A vision for converting buildings into carbon sinks

ARPA-E's HESTIA Program

Marina Sofos, Ph.D.
Program Director

October 12, 2023

Outline

- Introduction to ARPA-E
- Motivation for the HESTIA Program
- Overview of Life-Cycle Analysis
- Expansion of Material Choices
- Whole-building Design Approaches

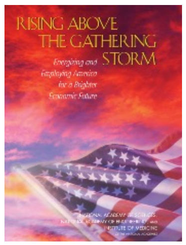
HESTIA

INTRODUCTION TO ARPA-E

CHANGING WHAT'S POSSIBLE

History of ARPA-E

In 2007, The National Academies recommended Congress establish an Advanced Research Projects Agency within the U.S. Department of Energy to fund advanced energy R&D.



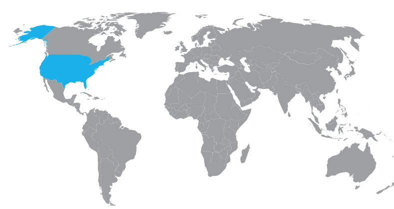
2007

Rising Above the Gathering Storm **Published** - warning policymakers that U.S. advantages in science and technology had begun to erode

America COMPETES Act **Signed** – authorizing the creation of ARPA-E

2009

American Recovery & Reinvestment Act **Signed** – Providing ARPA-E its first appropriations of $400 million, which funded ARPA-E's first projects



2023

1,468+ Awards
69+ Programs

Current Funding:
$470M
(FY23)

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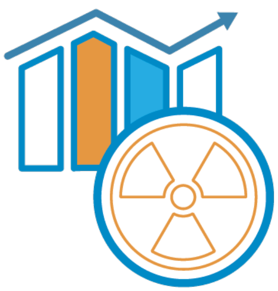
ARPA-E Mission

REDUCE
imports

REDUCE
emissions

IMPROVE
efficiency



IMPROVE
radioactive waste management

IMPROVE
energy infrastructure resilience


If it works…
will it matter?
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5

ARPA-E Impact Indicators 2023

Since 2009
ARPA-E has provided
$3.58 billion
in R&D funding to
more than **1,500 projects**
+ 42 selected projects

212 projects
have attracted more than
$11.5 billion
in private-sector follow-on funding

149 companies
formed by
ARPA-E projects

27 exits
market valuations worth
$21.8 billion
from mergers, acquisitions, and IPOs

300 projects
have **partered with other government agencies**
for further development

6,797
peer-reviewed
journal articles
from ARPA-E
projects

1,039 patents
issued by
U.S. Patent and
Trademark Office

323 licenses
reported from
ARPA-E projects

As of July 2023

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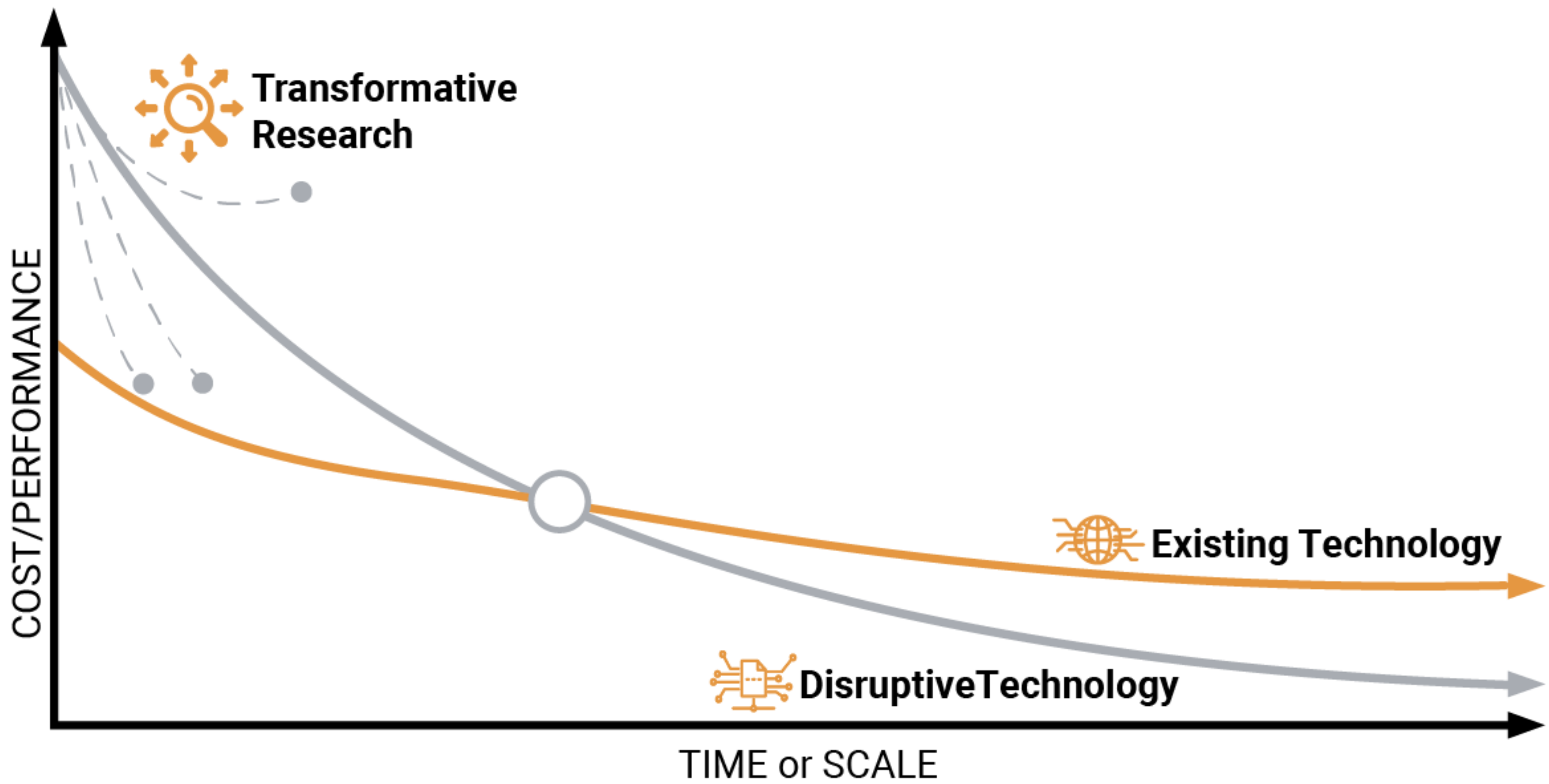
Creating New Learning Curves



MOTIVATION FOR THE HESTIA PROGRAM

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HESTIA

Harnessing Emissions into Structures Taking Inputs from the Atmosphere

Achieve **net carbon negativity** from material manufacturing through building operations & end-of-life using atmospheric CO_2* in the production process

Program Highlights:

- Store more carbon than emitted during manufacture & use
- Code-relevant performance testing (e.g., flammability, strength)
- Market advantage (beyond C-storage) over best-in-class incumbent
- Design for reuse, repurposing &/or recycling to extend service life

$45 M	4 years	2022 start

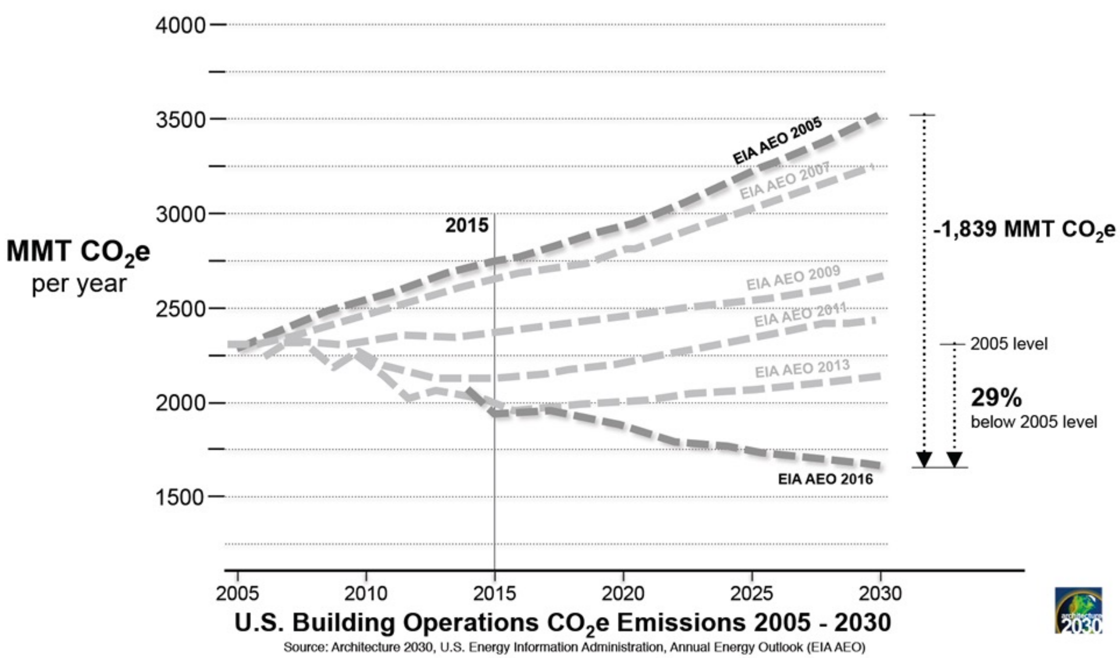
Life-cycle analysis (2 projects):
Cradle-to-grave including land use, C-storage tracking over time, & nascent material uncertainties

Novel materials (12 projects):
Range of feedstocks (e.g., forestry & purpose-grown products, ag. residues, direct C-utilization) & conversion pathways

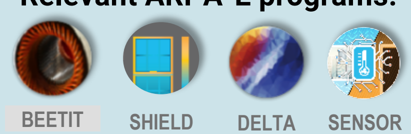
Whole-building designs (5 projects):
Link design decisions with material selection to maximize C-storage & performance

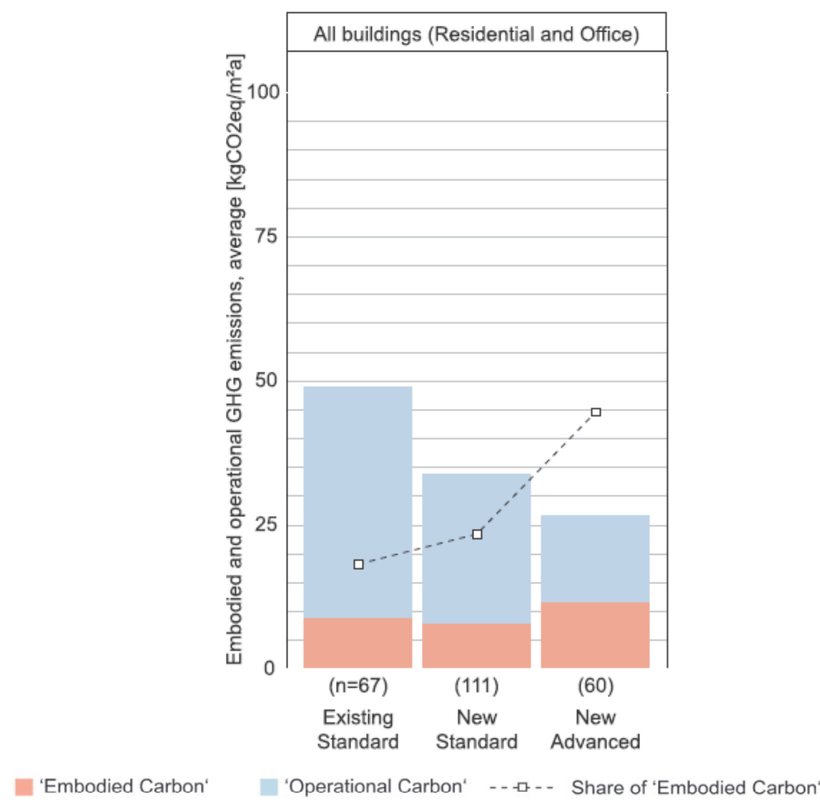
*Greenhouse gases (GHGs), measured in CO_2 equivalents, originally absorbed from the atmosphere through means including biomass growth and/or direct capture (from air or the ocean)

The shift from operational to embodied emissions in buildings



Relevant ARPA-E programs:





Source: *Rock, M. et al., Applied Energy 258, 114107 (2020)*

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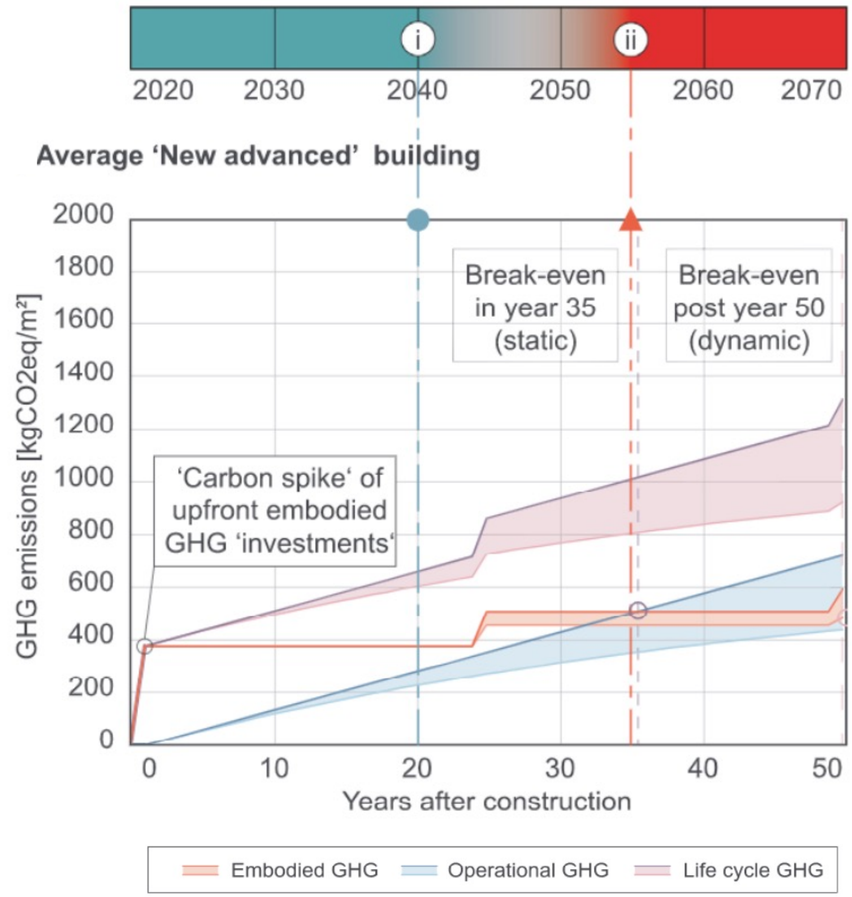
Addressing operational emissions is no longer enough

Today – 2021
United Therapeutics Unisphere, Silver Spring, MD



Source: Rock, M. et al., Applied Energy 258, 114107 (2020).

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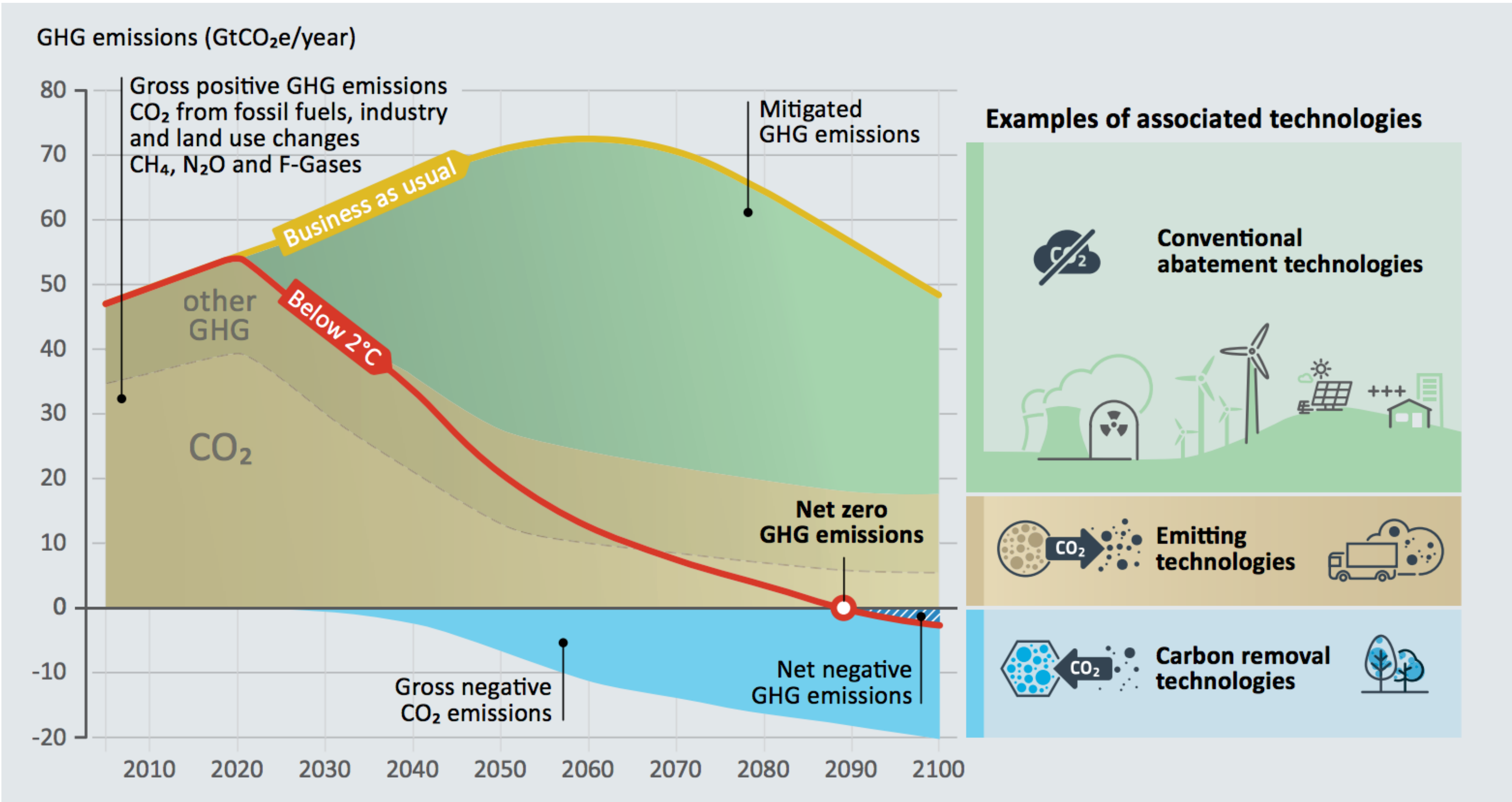
All paths go through zero – emissions avoidance is not enough



National Academy of Sciences. *Negative Emissions Technologies and Reliable Sequestration: A Research Agenda*. 2019. p. 3

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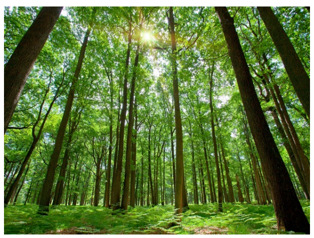
Number of strategies for servicing a negative emissions industry

Biological

Coastal Blue Carbon and Aquatic Systems

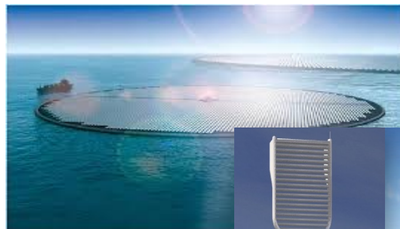


Forest and Land Management

Soil Carbon Sequestration

Soil Amendments & Nutrient Management

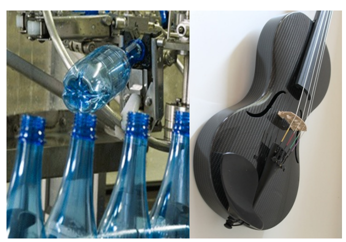
Engineered

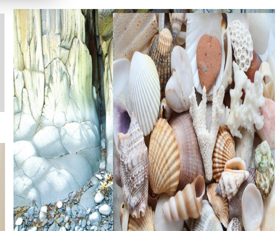


DOC

DAC

Utilized Functional Storage





Enhanced Weathering and Mineralization

Hybrid

HESTIA

New Carbon Buildings

BECCS

Biochar

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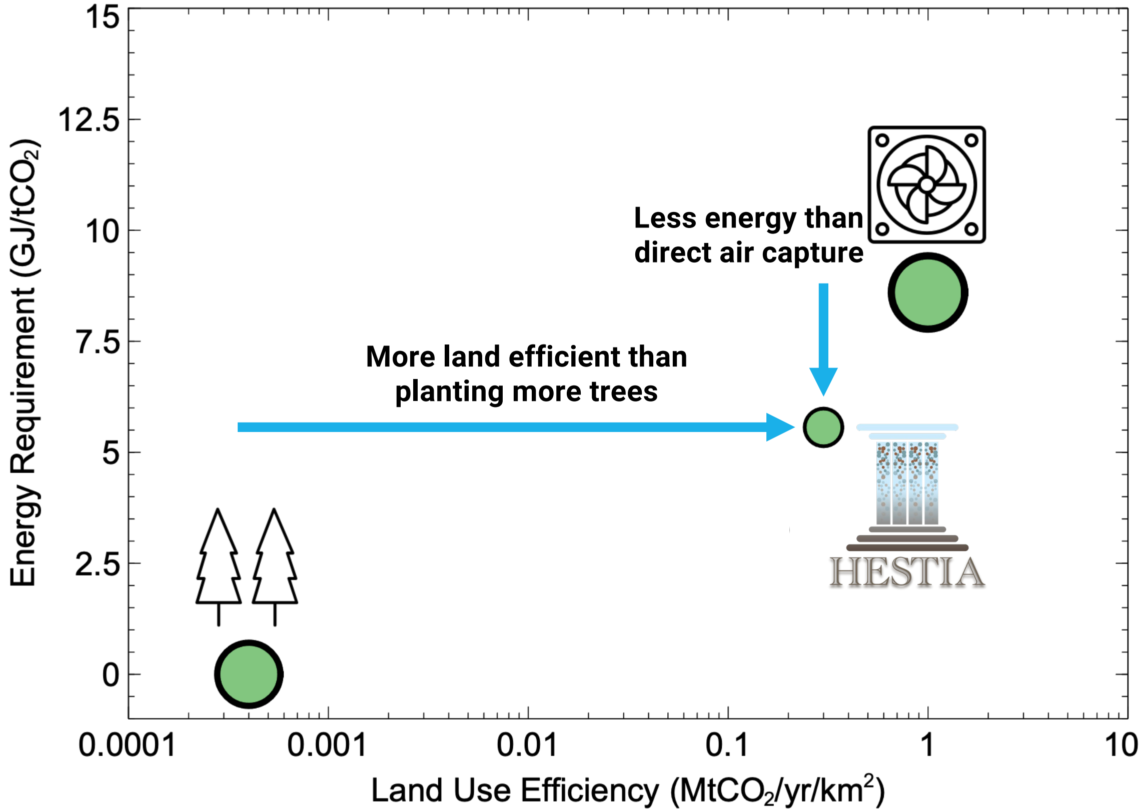
Building materials offer a unique role for durable carbon storage



Data from:
Srubar III, W.V. "Can We Grow Carbon-Storing Buildings?" in *Build Beyond Zero: New Ideas for Carbon-Smart Architecture.* B. King & C. Magwood, Eds. In press; BNEF; carbonplan.org

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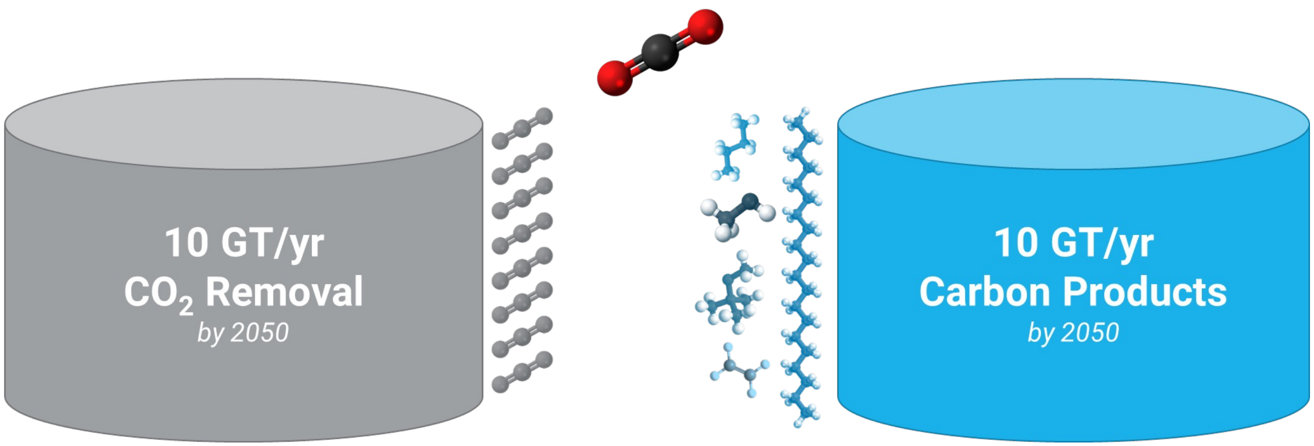
How we value carbon in the built environment matters

<u>Two *new carbon* buckets</u> need to be filled:



- We need removal of GHGs including CO_2
- But we still need and use C-containing products in the marketplace
- Carbon-negative building products can help achieve **both of these goals**

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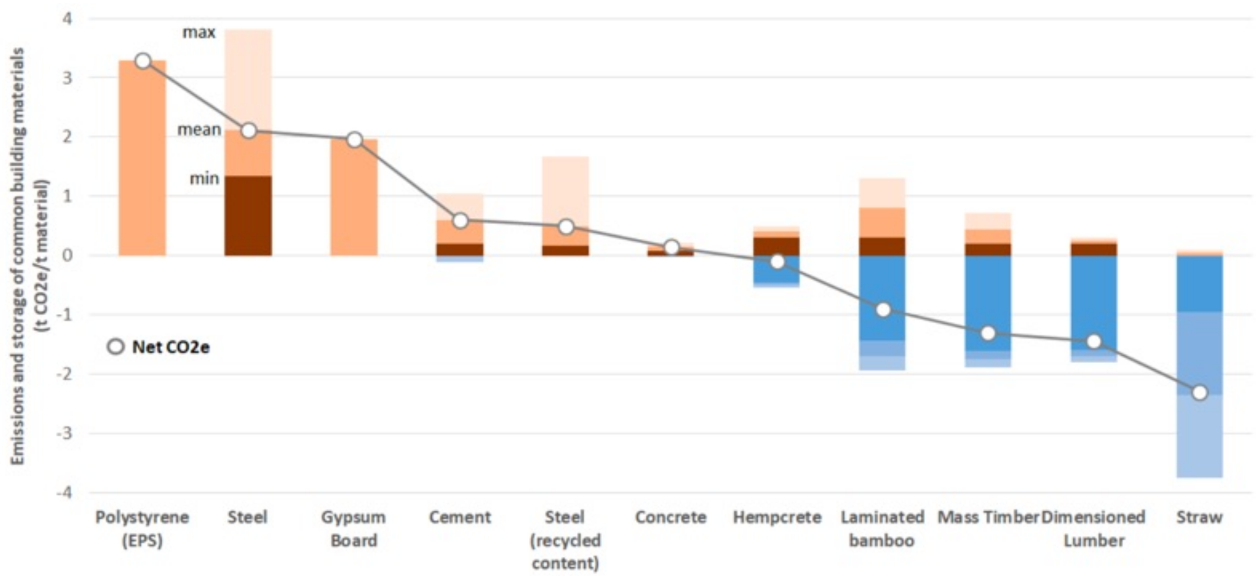
HESTIA seeks to address today's barriers to CO_2-derived building products

- Promising materials are emerging in use, but have limited code-compliant options
- Scarce, expensive, and geographically limited



Data from:
Pomponi,F.andMoncaster,A."ScrutinisingEmbodedCarboninBuildings:TheNextPerformanceGapMade Mainfest, "Renewable and Sustainable Energy Reviews, V. 81(P2), 2431-2442, 2018, DOI: 10.1016/j.rser.2017.06.049.
Ruuska.,"CarbonFootprintforbuildingproducts,"2013,https://cris.vtt.fi/en/publications/carbon-footprint-for- building-products-eco2-data-for-materials-an.

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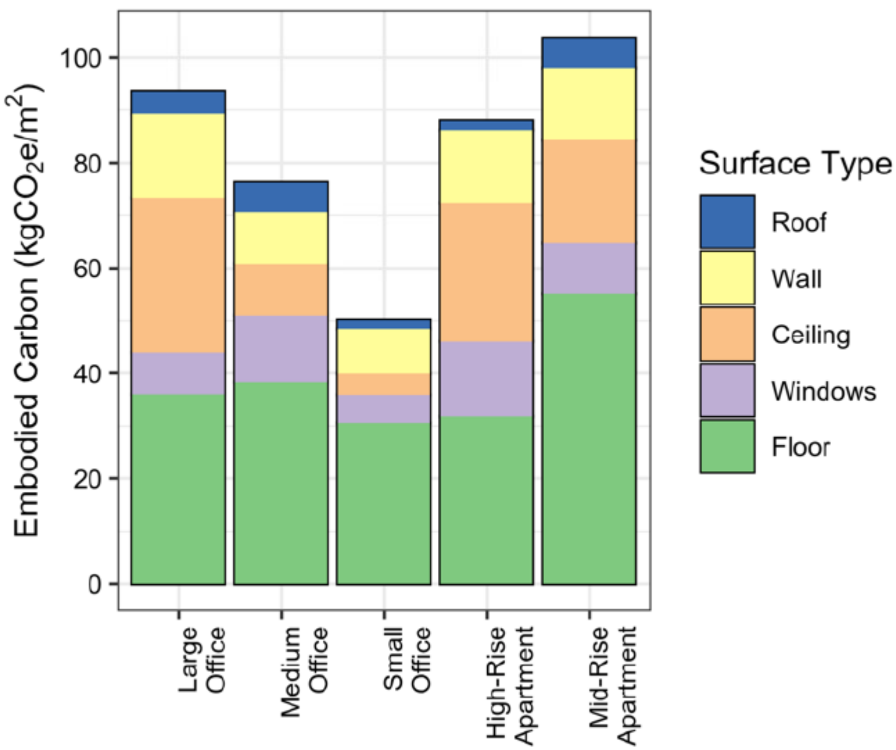
HESTIA is taking an all-of-the-above approach



- Embodied carbon contributions vary by building type
- Good data on embodied carbon is still difficult to find

Source: *Arehart, J. H.; Srubar, W. V.; Pomponi, F.; D'Amico, B. "Embodied Energy and Carbon Emissions of DOE Prototype Buildings from a Life Cycle Perspective" ASHRAE Trans.* ***2020****, 126, VC-20-C002.*

Both timescales are being pursued in HESTIA

Long-term: centuries time scale, including "permanent" storage options

- Mineral materials

Medium-term: "temporary" storage on the order of years to decades.

- Biogenic materials

Sources: *Blue Plant Systems Corp.; CalPlant*

Expansion of bio-based feedstocks intended to:
(1) lengthen time horizon for increasing CDR capacity; and
(2) increase C storage time scale for bio-based waste, residues

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**Short term storage, i.e. immediate use applications such as fuels, is out-of-scope for HESTIA*

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Achieving net-carbon storage cradle-to-grave

- **Target:** Carbon-negative building across entire building lifecycle
  - Includes use, demolition, end-of-life phases
- Based on building design with use of carbon negative material(s)
- Difficult to impossible with today's materials:

Theoretically achievable today or will be without ARPA-E →
- All-electric
- 100-yr lifetime
- Wind electricity only

ARPA-E innovation and targets needed; not achievable today →
- Zero to negative material production/end-of-life emissions
- Carbon negative materials

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OVERVIEW OF LIFE-CYCLE ANALYSIS

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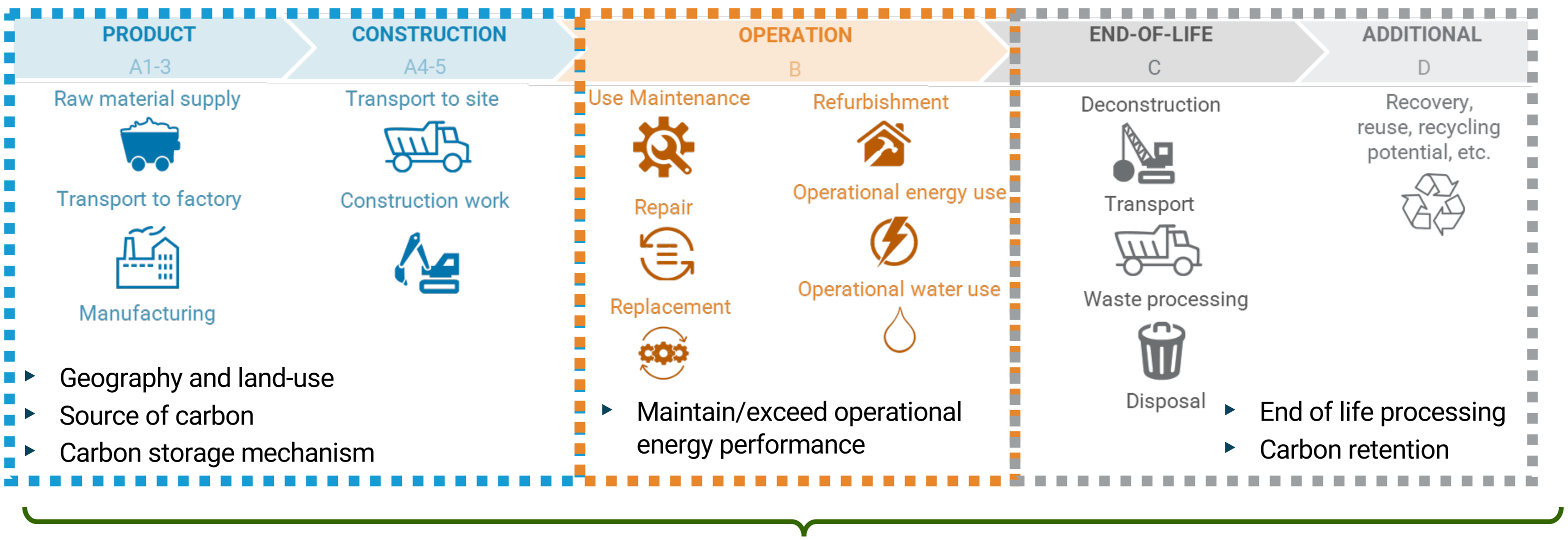
LCA as the method of evaluation for the HESTIA Program



Goal: Quantitative Cradle-to-Grave Analyses

Innovations in LCA for assessing carbon utilization

- **Modeling regional differences in biogenic materials production** (e.g. land use change, regional cultivation practices, etc.)
  - Spatially-explicit LCA models
  - Integrate forestry/land use sustainability metrics into product LCA

- **Tracking emissions/uptake over time**
  - Dynamic LCA (emission year by year) including carbon stored/released over time

- **Life cycle data for novel materials that do not exist in literature/databases**
  - Consider uncertainty
  - Develop new ways to predict LCI based on material properties

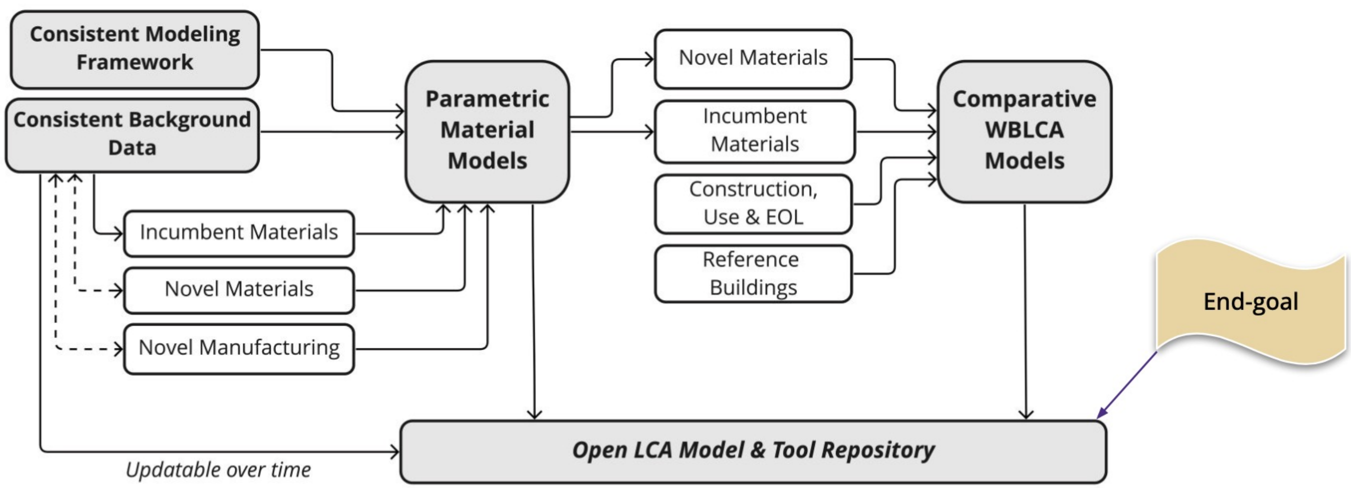
?

CLF Carbon Leadership Forum W UC DAVIS

Final deliverable: open-source LCA tools for use by the Architecture, Engineering, & Construction community

Parametric Open Data for Life Cycle Assessment (POD | LCA)

Goal: To develop a rigorous and parametric Life Cycle Assessment **(LCA) framework, aligned data, and process-integrated tools** in order to quickly and accurately assess the environmental impact of **novel carbon-storing materials** and **innovative building systems** during the rapid prototyping and design process.



ARPA-E Award No. DE-AR0001624: Parametric Open Data for Life Cycle Assessment (POD|LCA)

UNIVERSITY of WASHINGTON

Principal Investigators: Kathrina Simonen, Stephanie Carlisle, Indroneil Ganguly, Tomás Méndez Echenagucia, Chris Meek, Francesca Pierobon

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Overall approach

In this project:

ITERATIVE

- The UW Team will develop the POD|LCA Framework
- The HESTIA Teams will use the Framework to assess their novel products and designs
- The UW Team will collect feedback from the HESTIA Teams to improve and refine the Framework
- Publish open source: Methods, models, data, and tools

The **POD|LCA Framework** is a set of guidance documents, data, and tools that the UW Team is creating to help conduct LCAs of materials and building designs that have carbon-storing materials.

a.k.a. "**LCA Framework**" or "**Framework**"

EXPANSION OF MATERIAL CHOICES

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HESTIA – New Materials Development

HESTIA

Diverse portfolio of feedstocks, conversion routes, materials & finished products

Bio-Based Insulation

NREL – National Renewable Energy Laboratory

Beetle-killed wood → cellulose-mycelium

Aspen Products Group, Inc.

Recycled materials & ag residues → cellulose

UB

Cellulose/straw/hemp/wheat waste & silica aerogels → interlocking superinsulation panel

The University of Tennessee Knoxville

Waste lignin → non-isocyanate based polyurethane foam

New "Wood" & Composites

BAMCORE

Bamboo slats & chips → superinsulation panel

Oregon State University

Small diameter waste wood → wood wool cement composite

Purdue University

Fungi & bacteria → "living" wood structure

SkyNano Technologies

C-fiber waste, C-nanotubes & bamboo → composite

Cement

Wisconsin – University of Wisconsin–Madison

Upcycle industrial mineral waste via DAC → geopolymer cement

NREL – National Renewable Energy Laboratory

SAF production process waste → bio-ash SCM w/ biochar

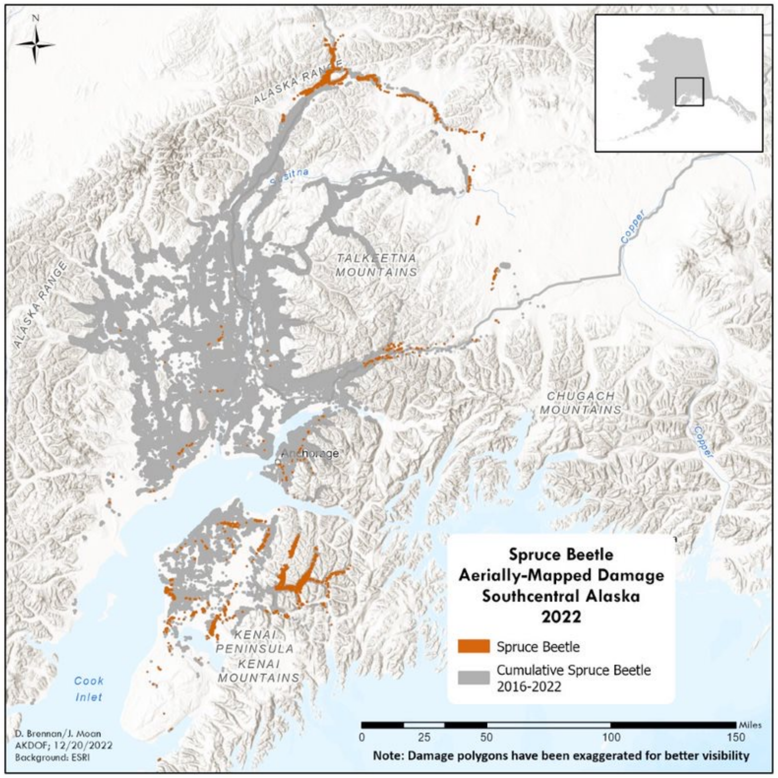
BIOMASON

Biogenic urea → bio-based cement

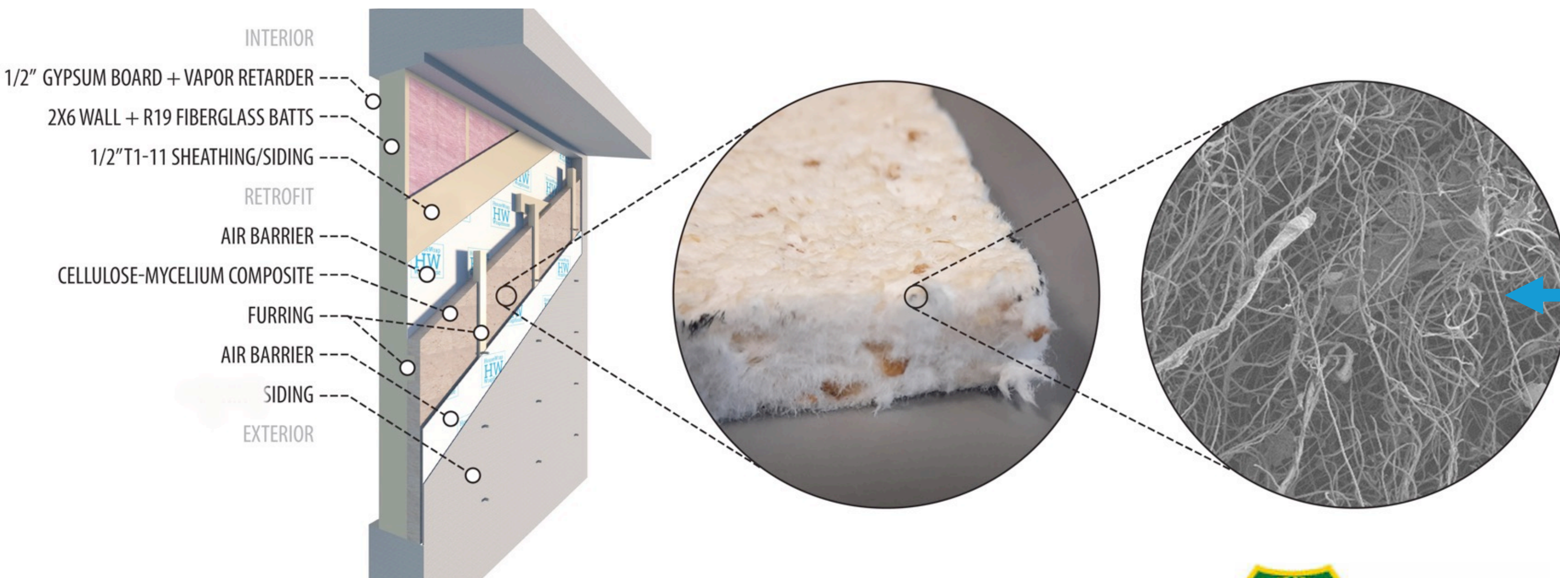
CU

Biogenic limestone ($CaCO_3$) from calcifying microalgae → bio-based portland cement

Using Local Resources to Solve Energy Challenges



NREL Cold Climate Housing Center & University of Alaska Anchorage (Anchorage, AK)



PI: Robbin Garber-Slaght & Philippe Amstislavski

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NREL NATIONAL RENEWABLE ENERGY LABORATORY

UAA UNIVERSITY of ALASKA ANCHORAGE

VTT

Forest Products Laboratory

COLD CLIMATE HOUSING RESEARCH CENTER

Technology to Market Plan

- Target market: Building envelop retrofits in Alaska
- Initial focus: Alaskan building retrofit market, specifically builders in remote Native Alaskan communities.
- Later focus: builders in remote communities in the contiguous US (CZ 4-7).
- Next steps to commercialization: scaling this process *up* out of the lab and then *down* into a mobile fabrication unit.

Photo Credit: M. Rettig, CCHRC

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C-Neg. Concrete Via Low-Value Byproducts From Biofuels Production

Objective: Reduce embodied CO_2 in construction and building materials by developing a carbon-negative, thermally insulating, and high strength 'LignoCrete' product

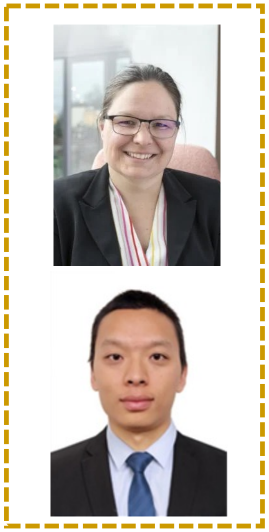
Project Team:

- **NREL** (PI: Mike Griffin, Technical Lead: Ana Aday)
- **Carbon Upcycling** (Co-PI: Apoorv Sinha)
- **CU Boulder** (Co-PI: Mija Hubler)

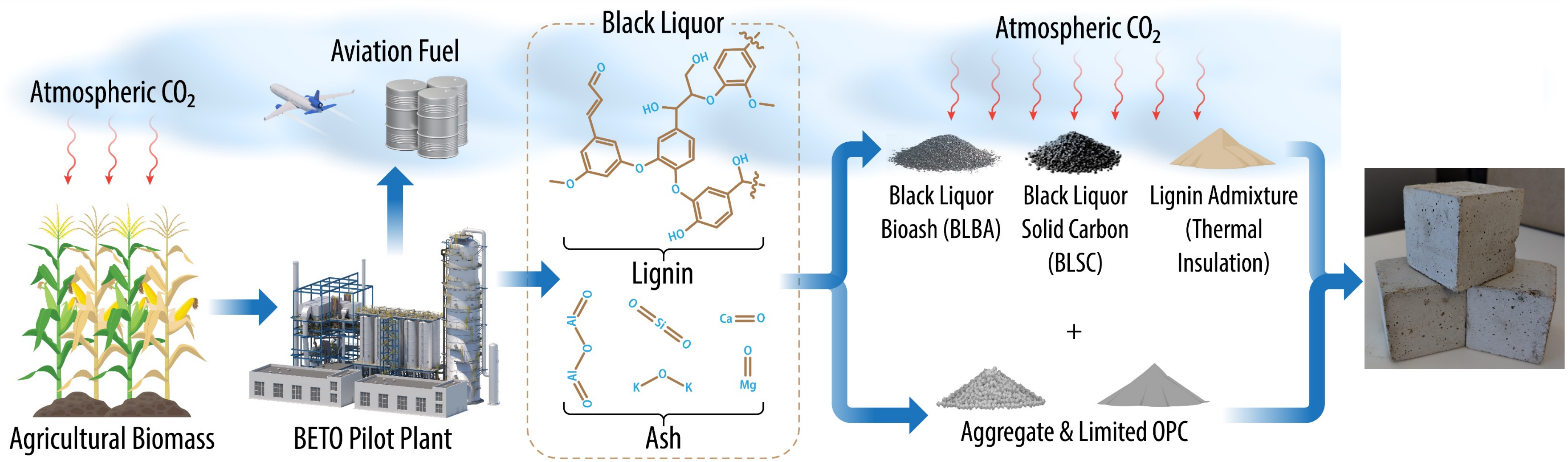
NREL
NATIONAL RENEWABLE ENERGY LABORATORY

carbon upcycling

University of Colorado Boulder



Technology Overview



Research Thrusts:

- Upcycling waste streams to produce supplementary cementitious materials (SCMs)
- Incorporation of atmospheric CO_2 using technology developed by Carbon Upcycling Technologies
- Performance and durability testing of mortar and concrete mixtures

BamCore: Next Generation Bio-based Framing Materials

Carbon-Storing Building Frames

1.

Carbon Sequestering Structural Fibers

Timber Bamboo & Eucalyptus

2.

Performance Tested Load Bearing Panels

Biogenic Carbon Offsets Embodied Carbon

3.

Code Compliant Low-Rise Wall Assemblies

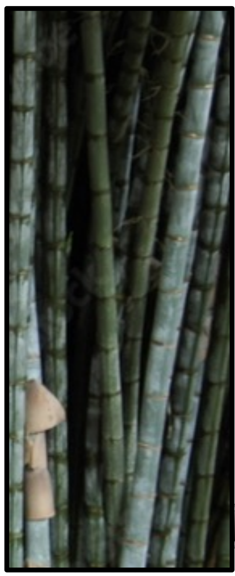
High Thermal Insulation Values

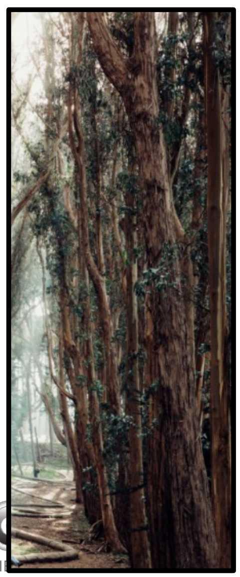
4.

Fast Install & Durable Frame Keeps Carbon In Buildings for Generations

Possible Re-use

PI: Nich Allan





Bamcore: Recent Success Story

Prime Wall product used in 5-unit 17,500 SF townhome in Utah.

First floor external framing completed in under 4 hours.

WHOLE-BUILDING DESIGN CASE STUDIES

HESTIA – Whole-Building Designs

HESTIA

Maximizing carbon utilization potential via new building designs

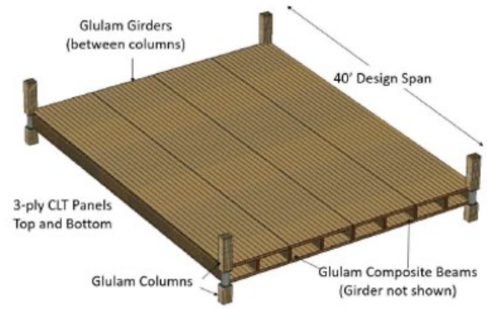
Residential

Pacific Northwest NATIONAL LABORATORY

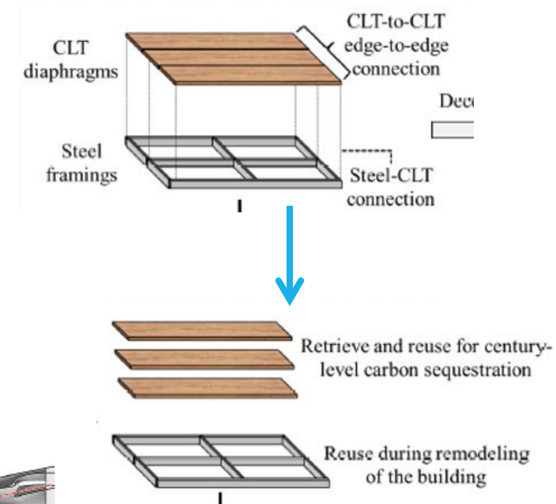
ATM

Commercial

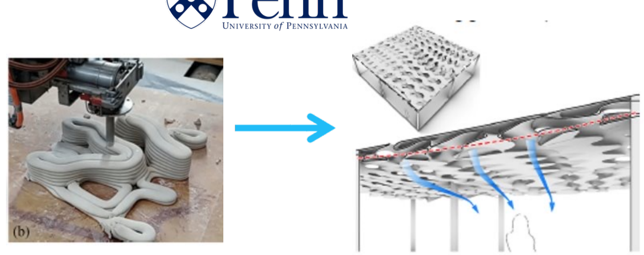
CLEMSON



Northeastern



Penn UNIVERSITY of PENNSYLVANIA

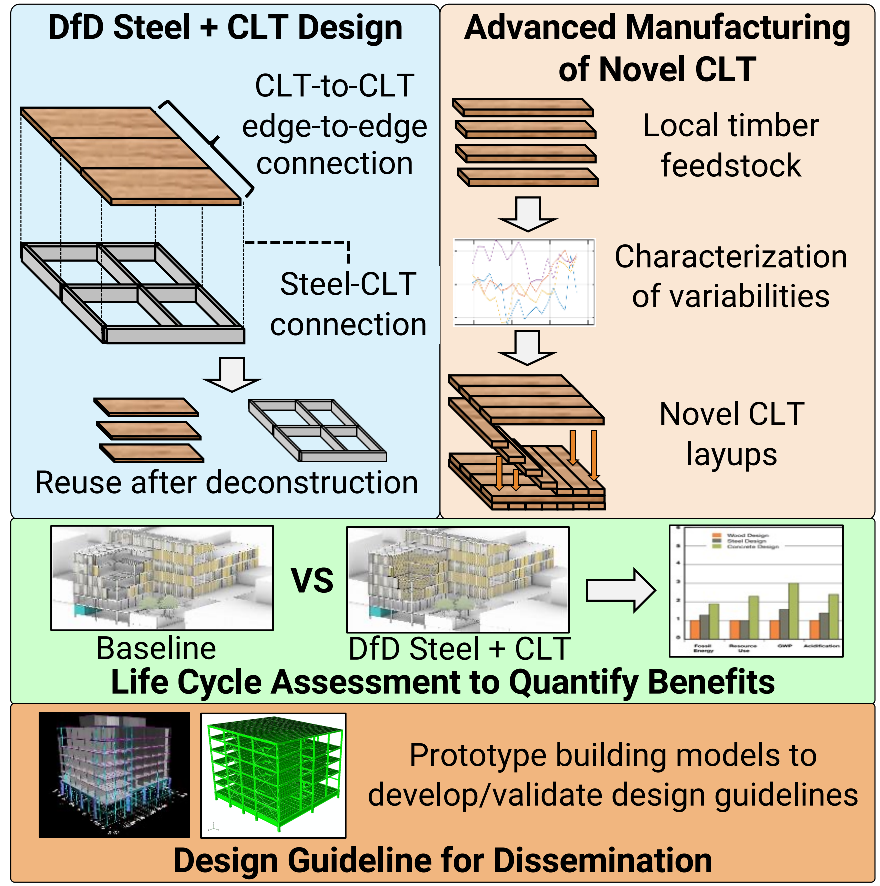


4C2B: Century-scale Carbon-sequestration in Cross-laminated Timber Composite Bolted-steel Buildings

- Develop and test steel+CLT hybrid building designs to store biogenic carbon
- Leverage current AEC steel-focused ecosystem for rapid market penetration

- **Innovations**
  - Design for deconstruction (DfD) and CLT reuse via novel connectors to reach century-scale carbon storage
  - Novel CLT layups minimizing carbon footprint and utilizing regional biomass resources
  - Use of short-cycle agricultural products into assemblies

- **Deliverables**
  - LCA results showing the value of the proposed works
  - Standards-based design guidelines of DfD Steel+CLT



Principal Investigators: Jerome F. Hajjar, Matthew J. Eckelman, Michelle Laboy

Circular Home

DEVELOPMENT AND DEMONSTRATION OF A NET-NEGATIVE-CARBON, REUSABLE RESIDENCE

PI: **Chrissi Antonopoulos, PNNL**

Offsite modular construction
- Fast Production
- High Quality
- Minimal Waste

Optimized for:
- Sustainability
- Resilience
- Durability
- Life-stages
- Adaptability
- Long use-life

Low embodied carbon and net zero operational carbon
- Plant-based products
- Minimal plastic and concrete
- Climate-tuned envelope
- Efficient equipment
- All-electric systems
- On-site renewables

Value retention for Iterative reuse
- Modules
- Sub-assemblies
- Components
- Materials

Non-destructive connectors add value by improving
- Building Performance
- Fabrication speed
- Ease of assembly/disassembly

Green Canopy NODE:
Darrin Griechen, Sadie Carlson

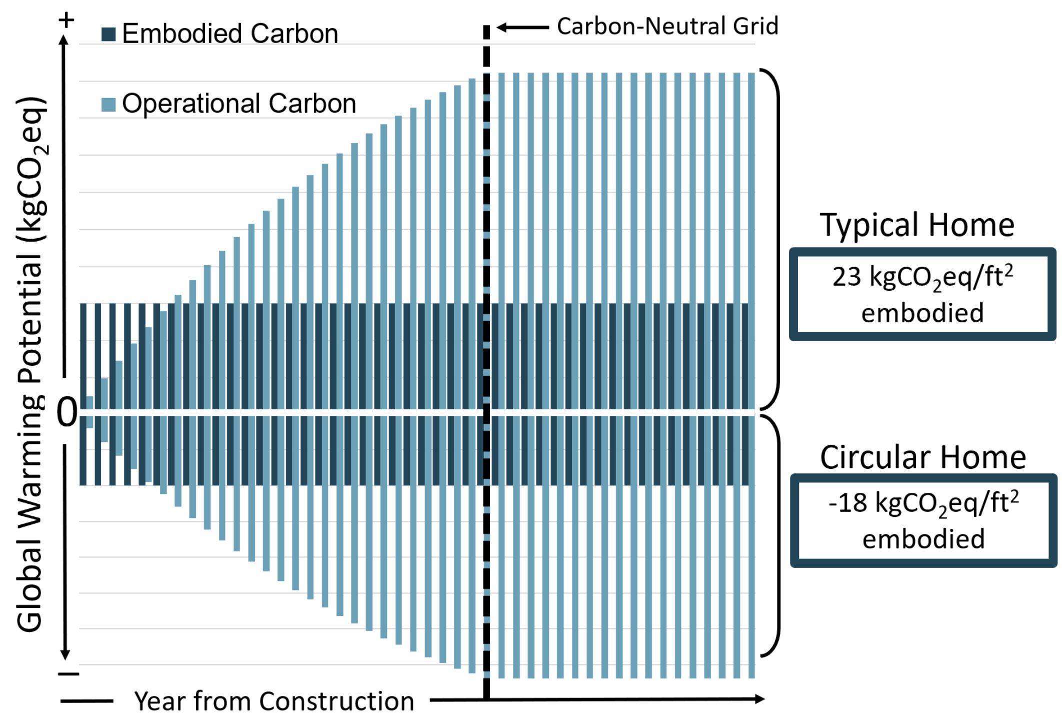
Washington State University:
Adam Phillips, Aivars Vilguts,
Karl Englund, Ji Yun Lee

Pacific Northwest National Laboratory:
Chrissi Antonopoulos, Patti Gunderson,
Kieren McCord, Luke Troup, Edwa Yun Joon Jung
Yan Chen, Tyler Pilet, Brittany Tarufelli

Additional Project Partners:
Mercer Mass Timber, Simpson Strong-Tie,
Building Deconstruction Institute, Timber HP.

Project Impact – Technical Approach

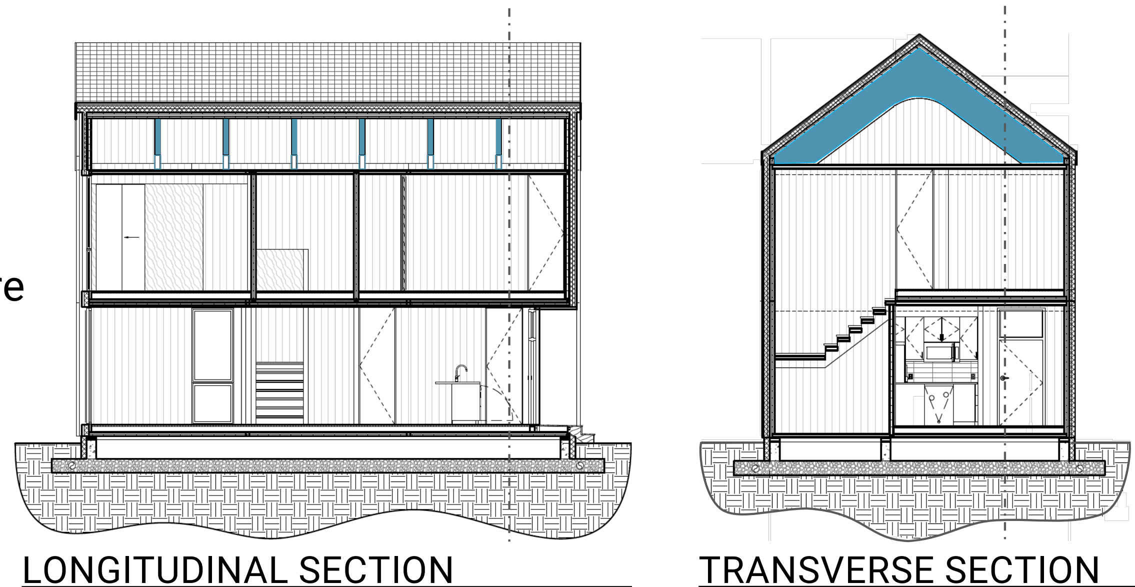
- Develop prototype design parameters.
- Structural testing for module and between module connections.
- Simulation studies for energy and moisture performance in all climate zones.
- Simulation study for seismic performance.
- Lifecycle and Technoeconomic Analysis.
- Constructability and code compliance assessment.

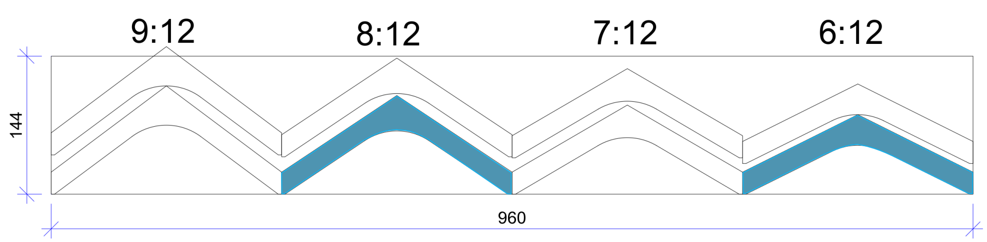


Recent Successes – Design & Structure

Innovative CLT Roof Arch:

- Leverages manufacturing plant capabilities to quickly cut an arch profile.
- Optimize geometry in FEM software to fit arches into one CLT billet for cost and material efficiency.
- Designed for high snow load.
- Streamlines supply chain and speed of construction.
- Prototype to be tested at Virginia Tech.





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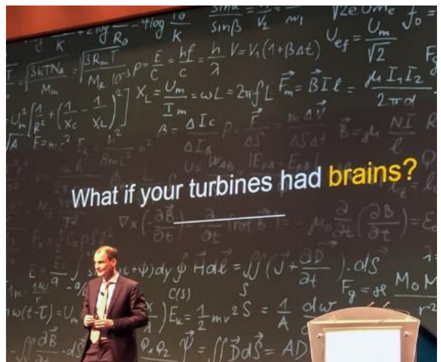
arpa·e energy innovation summit

Highly Selective Technology Showcase



Inspiring Keynotes

Unparalleled Networking

Fast-Paced Technology Pitches

arpae-summit.com

May 22-24, 2024 | Dallas, Texas

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The ARPA-E HESTIA Team

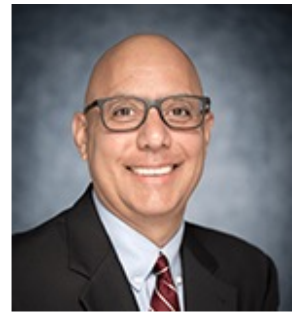
Program Director:

Marina Sofos

10/13/23

Laurent Pilon

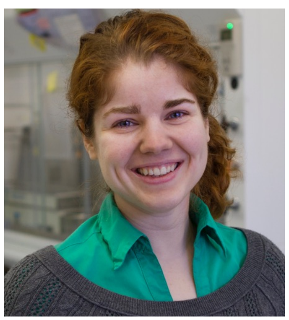
Commercialization Advisor:



Ken Pulido

Technical Advisors:

Daniel Garcia



Kate Pitman

Kalena Stovall

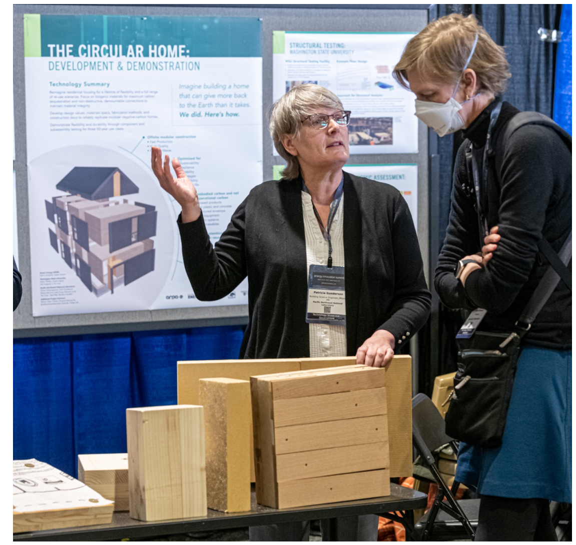
Programmatic Support:

Whitney White

Mike Connolly

CHANGING WHAT'S POSSIBLE

Thank you!



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