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Sustainable Low-Carbon Building Materials Workshop Report

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May 2022

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Buildings and Transportation Science Division

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FOREWORD

The manufacture of building materials is responsible for 10% of all anthropogenic CO_2 emissions, and for 26% of all emissions attributed to the buildings sector (UNEP, 2020). Although reductions in greenhouse gas emissions from the operation of buildings have been achieved over the past several decades, the embodied CO_2 is either levelled or increasing, and in some cases, it can represent up to 90% of the total building emissions (Röck et al., 2020). Carbon-intensive materials, such as Portland cement-, iron- and petroleum-based materials, are widely used for structural and nonstructural applications in the construction of cities and infrastructure. Efforts to decarbonize these industries and reduce the usage of these materials should be undertaken.

Although most technologies to reduce emissions from these difficult-to-decarbonize industries are still in their infancy or yet to be discovered, replacing carbon-intensive materials with low-carbon alternatives can be a viable path for the construction industry in the short- and mid-term future. Bio-based materials, such as forest products, mycelium, hemp, algae, bamboo, and cork, are receiving increased interest. Composites that combine these materials could offer structural and nonstructural solutions to buildings and infrastructures. Architects and designers are seeking feedstock materials that store atmospheric carbon and help reduce cradle-to-cradle emissions. Furthermore, reusing and recycling building materials will significantly reduce embodied energy that would otherwise be wasted.

1. INTRODUCTION AND GOALS

The virtual Sustainable Low-Carbon Building Materials Workshop, organized and held by the US Department of Energy's (DOE's) Oak Ridge National Laboratory (ORNL) on January 25, 2022, focused on identifying the technical barriers to the research, development, and deployment (RD&D) of low-carbon building materials, and on determining what can be done to overcome these technical barriers in the short-, mid-, and long-term future. The meeting brought together key players in the construction chain from industry, academia, and ORNL to promote collaborations that could help meet the goals of accelerating the development and deployment of low-carbon building materials in the United States, and of developing a net-zero (or even negative) carbon neighborhood in the Southeast United States by 2030.

2. PLENARY

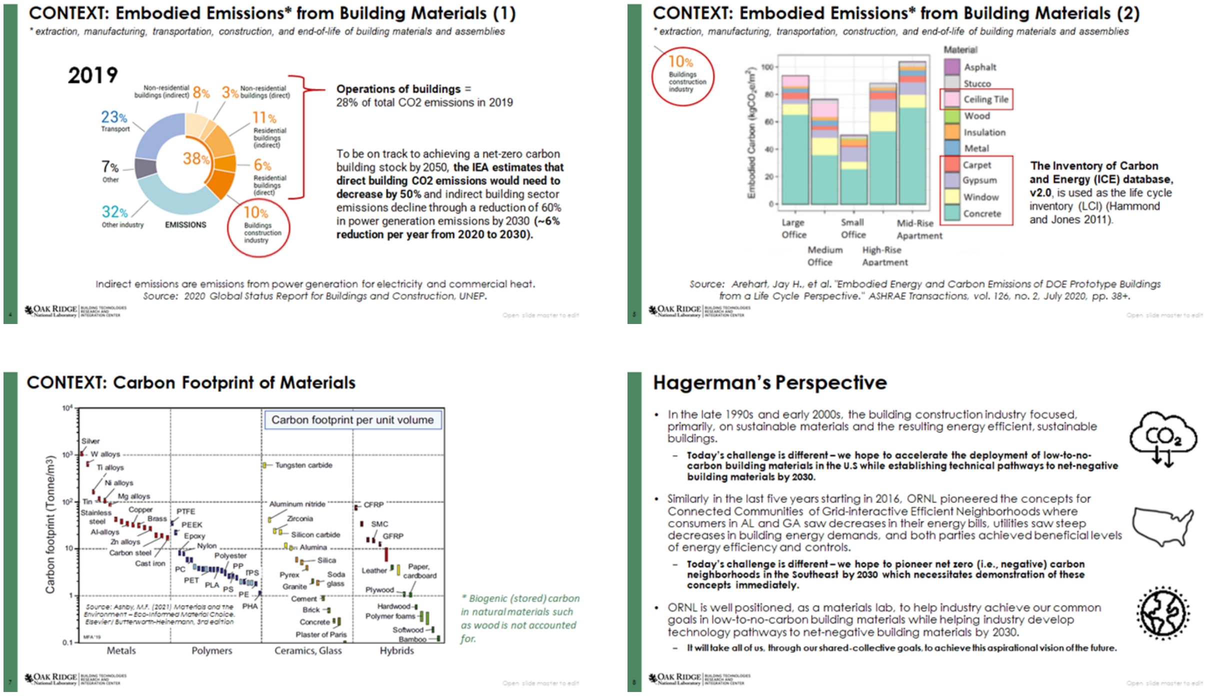
The meeting began with the introductory comments from **Dr. Xin Sun**, associate laboratory director for the Energy and Science Directorate at ORNL. Dr. Sun emphasized that the buildings sector is key to decarbonizing the entire US economy. The operational energy efficiency has been significantly improved. However, Dr. Sun highlighted that decarbonization efforts need to go beyond operational efficiency, given the global goal of carbon neutrality by 2050. Buildings are pioneers of electrification, and this sector has an opportunity to become the first net-zero sector, thus offsetting difficult-to-decarbonize sectors such as transportation and others. Dr. Sun explained that teamwork is needed to establish a net-zero neighborhood in the Southeast United States. The team that participated in the workshop is a comprehensive group capable of urgently achieving the decarbonization goal, including professionals from universities, government agencies, non-profits, industry (raw materials manufacturing and modular construction), and ORNL researchers. The objective of the workshop was to identify technical barriers and stretch goals.

Sam Petty, from DOE's Buildings Technologies Office (BTO), spoke next. He informed workshop participants on how BTO has embraced embodied carbon in the past 2 years. The building stock in the United States is expected to continue to grow: by 2050, it is estimated to be twice the size of today's stock, and by 2060, three times the size. Increased operational efficiency means that a larger portion of life cycle energy will be embodied energy, with the primary portion being from the new construction sector. According to Mr. Petty, the use of lower-carbon materials is one of the best ways to address this issue, and this workshop's goal was to identify solutions. Lower-carbon solutions must be researched while maintaining the building's structural integrity, durability, and occupant comfort. Cost-effective, carbon-negative materials must be identified, and the effects on disadvantaged communities must be identified as addressed as efforts on low-carbon materials move forward. BTO has started to develop a strategic plan that will be built into a roadmap for low embodied carbon. Furthermore, BTO is working with Guidehouse to set up workshops and roundtables; participants of this workshop had an opportunity to help define BTO's path forward.

Next, **Joe Hagerman**, ORNL's Building Technologies Research section head at that time and facilitator of the workshop, explained the goals and objectives of the workshop and presented his perspective. Between 1990 and 2000, the industry was focused on sustainability. Today, the science pathways to develop low-carbon to net-negative building materials are being defined. Similarly, in the past 5 years, ORNL pioneered Connected Communities of Grid-Interactive Efficient Neighborhoods with energy companies in the Southeast United States. After that, the Southeastern Focus Place-Based Technology Innovation Summit (Hagerman et al., 2021), hosted by ORNL in 2021, attempted to represent the development of neighborhoods with the best science and technologies, highlighting ORNL's leading position in using science to drive place-based results. Today, building materials must be developed and scaled to develop low- to net-zero carbon neighborhoods in the Southeast by 2030, which necessitates immediate implementation of these concepts. The Sustainable Low-Carbon Building Materials Workshop is a continuation of the efforts of the summit.

In his slides, shown in Figure 1, Mr. Hagerman highlighted that to achieve net-zero carbon building stock by 2050, the International Energy Agency estimates that the direct CO_2 emissions will have to be decreased by 50% between 2020 and 2030, which corresponds to a 6% reduction per year. The objective of this workshop was to address emissions from the building construction industry (embodied carbon), which make up 10% of all anthropogenic CO_2 emissions. A slide showing the areas that produce the most emissions in DOE prototype buildings, published by Arehart et al. (2020), was presented. Some of the materials use energy for low-temperature processes during manufacturing, such as drying. According to Mr. Hagerman, ORNL has heavily invested in this area, including recent work that helped the Information

Technology and Innovation Foundation with an industrial decarbonization report, which showed that there are much better uses of natural gas than for low-temperature heating. Another slide showed a comparative graph of the carbon footprint of many materials used in the buildings sector, published by Ashby (2021).


CONTEXT: Embodied Emissions* from Building Materials (1)

* extraction, manufacturing, transportation, construction, and end-of-life of building materials and assemblies

Operations of buildings = 28% of total CO2 emissions in 2019

To be on track to achieving a net-zero carbon building stock by 2050, **the IEA estimates that direct building CO2 emissions would need to decrease by 50%** and indirect building sector emissions decline through a reduction of 60% in power generation emissions by 2030 **(~6% reduction per year from 2020 to 2030).**

Indirect emissions are emissions from power generation for electricity and commercial heat.

Source: 2020 Global Status Report for Buildings and Construction, UNEP.

CONTEXT: Embodied Emissions* from Building Materials (2)

* extraction, manufacturing, transportation, construction, and end-of-life of building materials and assemblies

The Inventory of Carbon and Energy (ICE) database, v2.0, is used as the life cycle inventory (LCI) (Hammond and Jones 2011).

Source: Arehart, Jay H., et al. "Embodied Energy and Carbon Emissions of DOE Prototype Buildings from a Life Cycle Perspective." ASHRAE Transactions, vol. 126, no. 2, July 2020, pp. 38+.

CONTEXT: Carbon Footprint of Materials

Source: Ashby, M.F. (2021) Materials and the Environment – Eco-informed Material Choice. Elsevier/ Butterworth-Heinemann, 3rd edition

** Biogenic (stored) carbon in natural materials such as wood is not accounted for.*

Hagerman's Perspective

- In the late 1990s and early 2000s, the building construction industry focused, primarily, on sustainable materials and the resulting energy efficient, sustainable buildings.
  - **Today's challenge is different – we hope to accelerate the deployment of low-to-no-carbon building materials in the U.S while establishing technical pathways to net-negative building materials by 2030.**
- Similarly in the last five years starting in 2016, ORNL pioneered the concepts for Connected Communities of Grid-interactive Efficient Neighborhoods where consumers in AL and GA saw decreases in their energy bills, utilities saw steep decreases in building energy demands, and both parties achieved beneficial levels of energy efficiency and controls.
  - **Today's challenge is different – we hope to pioneer net zero (i.e., negative) carbon neighborhoods in the Southeast by 2030 which necessitates demonstration of these concepts immediately.**
- ORNL is well positioned, as a materials lab, to help industry achieve our common goals in low-to-no-carbon building materials while helping industry develop technology pathways to net-negative building materials by 2030.
  - **It will take all of us, through our shared-collective goals, to achieve this aspirational vision of the future.**

Figure 1. Some of the slides presented by Mr. Hagerman, ORNL.

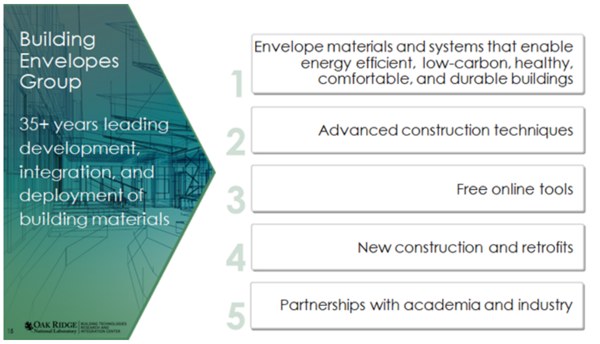
Dr. Diana Hun, ORNL's Building Envelope Materials Research (BEMR) group leader, presented an overview of the work done in BEMR to address the high contribution of building materials to the carbon emissions of the buildings sector in the following areas:

A. Technologies that directly reduce the embodied carbon of materials, such as bio-based insulating foams, low-carbon concrete, renewable formwork for the precast concrete industry, and wood-based structural elements (e.g., cross-laminated timber [CLT])

B. Technologies that reduce installation time and embodied carbon, such as the development of biobased preinstalled sealants for prefab components

C. Tools that accelerate the deployment of low-carbon building materials, such as a database on hygrothermal properties of low-carbon materials needed to run simulations that prevent moisture durability problems, and a machine learning tool that can accelerate development and integration of new low-carbon building materials in buildings

Some of Dr. Hun's slides are shown in Figure 2.



Building Envelopes Group

35+ years leading development, integration, and deployment of building materials

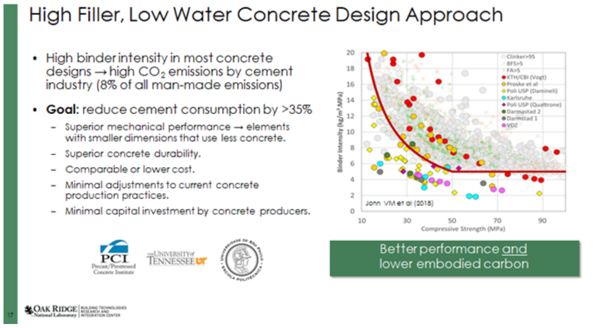
1 Envelope materials and systems that enable energy efficient, low-carbon, healthy, comfortable, and durable buildings

2 Advanced construction techniques

3 Free online tools

4 New construction and retrofits

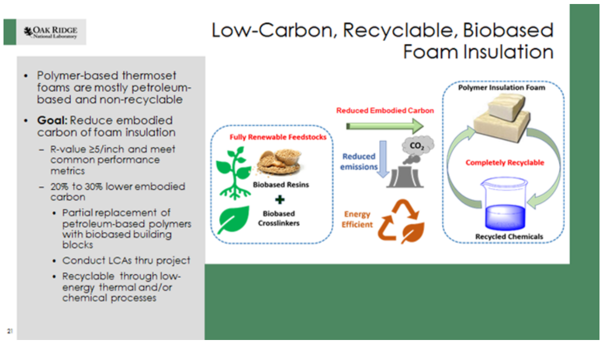
5 Partnerships with academia and industry



High Filler, Low Water Concrete Design Approach

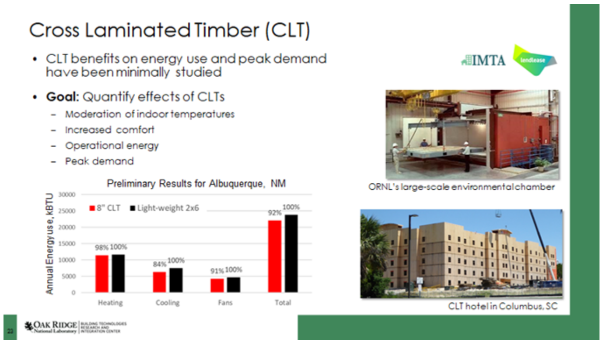
- High binder intensity in most concrete designs → high CO_2 emissions by cement industry (8% of all man-made emissions)
- **Goal:** reduce cement consumption by >35%
  - Superior mechanical performance → elements with smaller dimensions that use less concrete.
  - Superior concrete durability.
  - Comparable or lower cost.
  - Minimal adjustments to current concrete production practices.
  - Minimal capital investment by concrete producers.

Better performance and lower embodied carbon



Low-Carbon, Recyclable, Biobased Foam Insulation

- Polymer-based thermoset foams are mostly petroleum-based and non-recyclable
- **Goal:** Reduce embodied carbon of foam insulation
  - R-value ≥5/inch and meet common performance metrics
  - 20% to 30% lower embodied carbon
    - Partial replacement of petroleum-based polymers with biobased building blocks
    - Conduct LCAs thru project
    - Recyclable through low-energy thermal and/or chemical processes



Cross Laminated Timber (CLT)

- CLT benefits on energy use and peak demand have been minimally studied
- **Goal:** Quantify effects of CLTs
  - Moderation of indoor temperatures
  - Increased comfort
  - Operational energy
  - Peak demand

ORNL's large-scale environmental chamber

CLT hotel in Columbus, SC

Figure 2. Some of the slides presented by Dr. Hun, ORNL.

3. PARTICIPANTS' PERSPECTIVES

To understand perspectives on barriers for RD&D of low-carbon building materials, workshop participants were asked to answer the following two questions:

1. What are your organization's decarbonization efforts?

2. What are the technical barriers to deploy low-carbon building materials, and what are the research needs?

Twenty-eight groups or individuals described their current efforts to reduce the embodied carbon of building materials. They also described the many barriers that slow or halt their efforts to research, develop, and deploy low-carbon solutions in the marketplace. In total, more than 100 barriers were listed, including redundancies. They can be grouped into the following categories:

A. **Policies**: The lack of policies that favor the use of new, innovative, low-carbon building materials is seen as a barrier to their fast and widespread adoption in the marketplace, preventing the development of an economy of scale that would enable cost reduction of the new sustainable technologies. Consequently, a clear strategy and path leading to decarbonization, especially in manufacturing, is needed.

B. **Regulatory**: Barriers are related to the absence of building codes and standards specific to environmentally friendly materials that could accelerate their introduction. The definition of stakeholder-specific sustainability standards is also seen as necessary. Furthermore, the use of standards based on small-scale tests that provide less realistic results is perceived as a barrier.

C. **Awareness/education**: The barriers related to this category include the following:

    i. Mischaracterization and misperception of the environmental, mechanical, durability, and energy performance of sustainable materials, as well as their environmental, health, and safety factors, by one or more stakeholders in the construction chain, owing to their lack of knowledge and lack of expertise

    ii. Poor communication among stakeholders in the construction chain

    iii. The need to educate concrete producers on suitable low-carbon concrete technologies and their implementation in current practices

D. **Manufacturing**: Barriers include incompatibility of new materials with existing manufacturing equipment and current low manufacturing capacity of low-carbon materials.

E. **Technology development**: Several gaps were listed under this category. They include the following:

    i. The need for new chemistries for low-carbon materials of mineral, polymeric, biomass, CO_2-sequestering, and recycled wastes.

    ii. The need for better performing sustainable materials in terms of fire resistance, mechanical properties, water resistance, fungal development resistance, short- and long-term low toxicity, among others

iii. The lack of knowledge and data on the long-term performance and durability of new materials and systems

iv. The need to develop solutions to address feedstock variability that affects the performance of new materials

v. The need to develop solutions that account for the differences of materials characteristics in different geographies, and/or to develop region-specific solutions

vi. The need to align biomass properties with the most appropriate application

vii. The need to develop large-scale bio-based additive manufacturing for affordable/resilient housing construction, including the development and integration of bio-based materials into modular construction

viii. The need to accelerate the introduction of bioderived resins for engineered composites

F. **End-of-life management**: The lack of infrastructure for recycling and biodegradation is included in this barrier category, as well as the lack of raw material source traceability.

G. **Sustainability**: Barriers in this category include the following:

i. The high cost of building life cycle assessments (LCAs) and energy-simulating tools

ii. The complexity and differences of LCA modeling and the limited LCA practitioner credentials and certification, leading to inconsistent interpretation of life cycle inventory results

iii. The need to update LCAs to include carbon sequestration

iv. Insufficient support for LCA tools owing to incomplete, unavailable, or unreliable life cycle inventory databases

v. The need for LCA of carbon in the production and delivery of biomaterials, which includes stored carbon, such as wood-based materials

vi. Embodied carbon–focused tools that lead to do not consider operational carbon savings

vii. The absence or inefficient use of Environmental Product Declarations (EPDs)

H. **Scale-up**: Investments are needed to scale up new technologies demonstrated at the bench scale.

I. **Construction**: Construction efficiency must be increased by modular solutions and reduced waste.

J. **Cost**: Costs are often impractical if the decarbonization process is not widely adopted, recognized, or mandated. The lack of a universal cost of carbon was also listed as a barrier. Furthermore, perceived cost will remain high if the focus is on short-term costs rather than long-term analyses.

4. ACADEMIC INPUT

Six academics (listed as follows) were asked to make 5 min presentations describing how their research contributes to a net-zero carbon future, and what challenges or technical barriers they are addressing.

- Prof. Sulapha Peethamparan, Clarkson University
- Prof. Sabbie Miller, University of California, Davis
- Prof. Timothy Rials, University of Tennessee, Knoxville
- Dr. Susan MacKay, University of Maine
- Prof. Levente Denes, West Virginia University
- Prof. Wil Srubar III, University of Colorado Boulder

Prof. Sulapha Peethamparan described her efforts to replace Portland cement systems with alkali-activated binders (geopolymers) that do not use Portland cement. This technology allows 50%–100% CO_2 emissions reduction compared with cement. Several alternative precursors for the geopolymer systems, such as calcined clay, ground bottom ashes, and natural pozzolans, are being investigated by her group to address the scarcity of traditional precursors, with positive results. Prof. Peethamparan's group also focuses on enhancing the durability of concrete to prolong the service life of structures; utilizing recycled concrete to promote a circular economy; and developing cementitious materials that can sequester CO_2 and NO_x from the atmosphere. Prof. Peethamparan highlighted that a toolbox of low-carbon concrete technologies based on field data should be developed with sustained funding and support, thus enabling the application of solutions that address specific, local barriers, such as regional availability of raw materials, specific performance criteria, and available installation technology. To overcome the high upfront cost, opportunities for savings during the life cycle of the building component should be demonstrated. Policies that promote decarbonization efforts should be in place, such as New York's Low Embodied Carbon Concrete Leadership Act. Educating stakeholders is also critical to raise awareness and develop knowledge about options to decarbonize the construction chain.

Prof. Sabbie Miller's research integrates structural design, materials science, and industrial ecology to engineer materials and minimize their environmental impact. Prof. Miller highlighted that all stages of the life cycle of the material should be considered to evaluate its full environmental impact. The stages include the production, construction, use, and end-of-life, as well as recovery, repurpose, and reuse. Specifically for concrete, an approach that includes several decarbonization measures, such as cement decarbonization, cement replacement, concrete mixture optimization, design optimization, and extended service life, can reduce emissions from the concrete industry by 74% while still following most current codes and standards. Prof. Miller's work considers the impact of materials on the surrounding health, environment, and resources availability to achieve a full assessment of new and existing technologies. Work is also done by the group to (1) integrate food, energy, and materials production to develop an industrial symbiosis to facilitate a circular economy and benefit from the photosynthesis processes; (2) use waste streams in the production of materials; and (3) engineer materials to uptake and sequester CO_2 (i.e., to ensure that CO_2 is not returned to the atmosphere at the end-of-life).

Prof. Timothy Rials is a member of the Center for Renewable Carbon at the University of Tennessee, Knoxville. The Center has been investigating the use of lignin as a precursor for 100% renewable carbon fibers with improved interfacial properties that can be used for the development of functional, low-carbon composites. Bioderived resin systems are also a topic of research and development in Prof. Rials' group, focused on acrylics and radiation-curable types of resin systems. Another area of interest for the group includes mass timber, including the introduction of more efficient processes and technologies, as well as durability aspects of mass timber exposed to the high relative humidity observed in the Southeast United States. Other research areas include the development of post-fabrication treatments for termites, investigation of the effects of interfacial features of wood fibers on mechanical properties of plastic/fiber composites, conversion of lignin to graphitic materials, and use of foamed amorphous carbon for energy storage, filtration, insulation, and carbon storage. Challenges and technical barriers addressed by the group include (1) the expedited development of new materials by a rapid determination of process–structure–property–performance relationships through combined analytical methods and computational modeling; (2) adaptation of new technologies to existing manufacturing and materials flows, while developing new, efficient technologies for materials and recycling; (3) production of materials that perform as well as or better than existing technologies in extreme conditions; and (4) creation of value through product flow and involvement of industry for commercialization, thus reducing economic barriers.

Dr. Susan MacKay described several applied research projects conducted by her group at the University of Maine to develop low-carbon building materials, such as large format additive manufacturing (from bio-based molds for precast concrete to modular construction); development of 100% bio-based (nanocellulose) fiberboard; development of combinations of mycelium and nanocellulose to produce fiberboards and insulating materials that can easily be integrated with additive manufacturing of modular building elements; and research on CLT. A partnership exists between the University of Maine and ORNL to accelerate the advancement of nanocellulose and other forest product composite technologies, reduce the time from laboratory discovery to market impact, and facilitate the transition of bio-based additive manufacturing technologies to industry. This partnership's objective is to advance to carbon-negative buildings by (1) decreasing the energy and cost of construction through the development of advanced manufacturing methods, and (2) decreasing the embodied energy of building materials by replacing petroleum-based products with renewables.

Prof. Levente Denes highlighted the importance of wood as a sustainable building material; it has a high potential for carbon retention (1 m^3 of wood can store 1 t of CO_2), and the reuse and renewability of wood make it sustainable. Focusing on wood utilization is critical in the Southeast United States because of the huge wood reserves, mostly hardwood species. It is a sustainable feedstock because the annual removal from these areas is about 10% less than the annual growth. One of the main goals of the Division of Forestry and Natural Resources of the West Virginia University is to support the maximum value yield of the Appalachian Hardwoods through education and research activities. Prof. Denes listed the main barriers and obstacles to achieve this goal. They include the acceptance of hardwoods as building materials (hardwood is mainly used in furniture, sidings and other architectural applications), extending to very few research and product development efforts utilizing this type of wood. There is a lack of information, resources, mass timber production capacities for processing hardwoods, and a lack of research infrastructure and funding grants. To overcome these barriers, Prof. Denes' group at West Virginia University focuses on (1) determining the species of trees in the Appalachian region that have the most potential to produce CLT panels; (2) determining the dimensions and grade of boards that can be produced from these species; (3) determining the structural lumber grade within low-grade hardwoods that can be used for CLT production; and (4) demonstrating hardwood CLT production technology and use. Current research at West Virginia University includes bonding experiments with red oak and yellow poplar, grading of low-quality hardwoods by different methods, and CLT development from underutilized hardwoods.

Prof. Wil Srubar's research focuses on transforming buildings into carbon sinks. The paths taken by his group include two main mechanisms of storing carbon in building materials, namely photosynthesis (1 kg biomass = -1.83 kg CO_2) and carbonate mineralization (CO_2 reacts with Ca to produce limestone). The group works with trees, straw, hemp, and algae. Areas of research include alkali-activated binders; engineered living materials from fungus mycelium, lichen, and microbial-induced calcium carbonate precipitation (MICP); transparent wood and natural fiber composites; additively manufactured earthen materials; and cement decarbonization using bioinspired CO_2-storing Portland cement technologies.

Using CO_2-storing Portland cement technologies can help significantly reduce the carbon footprint of limestone cement and, combined with other technologies such as electrification of kilns for clinker production and carbon capture and storage, can transform Portland cement into a carbon sink. Whole-building LCA is also a focus of Prof. Srubar's work.

5. BREAKOUT SESSIONS

The overarching goal of the breakout sessions was to identify the technical, commercial, and/or regulatory challenges for the development and deployment of low-carbon, sustainable building materials, and to devise possible paths to overcome these challenges. More specifically, answers to the following questions were of interest to provide a clear path for action:

- What can be done in the near-, mid-, and long-term future to decrease the embodied carbon of building materials?
- What needs to be done by other entities, and how can the groups participating in this workshop help?
- What else is missing from this discussion?

All participants were split into four groups according to familiarity with different classes of building materials. For each group, one or two facilitators led the discussions to generate answers to the given questions. The facilitators of each group summarized the group discussions as presented in the following paragraphs.

5.1 GROUP 1: SUSTAINABLE MATERIALS AND PRACTICES

This summary was prepared by Dr. Anthony Aldykiewicz Jr. (ORNL).

What can be done in the near-, mid-, and long-term future to decrease the embodied carbon of building materials?

A. Metrics
   i. Near-term future
      - A reliable or standard labeling system is needed. There seems to be a lack of consistency in the generation of EPDs. Standards (e.g., ASTM, ISO) must be developed and enforced.
      - Labeling systems need to clearly identify/define CO_2 or embodied carbon. The labeling systems need to be consistent, similar to the nutritional labels on food products.

   ii. Mid-term future
      - Targets need to be established and enforced. Incentives are needed to encourage current (e.g., 2030/2050 carbon emission reduction goals) and new goals to be achieved.

   iii. Long-term future
      - Material end-of-life must be addressed. ISO standard 14068 addresses end-of-life, and UL is currently developing UL 3600 to address end-of-life. End-of-life also needs to be considered when addressing carbon emission reduction.

B. Performance
   i. Near-term future
      - Performance targets must be established with respect to embodied carbon. The following questions should be considered: Do we establish baseline values for current construction practices and then indicate levels of reduction compared with the baseline? Are calculations for embodied carbon specific to materials or is the entire system considered? Do operational

emissions factor into the system calculation? Does the calculation for carbon emissions consider economics and investment returns?

ii. Mid-term future
  - A consensus is needed to define a path forward and then drive an effort to codify it. For example, do we define product categories and then set prescriptive standards for these categories?

C. Manufacturing and scalability
  i. Near-term future
    - Manufacturing plant certifications could be developed to recognize facilities that are reducing carbon emissions holistically through efficiency improvements and the development and processing of materials that lead to products with a lower embodied carbon (like the LEED system for commercial buildings). Things that could help are maps of bio-based raw materials, consistency between bio-based raw materials and raw materials derived from waste streams, and technologies to facilitate recycling and the use of recycled content in products. Technical approaches are needed to handle variability of bio-based raw materials, waste, and recycled sources in production processes (e.g., composition, properties).

  ii. Mid-term future
    - Production of bio-based raw materials should be prioritized. The following questions should be considered: Is new manufacturing equipment required to produce bio-based raw materials at scale? What does a manufacturing process look like? Some of this knowledge is known but not used in the building materials industry. A path is needed for technology/knowledge transfer between the bio-based industry and building materials manufacturers to understand how to integrate these materials into current production processes minimizing capital investments. Freight also needs to be addressed. Currently, a significant portion of the cost of bio-based raw materials is freight. The cost of collocating facilities must be examined.

D. Durability and safety
  i. Near-term future
    - Standard test methods should be developed for specific product categories to address durability. Accelerated aging studies need to evaluate and adopted for new low-carbon materials. Current test methods could potentially be implemented. A literature review of the state of the art could determine whether there are studies examining accelerated aging of these materials.
    - The following questions should be considered: How do additional additives, such as chemicals to improve fire resistance, affect embodied carbon emissions? Is there a need to develop fire retardants, biocides/insecticides that have low embodied carbon? Since these materials are bio-based, will there be a need to increase the addition of biocides/insecticides? Work needs to be done to understand how these materials will age when exposed to the environment.
    - The industry needs a better definition of durability with respect to product categories.
    - Warranties and how product failures will be handled must be considered (e.g., whether the issue should be handled by the manufacturer, architect, or builder). A warranty system is needed to provide end users with some level of security when using these products.
    - The following questions must be addressed: Do the existing standards and test methods apply to new bio-based, low–embodied carbon building materials? Should standards be prescriptive-based or performance-based? Do current test methods and standards apply, or are changes required? Without answering these questions, it will be difficult for architects and engineers to begin to use these materials in current systems.

- Product safety and the building codes to determine safety through the implementation of a set of standards and test methods must be considered. Do the codes, standards, and test methods accurately capture the performance and safety of these new materials, or are additional standards and test methods required to ensure safety?

ii. Mid-term future
  - Manufacturers continue to build data on the performance of these materials. Would industry be willing to share data to address long-term durability? For example, data could be aggregated and then labs such as ORNL could leverage technical resources to address this issue (e.g., computational facilities). There are difficulties in handling or addressing proprietary concerns. Other concerns include product variability, manufacturing differences, composition, and formulation differences.
  - Additional safety concerns beyond the material need to be addressed, such as performance, exposure, and installation.

E. Supply chain

i. Near-term future
  - Locally sourced raw materials should be used. A map of bio-based raw material sources should be developed to help manufacturers with current production and long-term strategic planning.
  - Circularity and use of recycled materials (e.g., recycling program for carpets) must be considered. Some carpet manufacturers are taking back materials and trying to recycle them in new products to reduce waste. Perhaps something similar could be done for other building materials. The use of bio-based building materials to facilitate recycling needs to be understood.

F. Adoption

i. Near-term future
  - Demonstrations (both small and large scale to show scalability) are needed from the lab to real structures. Demonstration projects showing real-world applications would be especially useful.
  - Raw material sourcing reliability needs to be better understood. Seasonality may affect supply since some of the materials are agriculturally based.
  - The use of low-carbon building materials in government-managed projects could be a path to adoption. However, perceptions of these efforts may be a barrier.
  - A performance map is needed of low-carbon building materials/products compared with commercially available products (highlighting performance metrics), perhaps by industry consortia or a third party, and perhaps something comparable to ENERGY STAR. This effort relates to the fact that architects and engineers need to understand how these materials perform compared with the high–embodied carbon materials they expect to replace. Without that information, architects and designers cannot easily specify these materials in construction applications.

G. Voice of the customer

i. Near-term future
  - Customer benefits must be understood. It should be clear to customers if the low-carbon materials perform and cost similarly to traditional technologies. If there are codes that mandate a reduction in embodied carbon, then those would drive the use of low–embodied carbon materials. This could provide the mechanism to lower cost through economies of scale. Customers also need to be differentiated as homeowners, building owners, contractors,

  and builders. They may have needs that are not aligned, such as social and economic concerns.

H. Incentives
  i. Near-term future
    - The development of an incentive program similar to that for renewable energy should be considered. Utility companies offer incentives for increased insulation, more efficient HVAC systems, and more efficient appliances. An incentive model for low–embodied carbon building materials could be developed, but funding for this model would need to be determined (e.g., DOE, the US Environmental Protection Agency, local governments).

I. Regulatory codes and standards
  i. Near-term future
    - Codes are needed to promote the use of low-carbon building materials. Currently, no codes address carbon emissions and sustainability. IRC, IECC, ASHRAE codes do not address sustainability. There must be a consensus-led effort that includes industry, academia, and the labs to develop language that can be adopted by the codes. There also must be data to support the language.

What needs to be done by other entities, and how can the groups participating in this workshop help?

A. Test methods and standards are needed to facilitate the use of these materials in practice.
B. More participation is needed in developing codes.
C. Financial incentive programs need to be identified that encourage the use of low-carbon building materials beyond affordable housing.
D. Adoption by states and municipalities is needed.
E. Carbon limits or targets in building materials/systems need to be established and codified.
F. Homeowners should be incentivized, such as through tax benefits (e.g., a reduction in property taxes).

What else is missing from this discussion?

A. A solid technical foundation is needed for the quantitative benefits of low-carbon materials.
B. Improved communication is needed among all the players (e.g., academia, industry, consumers) along the value chain.
C. Science must be better communicated to the public.
D. Who the critical decision makers are in the construction process must be determined.
E. A carbon specification is needed to promote utilization.
F. The differences in the decision-making processes for commercial vs. residential buildings, and who is making decisions, must be understood.

5.2 GROUP 2: BIO-BASED MATERIALS

This summary was prepared by Dr. Diana Hun (ORNL).

What can be done in the near-, mid- and long-term future to decrease the embodied carbon of building materials?

A. Near-term future

i. New technologies are developed through intermediate steps in which current materials are blended with bio-based materials to demonstrate value and feasibility to industry and end users.
ii. Case studies are needed to demonstrate the performance of bio-based materials to reduce potential stigma regarding low performance.
iii. Tools are needed to estimate both operational and embodied energy.
iv. Evaluations are needed to determine
    - Which bio-based materials/feedstock are suitable for buildings,
    - What their level of sustainability is (e.g., yield per area, degree of fertilizers needed),
    - Where they are available,
    - How much material is available, and
    - How much material could be sustainably produced to meet demands from the building industry.

    This information could be made accessible through a preliminary version of a web portal.
v. Educational campaigns are needed to explain how biomass can be produced sustainably so that the stigma from using certain bio-based materials is reduced. For example, wood is a sustainable material; however, many people don't want to see trees cut down.
vi. Value propositions should be developed for contractors, given that they play a significant role throughout the selection of the building materials that are used and do not want to take risks with new materials.
vii. Government investments are needed to tackle the gap between development and commercialization of new technologies.

B. Mid-term future
i. Test standards that are tailored for bio-based materials are needed to evaluate durability.
ii. Tools are needed for end-of-life assessment and management that include:
    - Identification of best end-of-life approach for a specific material (e.g., recycle vs. reuse vs. energy recovery); and
    - Accelerated and validated biodegradation test standards that involve biodegradation at realistic scales.
iii. Performance metrics or rating for bio-sourced materials (e.g., ENERGY STAR).
iv. De-risking of bio-based technologies (e.g., demonstrate adequate performance) so that they can be more quickly commercialized.

C. Long-term future
i. Bioengineering and new chemistries can be used to improve durability, mechanical performance, and yield.
ii. Infrastructure is needed to recycle bio-based materials and/or prepare them for reuse.

5.3 GROUP 3: INSULATION MATERIALS

This summary was prepared by Mr. Mikael Salonvaara (ORNL).

What can be done in the near-, mid- and long-term future to decrease the embodied carbon of building materials?

A. Near-term future
i. Comparing the EPDs should be easier and more consistent.
    - EPDs need to be simplified.

i. A common language is missing when discussing EPDs between industry professionals and builders.
ii. The assumptions and variables vary between different EPDs, and poor comparison of EPDs can lead to the delisting of products.

- Architects, designers, and third-party verifiers need to be educated in interpreting and using EPD and LCA data. The credentials of the practitioners in LCA are inadequate.
    - i. Performing LCAs is complicated, and there is a lack of standardization, knowledge, and experience.

ii. Cost-competitive solutions must be found.

- Cost is prohibitive for new materials. If the product cost remains the same and additional manufacturing expenses are added by switching to new raw materials, manufacturers might not be incentivized to switch to these materials.
- Manufacturers should be able to include the cost of carbon in the total cost of the product. However, the question remains, who should pay for the carbon? An answer to that question must be determined.
- Products made from the waste stream of other products may be solutions rather than something completely new and highly efficient.
- The financial interests of different stakeholders in the construction process must be determined, as well as how to bring carbon into those interests.
- Environmental concerns must be addressed, including incentives for builders to develop low-carbon buildings.

iii. Incentives, policies, and codes are needed to increase the adoption of new low-carbon materials.

- Designers and contractors are reluctant to change, especially regarding untested new products.
- Contractors are often hesitant to use even cost-neutral new materials because of concerns regarding their long-term performance and potential changes in installation. These concerns need to be addressed.
- The likely path for adopting new materials could be through the custom housing market, with the rest of the market following its success.

iv. New performance metrics need to be developed that take into account carbon.

- The social cost of carbon must be considered. The products should get credit for their system performance benefits over their life cycle, not only on their individual performance values.

v. Field data are needed to evaluate accelerated testing in real conditions.

- Long-term demonstrations in buildings are vital to increasing confidence in adopting new products. For example, increasing energy efficiency and airtightness of building envelopes increases the risk of moisture problems. Therefore, high-performance buildings with bio-based products, which are often more vulnerable to moisture damage and mold growth, must be carefully designed and built. The system has to be durable, and replacing one material with a bio-based one may require changes in other materials in the system to address moisture concerns. Testing needs to start now to have data to compare with accelerated testing methods.

vi. Tools are needed to match low-carbon products to durable systems.

B. Mid-term future

i. A more inclusive database of reliable low-carbon materials is needed for LCAs.

- Currently, different databases and methods for evaluation exist.
- Whole-building energy savings should be considered, which is often not the case because it is not required.
- LCA analyses should be made cradle-to-grave instead of cradle-to-gate.

        - A baseline value should be created for LCAs, especially for energy savings, as there is no target other than to reduce carbon impact.
        - Service life should be considered for each material individually, rather than using the same service life for the products.
        - Increasing transparency of LCA data and use, including, for example, assumptions and variables, is needed to make fair comparisons.
        - LCAs should be used more for continuous internal improvement than direct product comparison.
    ii. Designs for durable, adaptive, and flexible buildings are needed to enable changes in building use without reconstruction to increase the life cycle of the buildings.
    iii. Ways of reusing or repurposing materials at the end of their life in their original use must be determined.
        - Installation methods that enable removal at the end-of-life need to be developed.
    iv. Scaling up the availability of raw materials is necessary before investing in new plants or manufacturing processes for low-carbon materials.
        - The availability of raw materials for low-carbon technologies is a bottleneck and concern for manufacturers. The sourcing of materials often competes with other industries, and manufacturing can be difficult.
    v. Policies must be developed to increase and simplify the adoption of new low-carbon materials.

C. Long-term future
    i. Must examine how to accelerate durability testing of new materials and make them more relevant to how the products perform in the field.
        - The durability of building materials is essential to reduce retrofitting and repairs. Unfortunately, these data are not available for new materials, and accelerated testing methods are the only way to acquire some information about durability.
        - Field testing must start in the near term to support this task.
    ii. Logistics must be developed to deconstruct buildings for material reuse in the long term, and to scale up recycling processes.
        - The biggest issue is getting the products from the building to the recycling processor.

5.4 GROUP 4: CEMENT SUBSTITUTES

This summary was prepared by Dr. Denise Silva (ORNL).

The group identified the main technical barriers to decrease the embodied carbon of cement-based materials. Measures that could be taken to overcome the barriers were also identified. The group focused most on actions that could be taken in the short- and mid-term future, given the contribution of cement to global CO_2 emissions, the opportunities that exist today to decarbonize the industry, and the urgency to avoid catastrophic climate change.

A. Several new technologies have been developed but need incentives to be scaled up.
    i. Near-term future
        - Field applicability must be demonstrated.
        - Motivation is needed to adopt new technologies.
        - Funding support for pilot-scale production and demonstration is needed.
    ii. Mid-term future

- Opportunities for innovation at the nexus at food, energy, water, and materials need to be identified.

B. The lack of durability data on new low-carbon technologies deters their widespread adoption.
  i. Near-term future
    - Results must be demonstrated in the short-term future via accelerated methods using standards that would help with acceptance.
    - Durability aspects and requirements of current standards to new technologies must be leveraged.
  ii. Mid-term and long-term future
    - Data must be generated on new technologies (lab and field applications).

C. Supplementary cementitious materials (SCMs) and alternative cementitious materials (ACMs) are regionally available; their availability, suitability, and variability must be considered. Various solutions must be developed. In addition, sources of SCMs and ACMs have uniformity issues.
  i. Near-term future
    - Possible replacements for cement (and fly ash) must be identified regionally, and the size of reserves must be determined.
    - SCM and ACM content should be increased in cement and concrete.
    - Ternary cementitious blends with supporting standards/codes (such as PLC adoption) should be added. Other countries have well established standards for ternary, low–clinker factor cements.

D. Sustainability
  i. Near-term future
    - More data for EPDs are needed.
    - LCA tools need to be harmonized.

  ii. Mid-term future
    - End-of-life management is needed.

E. Acceptance and adoption
  i. Near-term future
    - Incentives, education, policies, and building codes are needed.
    - Acceptance from state departments of transportation and other agencies must be considered.
    - Development of appropriate standards/codes must be expedited.
    - Performance-based requirements are needed.
    - Global warming potential must be benchmarked at the building level.
    - Customers' education/involvement is needed.
    - International certification of new technologies is needed.

6. CLOSING REMARKS

The Sustainable Low-Carbon Building Materials Workshop, organized and held by ORNL on January 25, 2022, gathered the construction chain's stakeholders from the industry, academia, and ORNL. Almost 60 participants worked together to identify the main barriers to research, develop, and deploy low-carbon building materials, and to implement a net-zero carbon neighborhood in the Southeast United States by 2030. The discussion revealed clear pathways to decarbonization, as well as many questions that need to be answered.

A summary of the identified barriers and the pathways to overcome them is provided in the following paragraphs.

Path toward a circular economy

A process that guides manufacturers and installers to change current practice of demolishing and rebuilding should be developed. More effort are needed on the development of materials that can be part of a circular economy, and on construction practices that lead to reuse and recycle. Ways of reusing or repurposing materials at the end of their life in their original use must be determined and accompanied by the development of the required infrastructure. Installation methods are needed that allow for removal at the end of life, as well as designs for durable, adaptive, and flexible buildings to enable changes in building use without reconstruction to lengthen the life cycle of the buildings. Logistics must be developed to deconstruct buildings for material reuse in the long term, and to scale up recycling processes. The most significant issue is getting the products from the building to the recycling processor.

Design for safety and durability

The durability of building materials is essential to reduce retrofitting and repairs. Unfortunately, these data are not available for new materials, and accelerated testing methods are the only way to acquire some information about durability. Using existing standards would help with acceptance, and leveraging durability aspects and requirements of current standards to new technologies could help address this concern. A report summarizing state-of-the-art materials is needed to identify studies regarding accelerated aging of new, low-carbon materials. Standard test methods may need to be developed for specific product categories (e.g., bio-based materials) to address durability.

To ensure product safety, a set of standards and test methods that accurately capture the safety of new materials must be implemented. Additionally, safety concerns beyond the material need to be addressed, such as performance, exposure, and installation. Warranties and how product failures will be handled must be considered. Specifically, a warranty system is needed to provide end users with some level of security when using the new products.

Performance metrics development

New performance metrics that consider carbon need to be developed. If a low-carbon material has lower performance than the traditional technology and its production is more costly, the product is noncompetitive in today's markets. Therefore, carbon impact should be factored into product pricing. Furthermore, current EPDs lack consistency; comparing the EPDs should be easier and more consistent to enable fair product comparisons, and a common language should be developed to simplify EPDs.

A standardized labeling system for categories of products needs to be implemented to compare embodied carbon, and a verification and certification process is needed to confirm that manufacturers are reducing carbon emissions from facilities that are developing products with low embodied carbon.

Demonstration and Deployment

Efforts to support the development and deployment of new, low-carbon technologies in real systems, thus demonstrating their field applicability, must be intensified to develop a better understanding of installation requirements, performance, and durability, and to motivate the industry toward adoption. Several new technologies at the lab scale need this push for deployment, and more support is needed. There is a need to continue to support the development and deployment of these materials in real systems.

Availability, suitability, and variability

Availability and suitability of raw materials may be a concern for the manufacture of some low-carbon building materials, such as cementitious binders and sustainable bio-based feedstocks. Furthermore, low-carbon building materials are typically less processed from original raw materials, such as biomass, and are more variable in composition, which can lead to performance differences in the final product. These factors must be considered for the development and deployment of solutions, and regional supply chain networks must be in place.

Acceptance and awareness

Adoption of low-carbon technologies of building materials can only be achieved with an organized effort and commitment of all stakeholders in the construction chain, from the suppliers to end users. Different value propositions may be needed based on stakeholder feedback. Education, policies, incentives, and codes/standards at the local, region, and nationwide levels are required. Standards and codes should be performance- and environment-based, rather than prescriptive, and they should enable uniform and consistent comparison of products and systems. The commitment and involvement of all stakeholders will enable the objectives for emissions reductions to be met to avoid the catastrophic effects of climate change.

However, the most significant barrier to development and deployment is the lack of economic and environmental drivers. The establishment of consensus targets for greenhouse gas reductions without legislative or code requirements would be difficult. For example, the deployment of materials for life safety in the construction of residential and commercial buildings is mandated by codes. Federal and local governments, working with manufacturers, need to develop a regulatory path to development and deployment of building materials with low embodied carbon. Cost is fundamental, and manufacturers and installers will not use materials that are currently more expensive unless they can alleviate those costs through other means, such as passing the cost to the consumers. In the absence of regulatory requirements, consumers will be hesitant to pay more to reduce carbon emissions. The current economy makes deployment even more challenging.

Finally, incentives to use low carbon materials may not be sufficient. A system to hold manufacturers and builders accountable for continuing to produce and use materials with high embodied carbon may need to be created.

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