themselves carbon-storing (Figure 7), a small number of LCA studies has shown them to incur a very low carbon footprint. Simply replacing concrete floors with earthen ones could reduce the overall carbon footprint of a building dramatically. By incorporating natural fibers for reinforcement and/or a carbon-storing aggregate (such as that from Blue Planet), earthen floor systems could also be rendered carbon-storing.[17]

Among those unaware of modern enhancements, the notion of an earthen floor tends to evoke associations of poverty and dirt, so the option is typically dismissed. For this

17 Note: the Carbon Storing Potential rating shown in the Radar Chart does not include natural fibers for reinforcement and/or the use of carbon-storing aggregate.

Figure 6. MIC radar charts for six transformative materials. Color key for score: blue = 5, yellow = 3, red = 1.

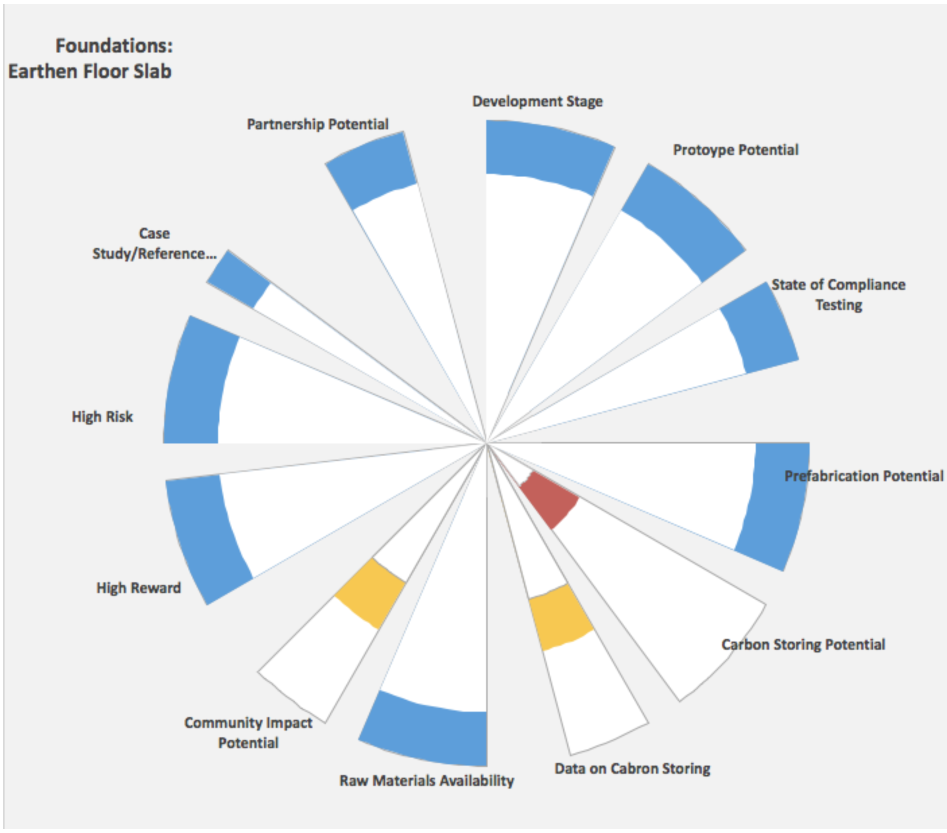

Figure 7. MIC radar chart with priority factors for earthen floor slabs.

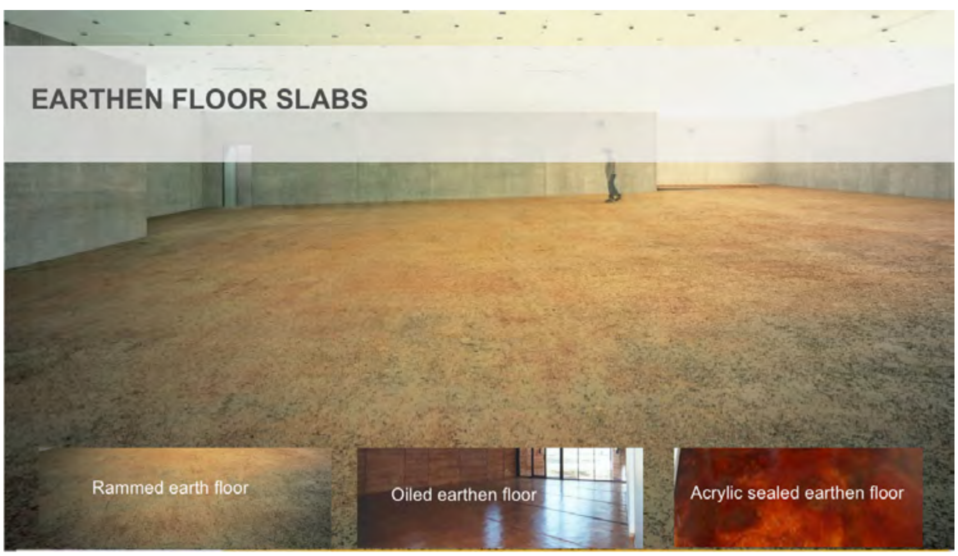

Figure 8. Earthen floor slab finishing options.

reason, the making of earthen floors has remained a niche market, one not yet applied to modern buildings or seen as meriting any significant study.

The benefits of developing earthen floors are many: not only are the raw materials low-cost, non-toxic, and widely available but the harvesting, mixing, and application machinery and techniques exist already within the concrete industry. A thorough study to explore mixes and structural properties has strong potential to unlock a low-tech solution to a high-impact problem.

4.2.2 Calcined clay-based alkali-activated cement (portland cement–free) concrete

Alkali-activated cements (AACs) comprise a class of novel portland cement alternatives formed via alkali activation – a process using an alkali- or salt-based chemical activator to promote the dissolution of an aluminosilicate precursor and subsequent precipitation of cementitious reaction products. AACs can be produced using a variety of precursors, with slag and calcined clays emerging as the more sustainable, compared to fly ash. Alkali activation of precursors can cause a series of either polycondensation reactions, in which water is produced as a result of reaction product formation, or hydration reactions similar to those of ordinary portland cement (OPC), in which water is consumed. The result is the same--cementitious matrices that exhibit comparable strength and durability compared to OPC. See Figure 9 for an MIC chart of this material, and Figure 10 for examples of this material.

AACs are promising, sustainable, clinker-free alternatives to OPC due to their often-reported low embodied carbon (CO_2) emissions. The exact level of these emission estimates varies widely, a range attributable to the wide variety of precursors and alkali activator sources available to make AACs. While many studies suggest that the embodied carbon of AACs is less than that of OPC, exactly how much less has been found to range anywhere from 10% to >90%.[18]

Because the use of AACs in lieu of OPC concrete results in net reductions of CO_2 only in comparison to OPC concrete, a rating of 1 was given to this material category in terms of its carbon-storing potential. The CO_2 storage could be enhanced if the material were used in tandem with other carbon-storing material technologies, such as carbon-storing aggregates and fillers.

Various AAC products, such as mortars and concrete, bricks, solid/hollow blocks, roofing tiles, insulation concrete, temperature-resistant coatings, and paving blocks, exhibited performance comparable to or even better than that produced with OPC. While the initial physical and mechanical properties of AAC concrete can be comparable to those of OPC concrete, the same durability considerations must also be considered (e.g., chloride-induced corrosion, freeze-thaw resistance).

18 Moseson, A. J., Moseson, D. E., & Barsoum, M. W. (2012).

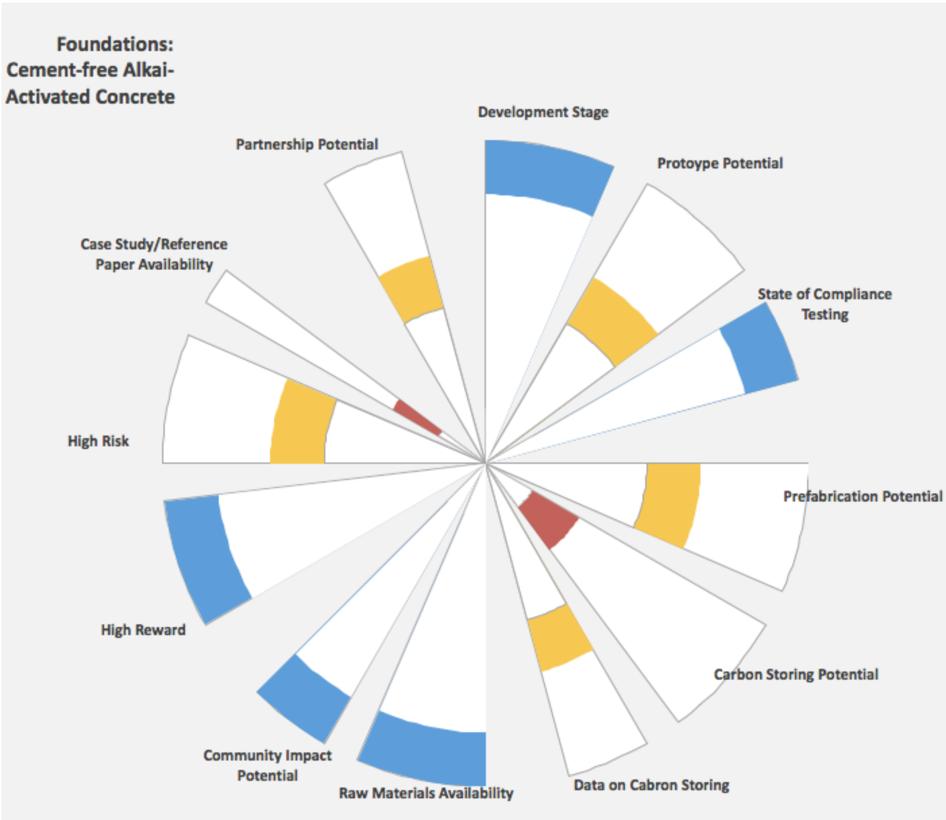

Figure 9. MIC radar chart with priority factors for cement-free alkali-activated concrete.

Figure 10. Left and center: alkali-activated slag mortar cubes. Right: 100% OPC cube. Photo courtesy of the University of Colorado Boulder College of Engineering and Applied Sciences.

4.3 Living materials

4.3.1 Algae

If photosynthesis is viewed as nature's efficient carbon capture and storage mechanism, then algae is arguably the champion of carbon fixation. Algae are photosynthetic unicellular organisms similar to plants. The high carbon fixation efficiency of outdoor cultivation of algae (~200 tCO_2/hectare/year) is due in large part to the exponential growth and carbon fixation efficiency of algal cells, which dramatically dwarfs the carbon fixation efficiency of forests by comparison (~3 tCO_2/hectare/year).

Large-scale cultivation of algae for advanced biofuel production is already underway in many regions of the U.S. One bonus attribute of outdoor algal cultivation is that it can be done on non-arable land. Thus, algae cultivation need not compete with agriculture and food production for land and water resources.

While much of the algal biomass is currently converted to fuels and/or incinerated for coproduction of bioenergy, algal biomass can also be used to create a myriad of carbon-storing or carbon-neutral materials. Algal biochar can be used in high-performance building materials (e.g., concrete, carbon nanofibers). Translucent algae panels have been used to create facades in daylighting applications by world-class architecture and engineering firms (Arup and Ecologic Studio).[19] Algal systems have been engineered to support indoor air purification (AlgenAir).[20]

4.3.1.1 Algae-grown bricks and panels

Currently, new startups are commercializing low-carbon and carbon-storing algae-derived material technologies in products such as algae-grown bricks and panels, described below. Grown from a mixture of sand, sun, seawater, and cyanobacteria, these "living bricks" are a concrete-like alternative that can be grown on demand. Multiple proofs-of-concept exist, and the University of Colorado Boulder team has licensed the technology to Prometheus Materials, an early-stage start-up establishing pilot-scale production. See Figure 11 for an MIC radar chart for this material. Researchers at the University of Colorado Boulder have produced algae-grown bricks using biomineralizing cyanobacteria (Figure 12).

19 https://www.arup.com/ and https://www.ecologicstudio.com/v2/index.php
20 https://algenair.com/

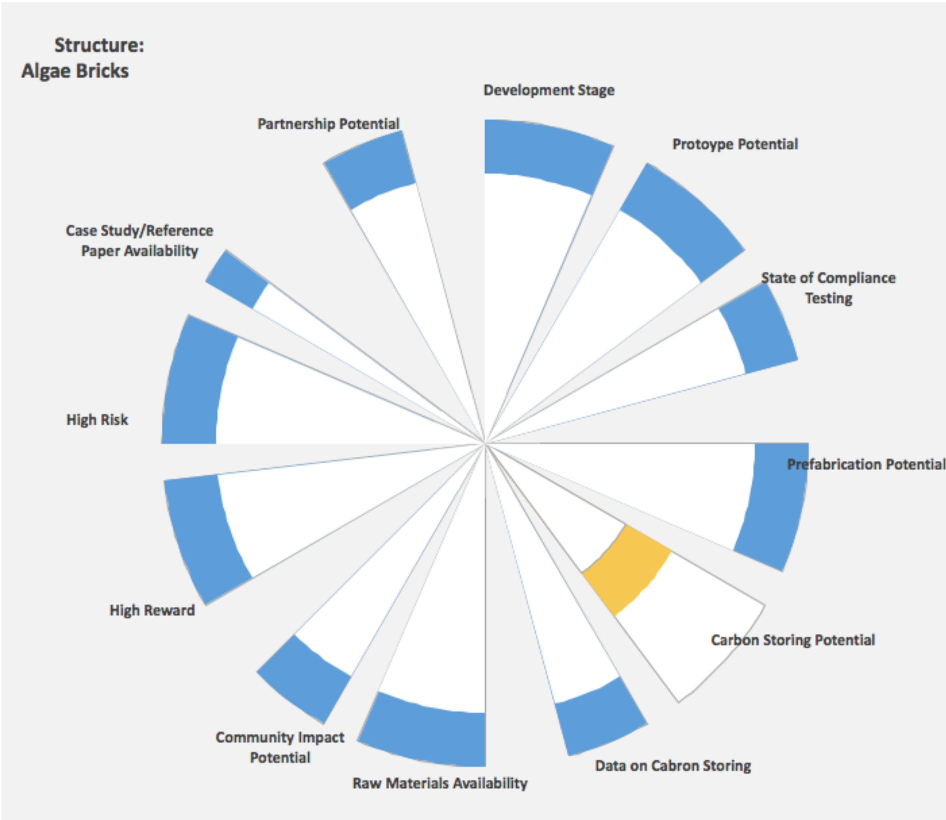

Figure 11. MIC radar chart with priority factors for algae-grown bricks and panels.

Figure 12. Algae-derived bricks developed at the University of Colorado Boulder. Photo Credit: University of Colorado Boulder College of Engineering and Applied Science.

4.3.1.2 Carbon-storing limestone fillers and other algae-derived materials for cement and concrete

Researchers at the University of Colorado Boulder's Living Materials Laboratory are also using algae as a source material for a number of other cutting-edge, carbon-storing and carbon-neutral building materials. Raw algae is being used in carbon-storing chemical admixtures for concrete. Freshly cultured photosynthetic diatoms, siliceous microalgae, are being explored as a sustainable alternative to supplementary cementitious materials like fly ash or slag. The lab is also using photosynthetic coccolithophores (calcareous microalgae), as limestone fillers to produce a biogenic Type 1L concrete carbon-neutral cement at scale, working in partnership with Minus Materials, an early stage company. Researchers at Arup and the University of Technology Sydney have also explored the intersection of living algae and building systems. Arup's SolarLeaf project was the world's first living façade system that cultivates micro-algae to generate heat and biomass as renewable energy sources. See Figure 13 for an MIC radar chart of carbon-storing limestone fillers and Figure 14 for an illustrative image of micro- and macroalgae cultivation.

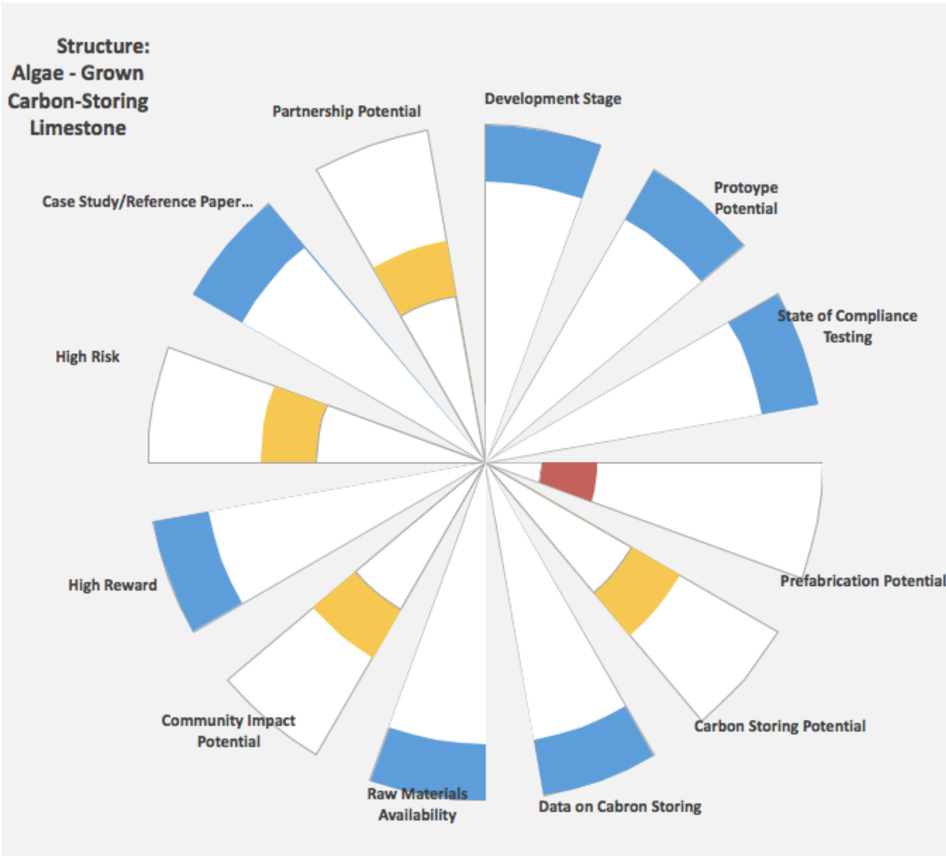

Figure 13. MIC radar chart with priority factors for algae limestone fillers.

Figure 14. Illustrative image of micro- and macroalgae cultivation.

4.3.2 Mycelium (and substrates) - tube structure

The past decade has seen a surge of explorations into the use of mycelium – the "root" structure of mushrooms – as a potential building material. The potential benefits are many: it's a purpose-grown carbon-storing material that shifts the paradigm of collecting raw materials from the earth and inducing land use changes in favor of cultivating fast-growing materials in a controlled, indoor setting that can be replicated anywhere at a range of scales. Initial material characterizations indicate that mycelium is naturally fire- and rot-resistant, typically grown in a substrate of agricultural residue, and provides carbon-storage benefits. See Figure 15 for an MIC chart of this material and Figure 16 for a visual example.

The first applications for mycelium building materials have been as insulation. This material has the potential to replace carbon-intensive products like petrochemical foam and mineral fiber. This pathway for mycelium products holds great promise, and our explorations of panelized enclosure systems point to a central and viable role for mycelium insulation.

Greater potential impact could result from developing structural components made from mycelium. A few small-scale iterations of structural tube and block materials attest to their potential to replace high-impact materials such as structural steel and masonry. Such uses of mycelium are in nascent stages of exploration but show revolutionary potential and thus comprise a focal point for this study. The University of Colorado Boulder and the Endeavour Center are already partnering with Okomwrks,[21] a small start-up, to explore the viability and applications for mycelium-based structural materials.

21 See https://www.okomwrks.co for more information on structural mycelium.

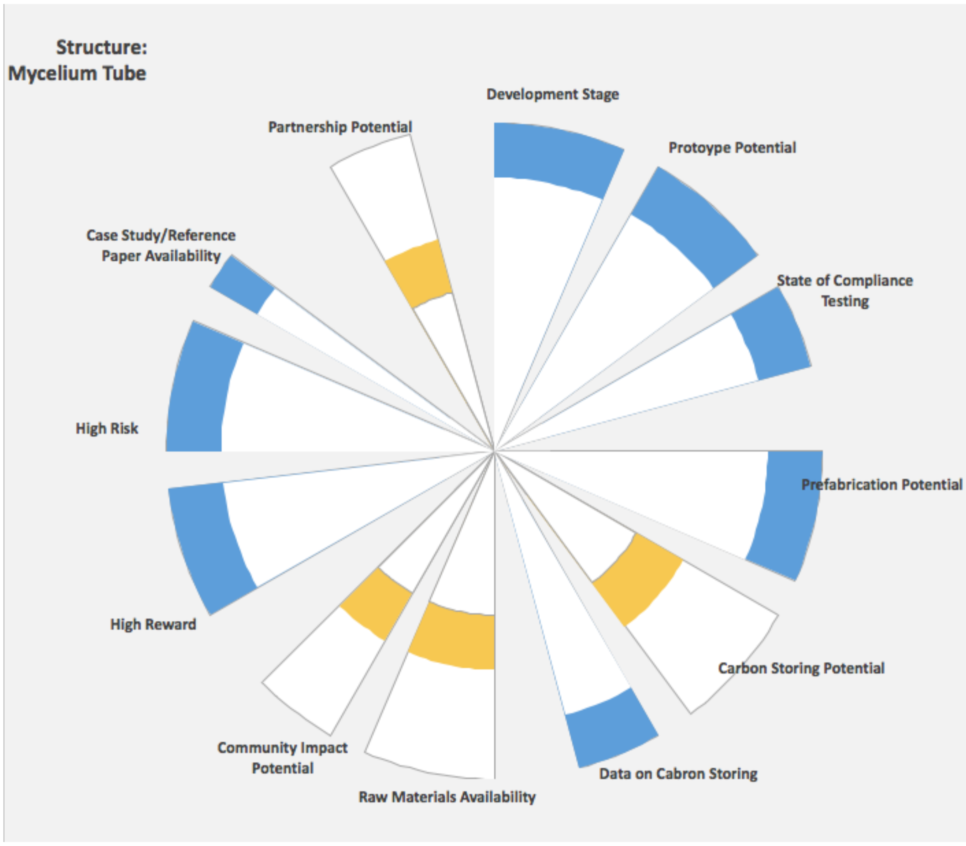

Figure 15. MIC radar chart with priority factors for mycelium tube structures.

Figure 16. Root structure for mycelium-based materials.

4.4 Agricultural products

4.4.1 Residue biomass[22]

Billions of tons of CO_2 are drawn out of the atmosphere each year by agricultural crops, the majority of this vegetation being inedible. Burning or rotting shortly after harvest typically causes this substantial pool of agricultural residues to release their carbon back to the atmosphere. Additional billions of tons of carbon are sent back to the atmosphere each year from our waste and recycling streams of biomass products such as paper, cardboard, and textiles. Collectively, these residues offer a tremendous potential to durably store some of these billions of tons of carbon in building materials without additional land use changes or increased production emissions. See Figure 17 for an MIC chart of straw panels and Figure 18 for a visual example.

Valuation and appropriate use of the carbon stored in this biomass could serve as an important driver to more widespread use in the building industry. Net carbon storage in residue materials is inherently high as the relatively low emissions from the source materials are "split" between the primary use – as food – and residue production, while manufacturing inputs tend to be low. Comparisons of LCA studies[23] and a limited number of EPDs consistently show that residue materials offer the highest net carbon storage in their material categories.

Residue materials come in a vast array of forms. Historically, residue fibers ranging from newsprint cellulose to denim offcuts have been recycled as insulation and batting. Agricultural residues – grain straw in particular – have a long history of use, often as a semi-structural insulation material. Use of these materials by a number of wall and roof panel startups has demonstrated high carbon-storage results in durable, affordable building components. Residue materials have also been used in composites and sheet goods, in which a variety of glues are used to bind the fibers. These products have been manufactured commercially on a small scale but have yet to reach their potential.

Available and potential pools of residue biomass have been thoroughly studied by governments and organizations interested their potential as energy sources. In the United States, accurate accounting for biomass stocks can be found on a county-by-county level and indicates that hundreds of millions of tons are sustainably available on an annual basis.[24]

This large category of materials ranges from nut shells that can replace concrete aggregate to long vegetation fibers with structural potential to be used as insulation. The exploration of residue materials in structural/insulated building enclosure panels, with a focus on grain straw products, holds great promise because of their global availability and the successful small-scale development already underway.

22 https://gramitherm.ch/?lang=en A European company opening its second factory producing insulation from grass cuttings on municipal and airport roadsides.

23 These EPDs and LCAs are based on the Builders for Climate Action's BEAM tool database that will be publicly available in the winter of 2021. Builders for Climate Action's BEAM tool, https://www.buildersforclimateaction.org/

24 The Promise of Biomass by Union of Concerned Scientists https://docs.house.gov/meetings/IF/IF03/20130723/101184/HHRG-113-IF03-20130723-SD024.pdf

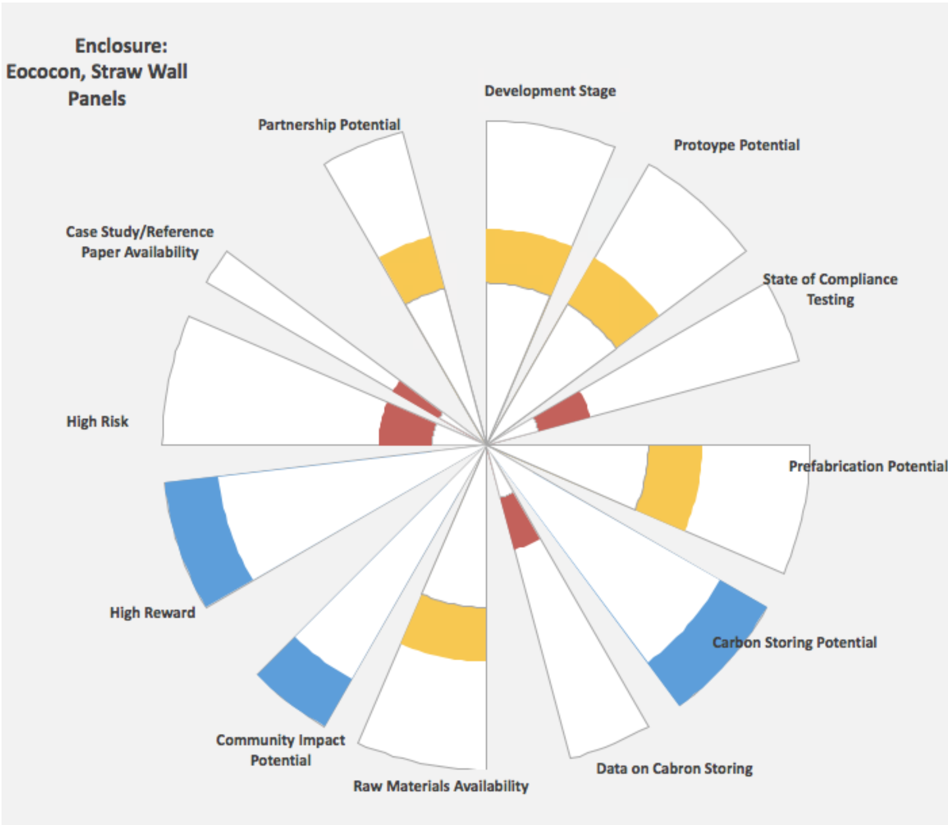

Figure 17. MIC radar chart with priority factors for straw panels.

Figure 18. Straw bale prefabricated panel.

4.4.2 *Purpose-grown fibers (bamboo, hemp fiber)*

Fibers can be cultivated specifically to provide building materials, with crops like bamboo and cork having been so harvested for centuries. Hemp, a relative newcomer to this space, has been noted for the great potential of both its fiber and the hurd (core) of the plant. See Figure 19 for an MIC chart of this material and Figure 20 for an example.

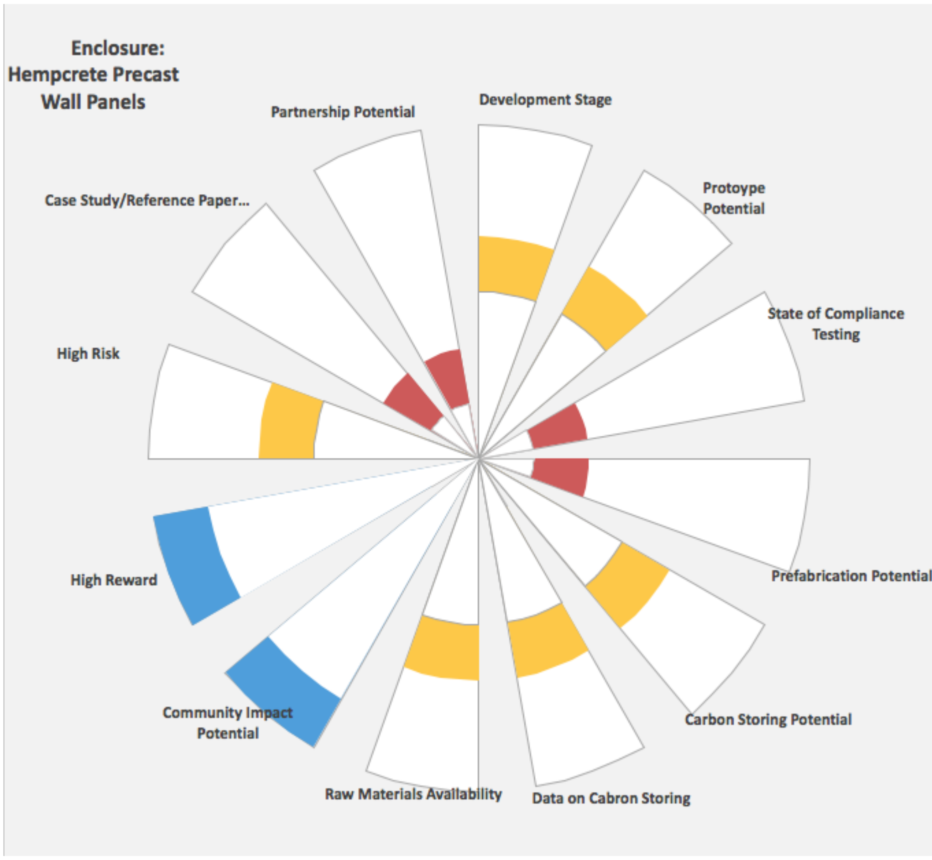

Figure 19. MIC radar chart with priority factors for hempcrete panels.

Figure 20. Hempcrete insulation derived from hemp shiv and a lime-based binder.

Bamboo can be used as a structural material in the form of laminated posts and beams, cross-laminated panels, and structural sheathing. Projects using these materials have demonstrated the potential to replace high impact materials like steel and concrete as well as timber-based materials with uncertain carbon-storing benefits.

Hempcrete, consisting of hemp hurd coated in a lime-based binder, is a semi-structural insulation material that demonstrates great potential to combine the carbon storage of plant-based material with excellent fire- and moisture-resistance. Explorations of this material may incorporate the substitution of other pithy plant residues such as sunflower, tobacco, and collards.

The carbon storage potential of these purpose-grown materials rivals that of residue biomass, but comes with additional responsibility to ensure that the associated land use impacts not add to climate or ecological burdens. Sustainable and regenerative practices can amplify the carbon storage benefits of these materials, but the displacement of current food and forest lands to provide building materials could negate their benefits. While a balanced approach is recommended, the superior benefit of using waste residue over cultivating purpose-grown materials on farmable land is clear.

4.5 Consideration of construction methods

4.5.1 3-D printing

Since the early 2000s, 3-D printing of whole buildings and building components has been occurring at an experimental level, with the potential to increase the speed of construction while lowering labor costs and improving accuracy.[25]

Current 3-D printing efforts tend to rely on building materials with high embodied carbon emissions, specifically cement and petrochemical plastics, typically in formulations that generate even higher carbon emissions due to the plasticity requirements of printing nozzles. Regardless of other efficiencies that may be gained using 3-D printing techniques, until the emissions of raw printing materials are addressed, this technology will not result in carbon-storing buildings.

Some efforts have been made, most notably by WASP in Italy,[26] to employ clay as a printing media. As noted in Section 4.2.1 of this report, raw earth materials produce exceptionally low material emissions and are available widely and globally. Perhaps this type of 3-D printing for buildings could combine the low-waste benefits of this technique with lowered initial emissions.

It should be noted, however, that regardless of the materials used, 3-D printing of whole buildings is typically achieved as a continuous, monolithic construction. Any building so created is difficult to modify in the future and does not lend itself to DfD construction methods, limiting the lifespan of the materials to their current form in their current location. Also, the range of dense structural materials currently used for 3-D printing affords virtually no insulation value. This "thermal mass" approach may be appropriate in certain climate zones, but in general any 3-D printed building will require an insulation and cladding strategy that may erase some or all of the speed and reduced labor achieved by 3-D printing. See Figure 21 for an MIC chart of this technology and Figure 22 for a visual example.

25 For more information see https://doi.org/10.1080/24751448.2018.1420968
26 WASP in Italy (https://www.3dwasp.com/en/3d-printing-architecture/)

A more positive impact from 3-D printing is likely to be found in using it to create factory-built building components. In a factory setting, printers might incorporate a wider range of materials and components and enable robotic assembly of components into larger sections, prefabricated panels, or modular components that lend themselves to DfD methods.

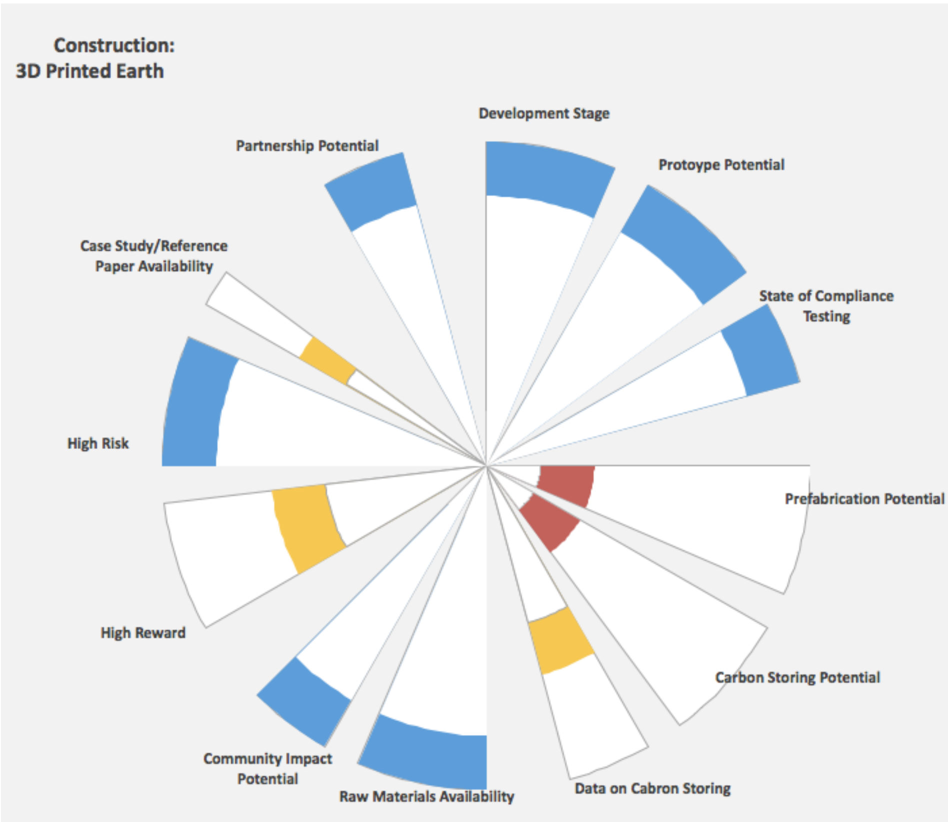

Figure 21. MIC radar chart with priority factors for 3-D printing.

Figure 22. 3-D Printing (WASP in Italy, https://www.3dwasp.com/en/3d-printing-architecture/).

4.5.2 Design for disassembly

The main uncertainty with the use of biogenic carbon-storing building materials is accounting for a pathway for the stored carbon at the end of the product and/or building's lifespan. Climate accounting models such as the Moura Costa method[27] indicate that one ton of biogenic carbon stored for 40-50 years – well within the lifespan of most buildings – has the equivalent climate impact of preventing one ton of emissions avoidance.

Most buildings are demolished to make way for new development and not because they have reached the end of their safe lifespan. DfD allows a preferable alternative of removing building components so they can be re-used in their existing form with no need for recycling. The graphic image shown in Figure 23 suggests that meaningful carbon storage is possible when design for disassembly and reuse are taken into consideration.

DfD can work at a range of scales, from removable finishes (allowing for minor building remodeling without scrapping existing materials) to moveable interior partitions (allowing for reconfiguration of interior spaces) to structural frames and enclosure systems that can be disassembled and rebuilt in their existing form or adapted to new building forms.

Buildings in general are unusual in this regard: they lack the removable and replaceable components designed into most manufactured products. If an automobile were constructed like a building, we would need to cut out the hood and replace it with a new one every time we wanted to check the engine. Every part of an automobile can be removed and replaced; once a car is no longer roadworthy, it becomes a source of parts for working cars. DfD emulates this basic premise and applies it to building materials and components. By enabling us to extend the potential lifespan of carbon stored in a reusable component beyond the lifespan of a single building, DfD extends the residency of the stored carbon from a typical 60-80 years to double or triple that value.

Every aspect of the design knowledge and building technology needed to make buildings fully capable of disassembly already exists. The benefits of this approach go far beyond extending the value of stored carbon, as it grants materials and whole buildings

27 Moura Costa, Pedro, & Wilson, Charlie. (2000). An equivalence factor between CO2 avoided emissions and sequestration – description and applications in forestry. ***Mitigation and Adaptation Strategies for Global Change***, 5(1), 51-60.

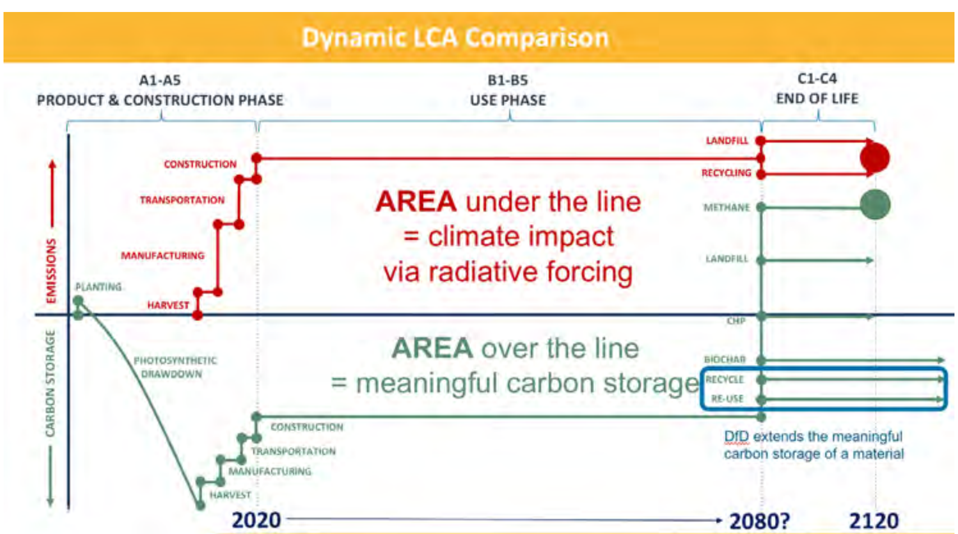

Figure 23. A dynamic LCA comparison. Adapted from Chris Magwood, 2021.

a previously unconsidered value beyond that of a fixed asset with a finite lifespan. See Figure 24 for an MIC chart of this method, and Figure 25 for an example of prefabricated construction.

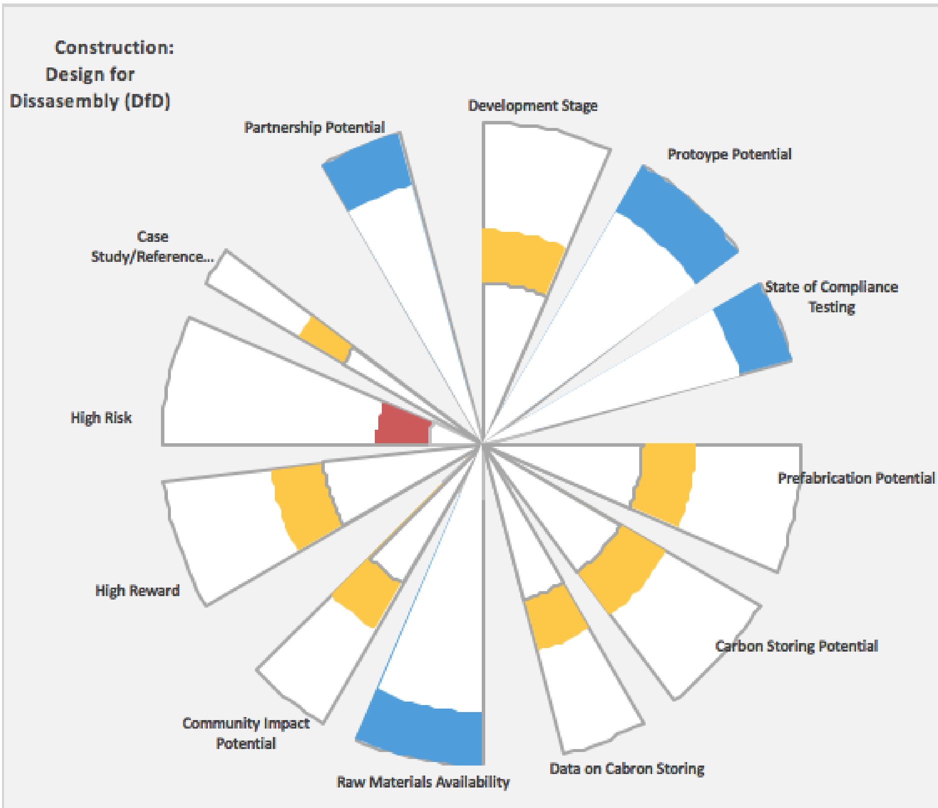

Figure 24. MIC radar chart with priority factors for design for disassembly.

Figure 25. Prefabricated wall panel construction.

4.5.3 Vertical architecture

The foundations and floor slabs of buildings are generally the largest contributors to embodied carbon emissions. If the same volume of space and floor area can be designed into a building with a smaller foundation, the overall carbon footprint of the building is reduced. As energy codes become increasingly stringent and wall enclosure materials and assemblies continue to improve with better insulation values and air tightness, carbon-storing cladding systems are well positioned to improve buildings' overall performance in terms of both operational and embodied carbon.

Early massing of project buildings with a high level life cycle analysis will be able to provide ample feedback about the potential carbon reductions achievable through vertical design. Carbon storing values for innovative enclosure and cladding systems can provide feedback on the potential increase in overall storage that would accompany vertical designs.

Vertical designs may also be more energy efficient and able to benefit from stack effect and other passive ventilation and heating systems. See Figure 26 for an MIC chart of this strategy, and Figure 27 for an example of design considerations for vertical architecture.

4.6 Discussion

4.6.1 Foundations: earthen / cement-free concrete

The WBLCA for the light industrial building under consideration in the Carbon-Storing Materials Study[28] showed concrete slab floors to be responsible for emissions totaling 2.48 million tons of CO_2e, representing nearly 25% of the total carbon footprint of the building. As the leading single source of emissions in the sample building, this component must be addressed. Even if a substituted material were not fully carbon-storing, a substantial reduction of these emissions would be achieved, enabling the whole building to reach net carbon storage more easily.

4.6.2 Earthen floors

Current LCA data for earthen floors indicates a carbon footprint of ~3.5 $kgCO_2e/m^3$, compared with ~290 $kgCO_2e/m^3$ for a typical concrete slab floor, amounting to a 98% reduction in carbon footprint. Millions of tons of emissions from every slab floor could be eliminated in this manner. A relatively small amount of carbon-storing aggregate (from Blue Planet or algal-grown sand) would tip an earthen floor into net carbon-storage, with the volume of aggregate varied to meet a given carbon storage target for the whole building. While availability and cost of carbon-storing aggregates may pose issues, small quantities to make a large impact in earthen floors would serve as a good early use of these materials.

4.6.3 Alkali-activated (cement-free) concrete

Existing LCA studies have shown that the embodied carbon of alkali-activated concrete can be significantly lower than that of traditional portland cement concrete. As previously noted, data from multiple studies suggest that the embodied carbon of AAC concrete can be from ~10 – 97% less than that of traditional concrete. Such a wide range of CO_2

28 Kriegh, Magwood, & Srubar, 2021. Carbon-Storing Materials. https://carbonleadershipforum.org/carbon-storing-materials/

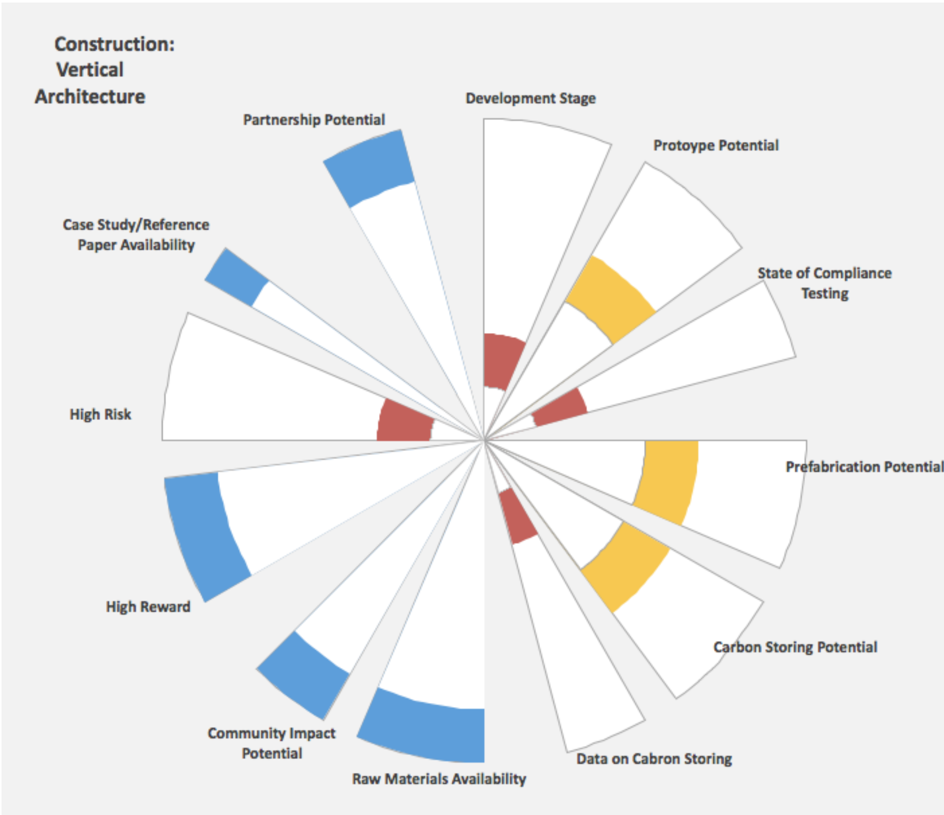

Figure 26. MIC radar chart with priority factors for vertical architecture.

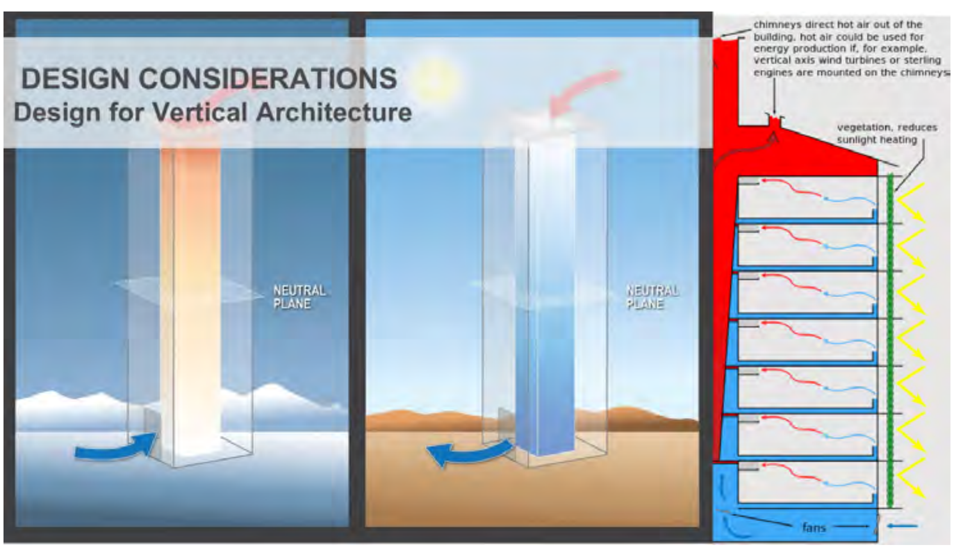

Figure 27. Design considerations for vertical architecture.

emission estimates exists due to the wide variety of precursors and alkali activator sources available. Regardless, the production of AAC concrete would yield only reductions in embodied carbon – not net storage – unless carbon storing aggregate were used to compensate for the remaining emissions.

4.6.4 Structure: mycelium tubes / algae bricks

The structural steel components in the current reference building design contribute 1.3 million tons of emissions, representing about 15% of the total building emissions and comprising the third-most impactful category. Researchers are exploring the production of load-bearing walls grown with mycelium or algae, including forming it into a dense mass with load-bearing capacities suitable for bearing wall systems. This prospect is being explored in two forms: mycelium grown in tubular forms and grown into bricks that are compressed. Both methods produce a mycelium-based material with increased density and structural properties.

Mycelium materials are grown in a carbon-rich matrix of dry plant matter such as straw, hemp, wood chips, and/or nut shells. Mycelium does not grow via photosynthesis, so the carbon-storage in these materials occurs when the mycelium breaks down the carbon content of the plant matter and incorporates some of this carbon for its own growth. Mycelium absorbs no additional carbon from the atmosphere, so the value of mycelium materials lies in their ability to transform loose biogenic fibers into a coherent material with little additional carbon cost. As with materials that use glue to adhere loose fibers, the net carbon storage of mycelium materials depends on the emission profile of the manufacturing (in this case, growing) process. Impacts from the manufacturing process must be further studied to ensure that these materials retain a net carbon storing profile.

4.6.5 Enclosure: fiber panels / algae panels

The thermal and moisture protection materials in the reference building contribute 2.43 million tons of emissions, representing 24% of the total and comprising the second-most impactful material category. Fiber panels offer a pathway to eliminate these emissions entirely and offer a great deal of carbon storage. The EPD of straw-based wall panels from Ecococon[29] shows net storage of 88 $kgCO_2e/m^2$ of wall area, indicating that a high degree of carbon storage is possible in this category.

As composites of a number of distinct materials, fiber panels are of particular interest when every element contributes to the overall carbon storage, as can be achieved through a wide array of individual material options. That each iteration will result in slightly different performance and carbon-storage characteristics can offer an advantage, allowing substitution of regionally available materials within a standardized panel size and performance index – but can also make this category of materials difficult to summarize. Each of these materials/systems requires differing degrees of moisture and fire testing/protection that will vary based upon the application. Exploration of these issues is beyond the scope of this study.

Enclosure panels are composed of four basic elements, each of which could be made from a number of different fiber-based materials:

29 https://ecococon.eu/us/the-panel

1. **Structural frame**. Products in this category currently rely on wood framing (dimensional lumber or engineered wood products), but these could potentially be substituted with hemp, bamboo, or other structural fiber materials, including mycelium tube structures.

2. **Interior and exterior sheathing**. Products in this category currently rely on wood products (plywood or OSB), but these could potentially be substituted with glue- or mycelium-bound fibers of many kinds. Sheathing products are already made from a wide variety of agricultural residues, including straw, hemp, corn stover, sugar bagasse, sunflower stalk, nut shells, and many other regional fiber sources. Waste stream fibers such as drinking boxes and textiles have also been recycled as effective sheathing materials.

3. **Insulation**. A wide range of carbon-storing insulation materials can fill panels. Existing options like cellulose (from recycled paper and/or cardboard) offer a low-cost, proven pathway with good carbon storage potential. Nearly any waste- or residue-fiber has the potential to insulate, with small scale examples of straw, hempcrete, and waste textiles demonstrating high net carbon storage values.

4. **Cladding**. Exterior and interior finishes can also store carbon. Conventional approaches include timber cladding and, to a lesser degree, cork. Composite materials derived from paper, cardboard, rice hulls, straw, and hemp fiber have also been found viable.

Each variation of fiber panel would carry its own carbon storage value and building science implications. Identifying fiber panel combinations with the greatest potential would help evolve this category of materials. In addition, developing a prototype study for prefabrication (inclusive of a variety of panel configurations) and DfD options would ensure that the lifespan of these building components extends beyond that of a single structure.

5 PROOF-OF-CONCEPT AND PATHWAY TO MARKET

This study recommends that technology industry leaders, as interested end-users of innovative carbon-storing building products that have yet to scale to the point of direct procurement, consider the following rules of engagement prior to prototyping and pilot-testing emergent material technologies:

5.1 Rules of engagement for acceleration and NDAs

5.1.1 Engage directly with the manufacturers of innovative carbon-storing building products

Direct engagement will likely necessitate completion of memoranda of understanding (MOUs) and non-disclosure agreements (NDAs) between technology industry leaders and manufacturers. This NDA will enable clear, transparent communication regarding the current maturity of the material technology and enable manufacturers to fully disclose the current scale of production, completed and planned testing, and achieved or yet-to-be-achieved certifications, as well as the cost and timelines associated with each. The MOUs and/or NDAs will also define terms of an intellectual property (IP) agreement between the two parties.

5.1.2 Technology industry leaders can select from two paths to partnership with manufacturers during Fiscal Year (FY) 2022: direct selection or request for proposals (RFPs)

Direct selection would involve technology industry leaders choosing 1-2 manufacturers with which to engage during FY 2022. By contrast, an RFP process would cast a wider net and enable technology industry leaders to ask for specific information, including current scale of production, testing, and certification, as well as facilities and current/existing partnerships that could be leveraged during FY 2022. The RFP could be issued by invitation only, enabling technology industry leaders to combine direct selection with the RFP process. Technology industry leaders could thereby obtain information regarding technology readiness level (TRL) of various materials prior to their selection for FY 2022 engagement and do so without first completing the MOU or NDA process. Such a hybrid process (RFP by invitation only) would enable technology industry leaders to select not only manufacturers with novel or lab/bench-scale materials (e.g., algae-grown bricks) but also some further along in small-scale production (e.g., fiber panels).

5.2 Prototyping, implementation, and desired use

5.2.1 Setting goals and expectations

Once selected for FY 2022 engagement, each manufacturer would discuss with technology industry leaders their specific, realistic goals and expectations for prototyping based on what technology industry leaders envision as the desired end-use application. These goals and expectations should align with the values and selection criteria (e.g., carbon-storing potential, high-risk/high-reward investment, impact potential) of the technology industry leaders.

5.2.2 Setting a scope of work

A clear discussion of goals and expectations will enable the manufacturers to establish a 9 –12-month scope of work (SOW) and cost proposal that aligns with the technology industry leaders' end-use requirements, as well as any suggested or mandatory partnerships that the technology industry leaders would require (e.g., design/productization, R&D, prototyping/assembly). Technology industry leaders should also require other terms of engagement such as a project kick-off meeting, meeting frequency, progress reviews, and final deliverables.

5.3 Prototyping and pilot testing

5.3.1 Plans for prototyping

The SOW and cost proposal outlined by each manufacturer should be submitted to and approved by construction industry leaders. The SOW should clearly outline plans for prototyping and/or pilot testing that aligns with construction industry leaders' goals, expectations, and end-use requirements.

5.3.2 Funding pilot testing

Once the SOW is approved, technology industry leaders will disburse the funds directly to the manufacturer to initiate and complete the SOW in collaboration with the design, R&D, and prototyping/assembly partners suggested (e.g., identified in this study) or selected by the construction industry leaders.

5.4 Compliance testing and certifications required and desired (opportunity/barrier) broadly

5.4.1 Compliance testing and certifications may be required for any novel materials to be used on projects

Testing and certifications may require financial support, longer project timelines during early adoption, and work with code officials to provide education and develop standard compliance pathways.

5.4.2 Acceptance of cross-laminated timber (CLT) provides an example for novel materials

CLT was recognized in the 2000s as a new building system by the wood industry and by architects and engineers interested in exploring this new material solution. However, existing building codes stipulated significant height restrictions for wood buildings. While industry trade organizations helped to support the testing to verify performance, volunteer architects and engineers organized (e.g., Seattle AIA Mass Timber working group), sharing resources and joining codes and standards committees to advocate for the use of this novel material solution. Such support from the users of wood products was instrumental to achieving the code changes. To scale a larger number of materials quickly to achieve climate goals will require similar direct support. The Carbon Leadership Forum focuses on providing technical support for emerging policy efforts and informing and engaging building industry professionals through our global network and regional hubs.

5.5 Compliance testing, related costs, and schedule

At any given time, every new material technology is situated on a research and development continuum which ultimately dictates which, if any, compliance tests must be completed before a manufacturer produces a minimum viable product (MVP). Any applicable standards and certifications must also be achieved prior to industrial application. For example, some products require structural testing while others require thermal conductivity testing, moisture, mold, and mildew ratings, fire ratings and/or acoustic testing. Nearly all would benefit from an Environmental Product Declaration (EPD). In order to confirm the environmental impact of material production, and use/end-of-life impacts, environmental life cycle assessments should be performed throughout the product development process. Which tests, standards, and certifications have already been completed and which are yet to be completed will ultimately determine the costs of compliance testing. In addition, the timeline for acquiring funds, scheduling tests, and producing results will shape the schedule for full-scale production.

5.6 Prototyping considerations for components in assemblies

Prototyping considerations include not only material testing, as described above, but also testing the material as a component in an assembly. Assembly testing is crucial to meeting the goals of technology industry leaders for accelerated production and use of carbon-storing materials. As such, multiple mock-ups or prototypes are required for each test and cost considerations often come into play as each mock-up is tested to failure.

5.7 Manufacturing and supply chain scaling potential

For transformative materials to scale and become available in the general building materials market requires that four major factors converge: (1) Increased awareness of the material within the building sector, (2) demonstrated market demand for materials to justify development of manufacturing infrastructure, (3) removal of policy hurdles to adoption, and (4) understanding and mitigating user concerns.

5.7.1 Increased awareness

For novel materials to be used more broadly, architects, engineers, contractors (AEC) and others in the building sector must become aware of their benefits and feel confident that a project in which they are specified will succeed. Strategies for increasing awareness include:

- Mapping the availability of materials to connect AEC practitioners with materials and manufacturers in their regions and limit concerns about the availability of raw material resources/capacity to scale (further discussed in Section 7);
- Constructing high-profile buildings as prototypes to provide case studies of how the material can be used and a template for construction details on future projects; and
- Development of assemblies or components that facilitate use of novel materials by integrating them into existing design and construction processes (e.g., wall assemblies that include a novel facade material to remove the need to research and develop new waterproofing techniques.

5.7.2 Demonstrated market demand

Scaling the manufacturing and supply chains of novel materials requires a major investment from manufacturers that can be difficult to hazard if they lack certainty about the market for their materials. Public policies and corporate sustainability commitments that require reductions in the carbon footprint of projects or materials are key to demonstrating market demand for development of these materials.

5.7.3 Removal of policy hurdles

Public and corporate policies create hurdles to scaling by making the process too costly or limiting markets/projects where materials can be used. Public policy hurdles include overly extensive testing and compliance pathways (as discussed above), but may also include the exclusion of novel materials from climate policies due to lack of awareness. Developing the life cycle assessment data already required of other materials (such as environmental product declarations) to document compliance with embodied carbon policies is key to communicating the value of these materials and the need for them to be added to policies targeting reduced embodied carbon.

Corporate policies also create hurdles for smaller companies seeking to be selected for a project. Some of the very requirements intended to increase the sustainability of a company's sourcing and supply chains, such as requiring certification of a manufacturing facility or a supplier code of conduct, can present barriers for small companies that as yet lack the resources to develop sophisticated management systems for environmental and social responsibility. Corporate procurement teams can consider adoptions of alternative pathways for smaller or newer companies while they scale, such as allowing a percentage of a project's budget to go toward small or growing organizations that meet climate or social justice requirements.

5.7.4 Surveying to understand and mitigate user concerns

User concerns and perceptions on the risks of using a new material present a significant hurdle to implementation of novel materials. AEC professionals may hesitate to use new materials with unknown performance or aesthetic characteristics. Identifying user concerns is a key first step mitigating fears about using novel materials, to be addressed via educational resources and training. The strategies identified to increase awareness of novel materials in the section above would also play a key role in mitigating user concerns. Better yet, administering an industry-wide survey to understand the underlying values, motivations, and perceived concerns surrounding use of novel materials would provide valuable data on why an AEC professional, manufacturer, supplier, and/or installer would or would not be motivated to use novel materials in the design and delivery of their projects.

6 DISCUSSION

6.1 Why promote early-stage material development research and opportunities now?

Low-carbon and carbon-storing materials have a long history of research, development, and use. Engagement with these types of natural materials has typically been motivated by concern for positive occupant and ecological health impacts and/or material efficiency. However, recent recognition of the severity of the climate crisis and the urgent need for major, impactful interventions has accelerated interest in materials that can redress the emissions arising from conventional building materials. Decades of work to develop, improve, and implement these materials now provide a helpful foundation of research, product development, and case studies that can help to accelerate the drive to bring these materials to market quickly.

Past experience bringing cross laminated timber and mass timber materials to market has shown that low-carbon and carbon-storing materials are feasible and attain parity with more conventional alternatives in terms of cost, code compliance, and construction schedules. However, these materials, lacking leverage on any of these fronts and needing significant investment to scale up production, have not achieved mainstream status. Their collective potential for massive climate impact compels us to harness their properties in order to redirect the climate profile of buildings from a leading driver of climate change to a leading asset for reversing it.

6.2 Environmental justice implications

Material manufacturing and transportation are often co-located with low-income communities and communities of color. Material evaluations based solely on global greenhouse gas emissions ('carbon') can miss addressing the significant human health impacts of local emissions upon these communities, as well as other critical public health, equity, justice, and labor concerns. Integrating climate justice into material choices is necessary to avoid unintended negative consequences of actions developed with an overly-narrow focus on decarbonization. This is an area of increasing interest to the Carbon Leadership Forum. The CLF believes significant work needs to be done to better understand how to ensure that material development and supply chain engagement can support climate justice goals.

As manufacturing supply chain materials scale to increase availability of transformative materials, an opportunity arises to integrate equity and justice as key priorities from the outset, rather than trying to mitigate harm after supply chains and facilities are established. These priorities mean ensuring that facilities do not add to the existing environmental health burdens on frontline communities, but also could mean identifying manufacturing partners and hubs that provide economic opportunities for historically excluded communities.

6.3 Opportunities for broader impacts

6.3.1 Manufacturing carbon negative materials to reduce embodied emissions in buildings

In early 2021, the US Department of Energy's Advanced Research Project Agency

– Energy (ARPA-E) – released a request for information (DE-FOA-0002506) for a proposed new grant program, “Manufacturing Carbon Negative Materials to Reduce Embodied Emissions in Buildings.” This program, the goals of which are likely to align well with the recommendations of this study, clearly signals that the topic is now on the federal government’s radar. One aspect of these funding opportunities is the often mandatory requirement for cost-sharing. Such grant monies present an opportunity to multiply a technology industry leader’s investment in low-carbon and carbon-storing building materials.

6.3.2 Materials mapping to climate and regional availability

Two studies of biomass availability in the U.S. have been conducted, the first by the US Department of Energy’s Oak Ridge National Laboratory (ORNL) and the second – in response – by the Union of Concerned Scientists (UCS).[30] Both focused on the availability of biomass for energy production, not for building materials, but they nonetheless provide a county-level assessment of available biomass in the categories of forestry and agriculture residues, waste streams, and purpose-grown crops, aligning with the categories of biomass materials in this study. ORNL’s highest estimate cited 1 billion tons of available biomass annually, while the UCS, imposing higher ecological standards, estimated 680 million tons. Both studies, highlighting the vast pool of raw materials for potential carbon-storing materials, can help refine efforts to identify and source these materials across the country.[31]

30 https://docs.house.gov/meetings/IF/IF03/20130723/101184/HHRG-113-IF03-20130723-SD024.pdf
31 https://www.ucsusa.org/resources/biomass-resources-united-states

7 CONCLUSION, LIMITATIONS, AND FUTURE OPPORTUNITIES

7.1 Conclusion

The potential for meaningful climate impact through low-carbon and carbon-storing materials foregrounds materials that have the potential to change the climate profile of buildings from a leading driver of climate change to a leading carbon reservoir reversing it.

Findings from this study highlight six materials for use in building foundations, structure, and/or enclosure systems. These materials – earthen slabs, non-portland cement concrete slabs, algae-grown bricks/panels, mycelium structural tubes, purpose-grown fiber, and agricultural waste panels – warrant realistic enthusiasm and are worthy of investment to aid and accelerate their prototyping, scaling, manufacturing, and marketable use in the building industry supply chain. In addition, opportunities exist for investment in educational and training opportunities in embedded apprenticeships in research, design, and construction labs, at manufacturing sites, and with AEC professional design firms.[32]

7.2 Limitations

One limitation of this study is that its scope precluded an industry-wide survey. Targeted survey questions could identify the underlying values, motivations, and perceived concerns of industry stakeholders regarding the use of novel materials, all which is essential to understanding the opportunities for and barriers to market success. Such a survey would provide concrete data around why AEC professionals, manufacturers, suppliers, and installers would be motivated to use novel materials in the design and delivery of their projects.

7.3 Future opportunities

The Micro-Cloud[33] is a concept that incorporates the prototyping of materials, mocking up of assemblies, and deploying of small-scale buildings (data centers) globally (for conceptual roadmap see Appendix II). It presents an opportunity for Microsoft to leverage multiple goals and strategies to implement its values and meet its goals for decarbonization globally.

Prefabricating low-carbon and carbon-storing material components into panelized systems makes plausible the construction of a small-scale data center structure to serve as a module embodying DfD strategies and thus capable of being assembled and reassembled multiple times for numerous deployments. The design utilizes all six materials identified in this study – earthen slabs, non-portland cement concrete slabs, algae-grown bricks/panels, mycelium structural tubes, purpose grown fiber, and agricultural waste panels – to create modularized structural panels that can be transported to various project sites for assembly.

Furthermore, the Micro-Cloud concept readily adapts to the programmatic requirements

32 The IDEA Labis adapted from proposals by Drs. Lee, Kriegh, and Dossick (UW College of Built Environments); Dr. Srubar (UC Boulder); and Executive Director Magwood (Endeavor Center) that were initiated in early 2021.

33 The term Micro-Cloud was first coined by Dr. Chris Lee (UW College of Built Environments, Dept. Construction Management) at a CIRC consortium workshop between the Universities of Washington and Arizona in 2020.

of a given site, whether rural or urban, in a developed or underdeveloped country, vertically stacked or horizontally distributed, to serve the computing needs of a community, business, or educational institution as a socially-environmentally just technological enterprise.

8 CONFLICT OF INTEREST STATEMENT

The research team would like to acknowledge the authors' involvement in related activities in the interest of transparency.

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APPENDIX 1: TRANSFORMATIVE MATERIALS INDEX

Transformative Materials Analysis

Kriegh, J., Magwood, C., Srubar, W.,Lewis, M., Simonen, K. (6.30.2021)

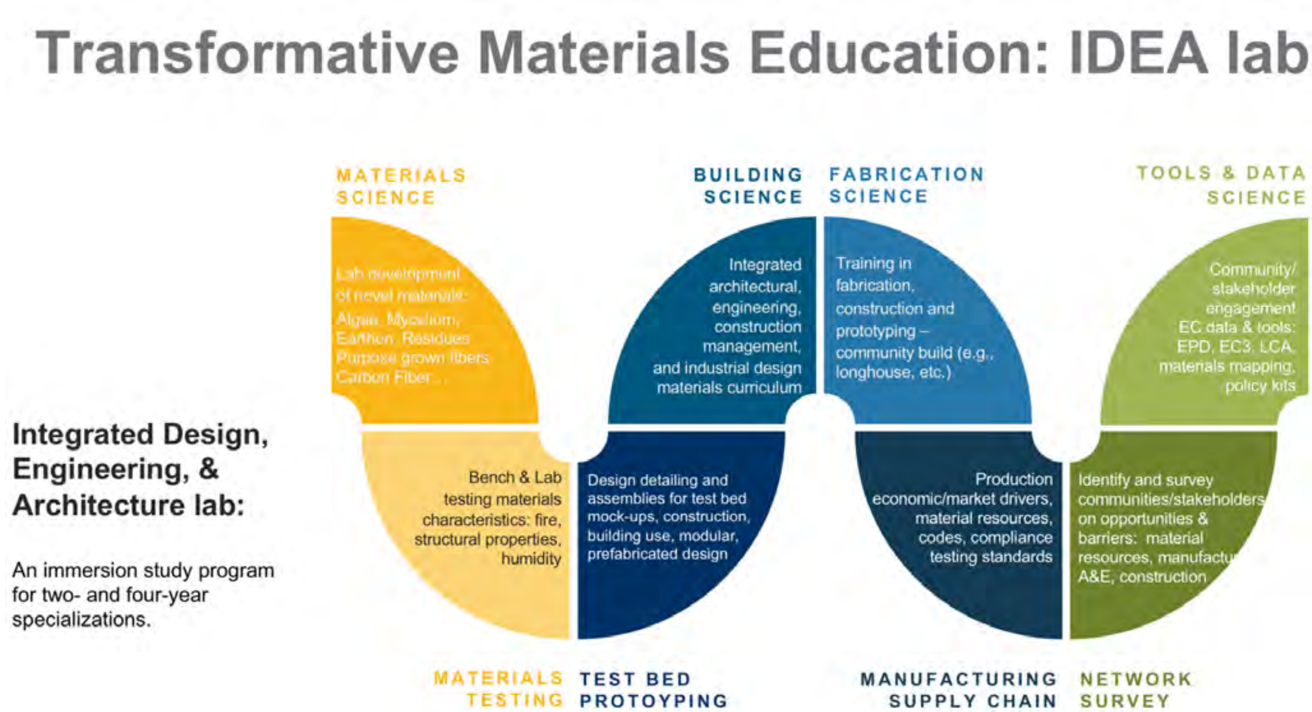
Use	Material	Development Stage	Mockup / Prototype Potential	Compliance Testing	Construction assemblies and prefabrication/modularization Potential	Carbon Storing Potential	Data - carbon storing	Potential Availability (RAW MATERIALS)	Potential Community Impact (job creation, reduces pollution burden, increases resilience...)	Reward	Risk	Reference/paper/case study		Total
Rating Methodology		5 - Early stage: R&D and lab testing. (24-36 mo) 3 - R&D/small scale deployment, testing/EPD req'd (12-24 mo) 1 - Product(s) deployed, scaling and/or code compliance and regional standards required (6-12 mo)	5 - Prototype would be revolutionary 3 - Prototype would be precedent-setting 1 - Prototype would confirm viability	5 - None exist or very minimal 3 - Testing to non-code standards 1 - Testing to some/all standards	5 - None established 3 - Prefabrication/modularization needs development but assemblies established 1 - Details and assemblies already established	5 - High: net storage of 1kgCO2/kg 3 - Moderate: 0.5-1 kgCO2/kg 1 - Low: 0-0.5 kgCO2/kg	5 - No verified documents 3 - LCA study(s) exist 1 - EPD existant	5 - Global 3 - Most Geographies 1 - Some Geographies	5 - High 3 - Moderate 1 - Low	5 - High 3 - Moderate 1 - Low	5 - High 3 - Moderate 1 - Low	5 - None or minimal 3 - Early explorations 1 - Peer reviewed		
Foundations														Score
	Earthen Floor Slab	5	5	5	5	1	3	5	3	5	5	5	5	52
	Rammed earth and oiled earthen floors	Technique has been developed at a small scale, with thousands of floors less than 2,000 ft2. Material properties understood but not measured. Material formulation and physical property testing R&D required to develop an approach that can scale to large slabs.	Skill set and materials exist to create a Mockup. Small, US-based supplier Claylin could provide mix and finishes for Mockup. Demonstrations of earthen floors are transformative, hard to believe "dirt floor" can be so resilient and beautiful.	None. Testing requirements and protocols well established. Small R&D and testing budget would have major impact.	In-situ application only, not suitable for prefabrication.	Substitution of earth material for concrete would provide very large carbon reductions. Addition of ag fibers and small quantity of carbon-storing aggregate would push the material into carbon storing territory. The carbon storage could be "tuned" by volume of CS aggregate to influence WBLCA results. Low-strength concrete is ~200-300 kgCO2e/m3. Earthen floor could reduce emissions by 90-95%.	LCA by Lola Ben-Alon https://www.natmatlab.com/publications-1 shows 17.2 kgCO2/m3 for a clay/sand/straw mix that could be used for earthen floors (no accounting for storage for the straw component). Plant-based polymerizing oil needs to be included, but will be close to net zero emissions.			Extremely low embodied carbon, can be made carbon storing, zero waste, long-lasting, material available globally. Existing concrete contractors have knowledge and ability to install.	Skepticism from designers, builders, code officials. Testing to establish parameters for material. Not as strong as concrete, but "strong enough?" Perceptions on impacts to schedule			
	Cement-Free Alkali-Activated Concrete	3	4	5	3	1	3	5	5	5	4	1	4	43
		Lab and engineering-scale prototypes and some R&D with ready-mix concrete companies are complete. Trial batches at U Colorado and US Concrete (or similar) required for full-scale prototype installation.	3-5 Highly feasible. Relationships and technical requirements established.	Small-scale R&D project with partners to optimize mixes and measure durability according to ASTM standards.	Potential for precast concrete panels.	Substitute would be very low-carbon option compared to traditional OPC concrete. Use of Blue Planet aggregate and/or Minus Material carbon-negative fillers could make it carbon-neutral or carbon-storing.	Multiple LCA studies exist; depends on mixture design formulation.			Up to 90% reduction in embodied carbon.	3-5 Acceptance/education; unfamiliarity with material.			
Structural														
	Mass Timber	1	1	1	1	3	1	3	1	4	1	1	1	19
		Technology and techniques well established, beginning to see wider adoption and use on large buildings. (Sustainable Forest Cycle)	Highly feasible. Demonstration projects already exist so need for Mockup/prototype not great.	Well established.	Assemblies and detailing well established.	? The big question! Work is ongoing to establish the value of carbon stored in mass timber products.	Industry efforts underway to evolve an appropriate LCA methodology			3-5 Key partner in bringing mass timber to larger scale & establishing sustainable forestry practices.	Not risky enough. The sector already has lots of momentum and players.			
	Bamboo structural columns and beams	3	3	3	3	5	3	3	3	5	4	2	2	39
		Bamboo glulam, cross laminated bamboo, and structural bamboo plywood already exist but have substantially less use/uptake compared to mass timber. Testing required for North American and European markets.	Highly feasible. Some manufactured products already exist. Very little use in North America, demonstration would be precedent setting. Potential for composite components and assemblies with other materials (e.g., Resource Fiber)	Testing protocols well established. Individual products will require testing.	Assemblies still in development. Much can be adopted from mass timber.	Shorter growth cycles and reduced soil disturbance result in more verifiable storage. Forestry practices require regulation and oversight.	Emissions: 210 kgCO2e/m3 from Net storage: ~1,000-1,400 kgCO2/m3 1 m3 = 875 kg 437.5 kg carbon content per 1 m3 1,605 kgCO2 per 1 m3			Bamboo has growth potential in global south. Microsoft helps establish a carbon storing technology that brings new forestry and manufacturing to less developed economies where majority of construction will take place in coming decades.	3-5 Developing products in markets outside NA and EU that may not be cost-effective in those markets.	1-3 Example: Resource Fiber's Bamboo Nail Laminated Timber System, Bamboo Biocomposite materials (plastics), Bamboo Industrial Fiber (3D printing)		
	Biofiber structural columns/beams	5	5	5	3	5	4	3	5	5	4	4	3	51
		Hemp & straw lumber; mass plywood made from ag-residue. R&D required for proof of concept.	Mockup/prototype would be first of its kind.	Protocols well established. No previous testing of materials in this configuration.	No assemblies yet developed. Mass timber can provide guidelines	High. Largest factor is glue/adhesive; better adhesives will achieve better carbon storage results	3-5 No LCA data currently. Figures would be similar to bamboo glulam (above).			Sidestep carbon storage debate surrounding mass timber by using annually renewed ag-residues for structural use.	3-5 Early development stage. Products exist, but have not been used for structural purposes.	44260		
	Mycelium tube structural	5	5	5	5	4	5	3	4	5	5	5	3	54
		Very early stage development; Initial material property testing required.	Feasible. Small-scale mockup/prototype could be completed after a round of initial property testing.		No assemblies yet developed. Could replace dimensional lumber.	3-5 LCA would need to be completed to confirm potential.	No LCA data.			Major disruption of structural materials market with first purpose-grown material	Very early development stage. Potential has to be confirmed with R&D and testing.			
	Algae carbon fiber	5	5	5	5	3	5	5	3	5	5	5	5	56
		Lightweight frameworks- Very early stage development; Potential for substructure for "growing" materials, conceptual	Mockup/prototype would be first of its kind.	5	High potential; can be integrated into panelized modules with other materials.	? LCA would need to be completed to confirm potential.	No LCA data.			Major disruption of structural materials market with first composite / purpose-grown material hybrid	Very early development stage. Potential has to be confirmed with R&D and testing.	Case study of structural framework		
	Algae - grown bricks	5	5	5	5	3	5	5	5	5	4	5	5	57
		Lab-scale testing complete; company formation complete. Engineering-scale prototype capability (12 months); commercial product availability (algae biocement) in 24-36 months.	Highly feasible if smaller scale (12 months); highly feasible for full-scale prototype (24 months).	Depends on final application; only a few ASTM tests required.	No assemblies yet developed.	Net-zero to moderately carbon storing; tremendous reduction in carbon compared to CMU blocks (target replacement).	No LCA data.			First application of algae brick technology; major disruption by using living (vs. once-living) building materials.	3-5 Proof of concept proven at lab scale; pilot/prototype scale is higher risk, but feasible in 12-24 months.	https://www.sciencedirect.com/science/article/pii/S2590238519303911 https://www.nytimes.com/2020/01/15/science/construction-concrete-bacteria-photosynthesis.html		
	Algae - grown carbon-storing limestone	5	5	5	1	5	5	5	5	5	4	5	5	55
	for OPC or alkali-activated cement concrete	Lab-scale proof of concept; Minus Materials received funding for engineering-scale prototype. Development requires funding for kg-scale prototype and first application in cement and concrete.	Feasible if small scale (12 months); highly feasible for full-scale prototype (36 months).	Chemical composition of limestone fillers; virtually no tests. Risk primarily related to producing fillers at-scale.	Details/assembly development not required as it just replaces ingredient in concrete	Extremely high; 1kg captures 1.83 kg CO2.	No LCA data.			First application of algae-grown limestone technology as a carbon-sink aggregate for cement and concrete; legitimizes a biological aggregate competitor to Blue Planet aggregates (chemical process).	3-5 High; microbial precipitation of aggregates feasible at-scale but currently at ~1g scale in the laboratory	https://www.colorado.edu/ceae/2020/03/17/srubar-will-use-new-nsf-award-create-carbon-sink-concrete https://www.nsf.gov/awardsearch/showAward?AWD_ID=1943554&HistoricalAwards=false		
Enclosure														
	Agriboard, straw SIP	1	1	1	1	5	3	3	5	3	1	3	1	28
		Been around a long time, developed strong technology; market break and development of better sheathing product required to break through; EPD and some assembly testing may be required	Very feasible, product exists today but is not widely known or used.	Full ASTM testing completed.	Structural insulated panel with fully developed assembly details.	Company LCA would need to be supported by EPD.	Company LCA shows 870 kgCO2 storage per panel at size of 24' x 9' x 8" http://www.agriboard.com/carbon/Embodied%20Energy-AgriBd.pdf			Major disruption of structural panel market.	Not a new product. Would be breathing new life into an older idea.			

Transformative Materials Analysis

Kriegh, J., Magwood, C., Srubar, W.,Lewis, M., Simonen, K. (6.30.2021)

Use	Material		Development Stage	Mockup / Prototype Potential	Compliance Testing	Construction assemblies and prefabrication/modularization Potential	Carbon Storing Potential	Data - carbon storing	Potential Availability (RAW MATERIALS)	Potential Community Impact (job creation, reduces pollution burden, increases resilience...)	Reward	Risk	Reference/paper/case study	Total
Rating Methodology			5 - Early stage: R&D and lab testing. (24-36 mo) 3 - R&D/small scale deployment, testing/EPD req'd (12-24 mo) 1 - Product(s) deployed, scaling and/or code compliance and regional standards required (6-12 mo)	5 - Prototype would be revolutionary 3 - Prototype would be precedent-setting 1 - Prototype would confirm viability	5 - None exist or very minimal 3 - Testing to non-code standards 1 - Testing to some/all standards	5 - None established 3 - Prefabrication/modularization needs development but assemblies established 1 - Details and assemblies already established	5 - High: net storage of 1kgCO2/kg 3 - Moderate: 0.5-1 kgCO2/kg 1 - Low: 0-0.5 kgCO2/kg	5 - No verified documents 3 - LCA study(s) exist 1 - EPD existant	5 - Global 3 - Most Geographies 1 - Some Geographies	5 - High 3 - Moderate 1 - Low	5 - High 3 - Moderate 1 - Low	5 - High 3 - Moderate 1 - Low	5 - None or minimal 3 - Early explorations 1 - Peer reviewed	
Enclosure														
	Strammit, compressed straw board	3	3	1	1	5	3	3	5	5	3	3	3	38
			Been around a long time, huge potential for interior partitions and additional exterior insulation; Development of commercial/industrial assembly detailing, EPDs and testing specific to panel design required	Very feasible, product can be imported from Europe for demonstration.	Full EU testing completed	Can be part of structural panel and/or used as interior partition wall system.	Company LCA would need to be supported by EPD.	Company LCA shows 549 kgCO2 storage per 1 m3 of material			Major disruption of interior partition market. Greater carbon storage potential exists in building interiors than exteriors. Makes high carbon storage possible in existing and large buildings. Built-in potential for design for disassembly.	Not a new product. Would be breathing new life into an older idea.		
	Hempcrete precast wall panels	3	3	1	1	4	3	3	5	5	4	1	1	34
			Small scale deployment in Europe has occurred; Development of commercial/industrial assembly detailing, EPDs and testing specific to panel design required	Very feasible. Products available or can be cast in situ for demonstration.	EU & UK testing completed for several product types.	Structural insulated panels and/or blocks.	44260	LCA studies exist proving carbon storage capabilities, depending on mixture formulatin: https://www.sciencedirect.com/science/article/abs/pii/S095965262031893X			5 Provide major support for nascent hemp farming sector. Highly fire resistant plant-based option.	3-5 Supply chain is in early development. Raw materials may be costly early in development.		
	Ecococon, straw wall panels	3	3	1	3	5	2	3	5	5	1	1	3	35
			1-3 Strong product, eager to expand into markets outside Europe; clay or lime panels for fire resistance; Production facility in eastern Europe. Potential for North American manufacturing is very high.	Very feasible. Product available for import for demonstration.	EU testing completed.	Structural insulated panels.	Very high. Company EPD would need to be updated for US market	1-3 Product EPD VTT-CRM-158424-18 shows 88.7 kgCO2e storage per 1 m2 of wall area			Minor investment for major impact. System is market-ready but currently obscure.	Low risk, system well developed.		
	Bamcore, bamboo SIPs	3	1	1	3	5	2	3	5	3	1	1	3	31
			Strong product, market-ready, potential to scale and combine with bamboo structural elements; US production facility just being established. Development currently at residential scale, would need testing to scale up to larger buildings.	Very feasible. Product currently available for demonstration.	US testing underway	Structural panels.	No EPD, but company LCA for whole building includes encouraging results. Figures should be similar to glulam bamboo (above). When combined with carbon-storing insulation, this system has very high carbon storage potential	1-3 Company LCA for whole building shows bamboo components to be carbon neutral in A1-A3 phases. https://www.bamcore.com/wp-content/uploads/2019/11/BamCore_Report_10-21-2019_Quantis.pdf			New idea ripe for major uptake. Can be manufactured in many locations globally. Easy to combine with local bio-based insulation.	Low risk, system meshes well with current engineering standards.		
	Ecovative Foam	4	5	1	1	4	3	3	3	4	4	3	3	38
			3-5 On-demand growth kit for insulation and partition panels. ASTM testing for building insulation completed. Production needs to scale to provide market ready products.	Very feasible. Product currently available for demonstration.	Testing complete.	High potential; can be integrated into panelized modules with other materials.	3-5 Unknown but likely very high; LCA needs to be performed to understand if biogenic storage outweigh impacts due to processing.	No EPD yet. Early company LCA shows near-neutral carbon results.			3-5 System is market-ready; coolness factor is high, but Microsoft will not be the first to implement.	3-5 Low risk; system well developed.		
	Earthen Precast Wall Panel	1	1	1	3	1	3	5	5	4	5	1	5	35
			Technique has been developed at a small scale-primarily residential.	Very feasible.	Testing complete for walls; would need some testing in location of application.	Prefabricated modules blocks availabe; more development is possible.	Substitution of earth material for concrete would provide very large carbon reductions. Addition of ag fibers and small quantity of carbon-storing aggregate would push the material into carbon storing territory.	LCA studies of rammed earth wall exist; shows low-embodied cabron potential.			3-5 Extremely low embodied carbon, can potentially be made carbon storing, zero waste, long-lasting, material available globally. Existing concrete contractors have knowledge and ability to install.	Skepticism from designers, builders, code officials. Testing to establish parameters for material. Not as strong as concrete, but "strong enough?"		
	Algae - grown brick veneer wall panels	5	5	5	5	3	5	5	5	5	4	5	5	57
			Lab-scale testing complete; company formation complete. Engineering-scale prototype capability (12 months); commercial product availability (algae biocement) in 24-36 months.	Highly feasible if smaller scale (12 months); highly feasible for full-scale prototype (24 months).	Depends on final application; only a few ASTM tests required.	No assemblies yet developed.	Net-zero to moderately carbon storing; tremendous reduction in carbon compared to CMU blocks (target replacement).	No LCA data.			First application of algae brick technology; major disruption by using living (vs. once-living) building materials.	3-5 Proof of concept proven at lab scale; pilot/prototype scale is higher risk, but feasible in 12-24 months.	https://www.sciencedirect.com/science/article/pii/S2590238519303911 https://www.nytimes.com/2020/01/15/science/construction-concrete-bacteria-photosynthesis.html	
Design / Assembly / Construction														
	Vertical architecture	1	3	1	3	3	2	5	5	5	1	5	5	39
			Design for passive systems energy, Minimize foundation impacts by stacking stories and functions Use stack effect inside building to assist with passive conditioning					1 - 3			Cost! (land, mech, systems)			
	3D Printed Earth	5	5	5	1	1	3	5	5	4	5	4	5	48
			5 Icon- Austin, Columbia Lab	Would be revolutionary for data centers	Virtually no testing done on 3D printed earth.	Would have to be done on-site	Substitution of earth material for concrete would provide very large carbon reductions. Addition of ag fibers and small quantity of carbon-storing aggregate would push the material into carbon storing territory.	LCA studies of rammed earth wall exist; shows low-embodied cabron potential.			3-5 Extremely low embodied carbon, can potentially be made carbon storing, zero waste, long-lasting, material available globally. Existing concrete contractors have knowledge and ability to install.	3D printing of earth unproven at-scale. Skepticism from designers, builders, code officials. Testing to establish parameters for material. Not as strong as concrete, but "strong enough?"	44260	
	Design for Disassembly (DfD)	4	5	5	4	4	4	5	4	4	1	3	5	48
			All structural frames and enclosure panels designed for easy disassembly and re-use - Plan for secondary use at initial design phase- (community structural, affordable housing); Development requires a kit of parts panel assembly where the panel is switched out depending on the region and material availability but the panel assembly is similar	Mockup proof of concept- engage local underrepresented communities in the northwest to train in construction and production- mock up as a longhouse representing indigenous populations		3-5 Prefabricated assemblies are a key component of DfD techniques, to allow for easy replacement or deconstruction of panelized modules.	3-5 Building with biogenic materials for a carbon-positive future.	3-5 Data- panels are easily assembled and reassembled based - materials are tested in wall panels			3-5 Lead by example, spur industry, partnerships that are mutually beneficial (reciprocal)	Low risk; system to be developed.		

APPENDIX 2: IDEA LAB[1]



1 The IDEA Lab is adapted from proposals by Drs. Lee, Kriegh, and Dossick (UW College of Built Environments); Dr. Srubar (UC Boulder); and Executive Director Magwood (Endeavor Center) that were initiated in early 2021.