A Vision for Decarbonizing Building HVAC Operations via Co-Designed Modular Direct Air Capture Systems

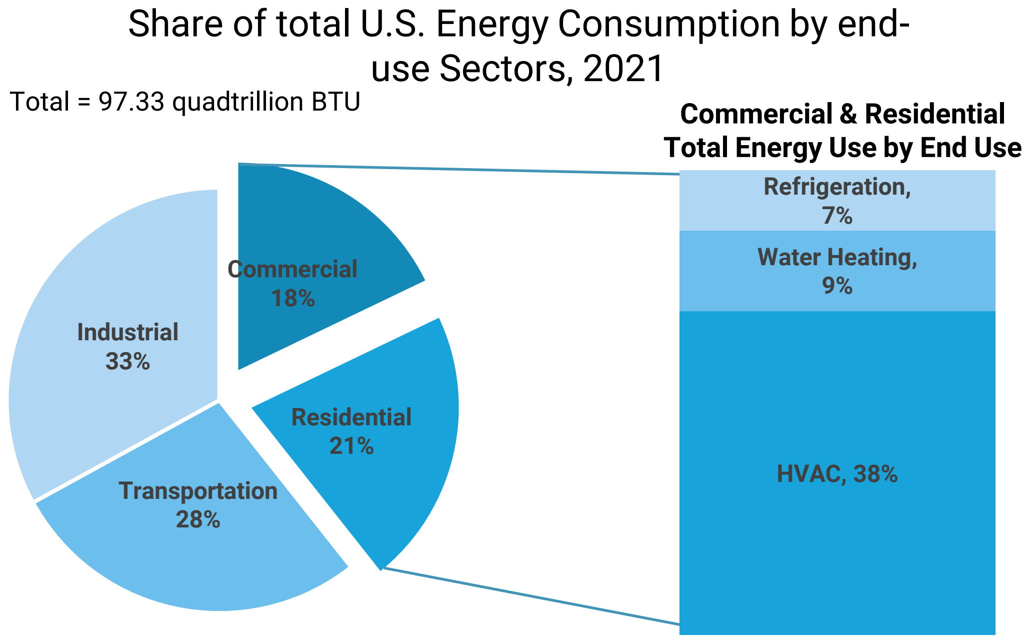
Marina Sofos, Ph.D.
Program Director @ ARPA-E

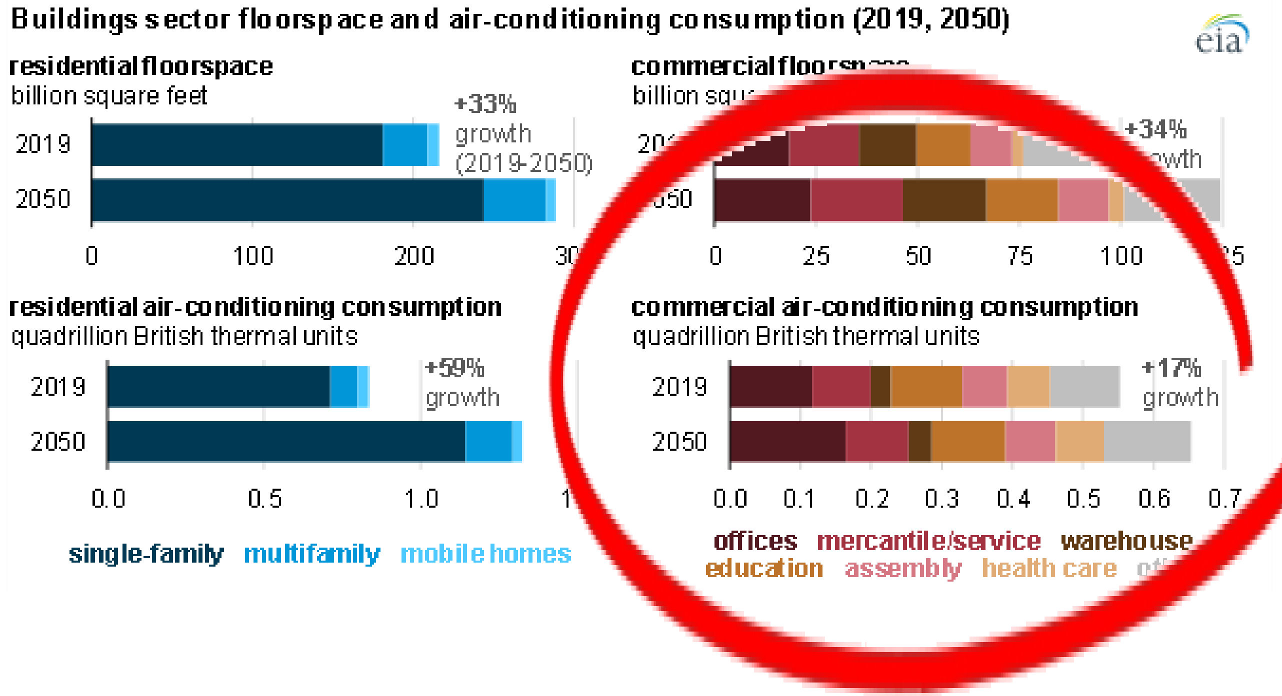
ARPA-E Workshop - Day 1

February 27, 2023

Improving commercial HVAC efficiency can have a big impact

HVAC systems are responsible for the largest category of end-use energy consumption in buildings





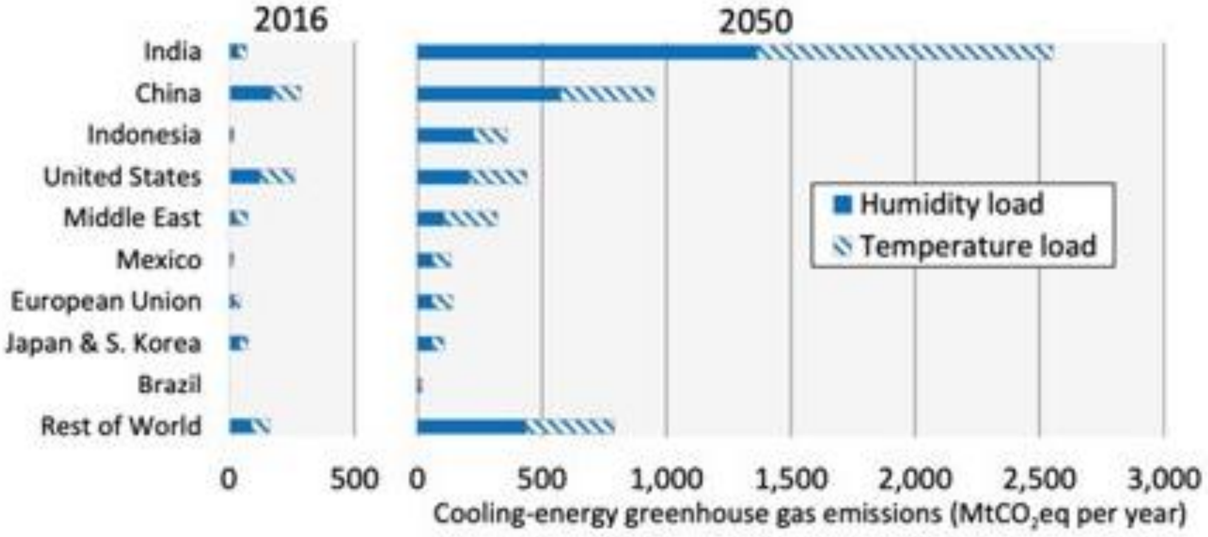
Even with continual efficiency improvements, overall AC usage is rising due to increased demand

arpa·e CHANGING WHAT'S POSSIBLE

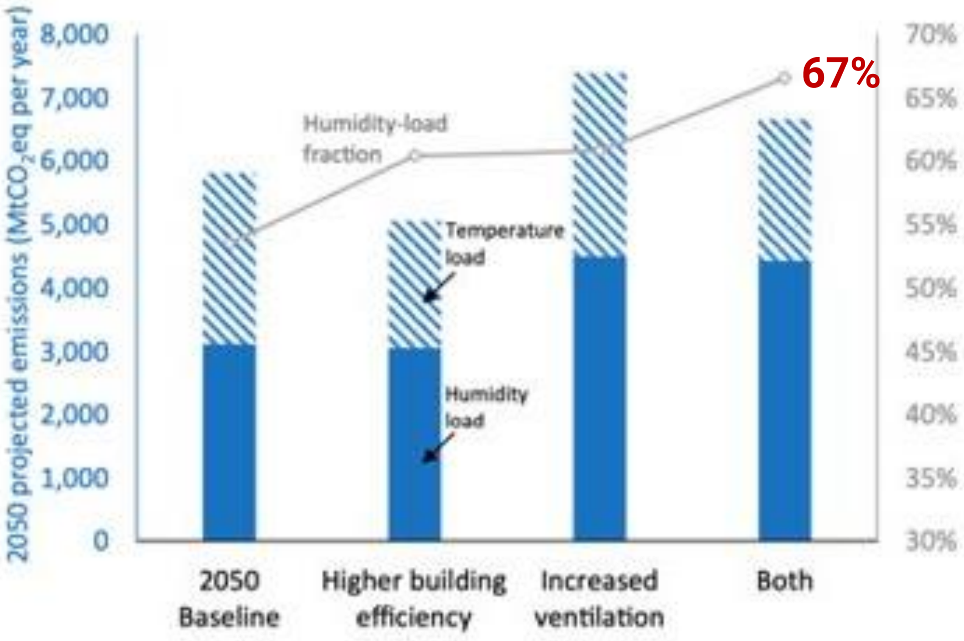
Sources: EIA Annual Energy Outlook 2022; "EIA Projects Air-Conditioning Energy Use to Grow Faster than Any Other Use in Buildings." U.S. Energy Information Administration.

The contribution from dehumidification is rising

- Humidity loads – 600 $MtCO_2eq$ or 1/3 of annual HVAC emissions & growing



Annual emissions from cooling energy – Humidity load emissions 5x greater by 2050



Fraction of cooling-related emissions from humidity likely to increase due to trends in building efficiency & ventilation requirements

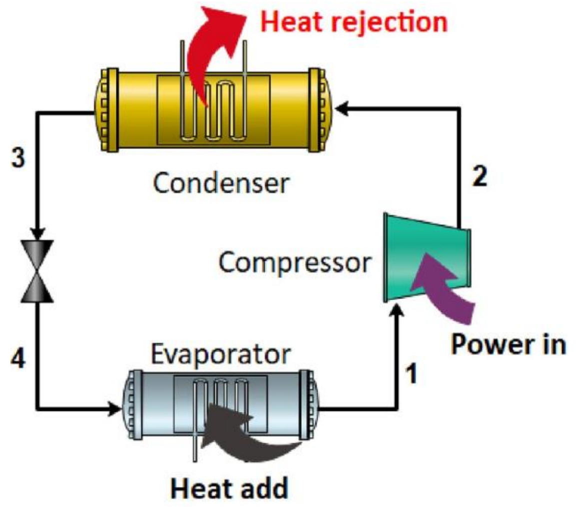
CHANGING WHAT'S POSSIBLE

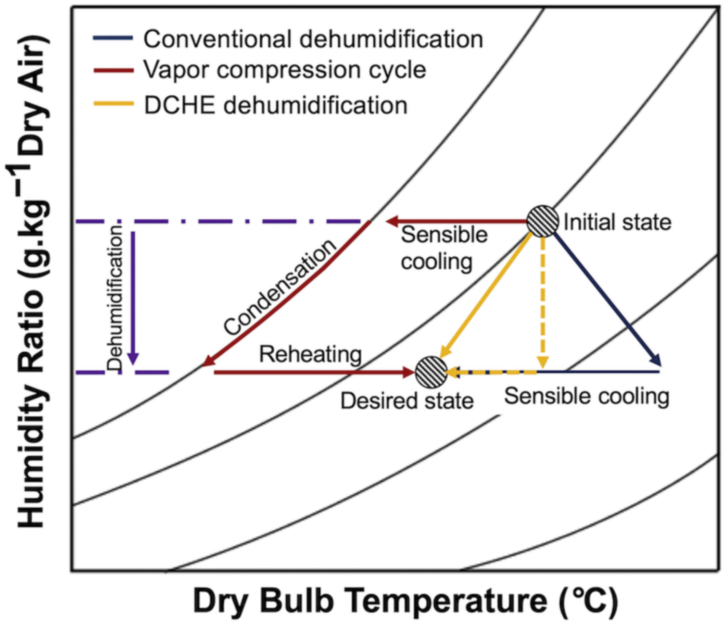
Source: Rivest et al., Joule 6, 726-741, 2022

Conventional systems "overcool" to remove humidity

Controlling Moisture in Ventilation Air:

- Conventional vapor compression refrigeration cycles make up to **99% of space cooling systems**
- Cool process air below its dew point T to dehumidify the air and typically reheat to desired T
- Energy intensive & inefficient process due to large latent load and additional load due to reheating of the air
- Latent load takes up to **76% of total energy load required to condition a space**

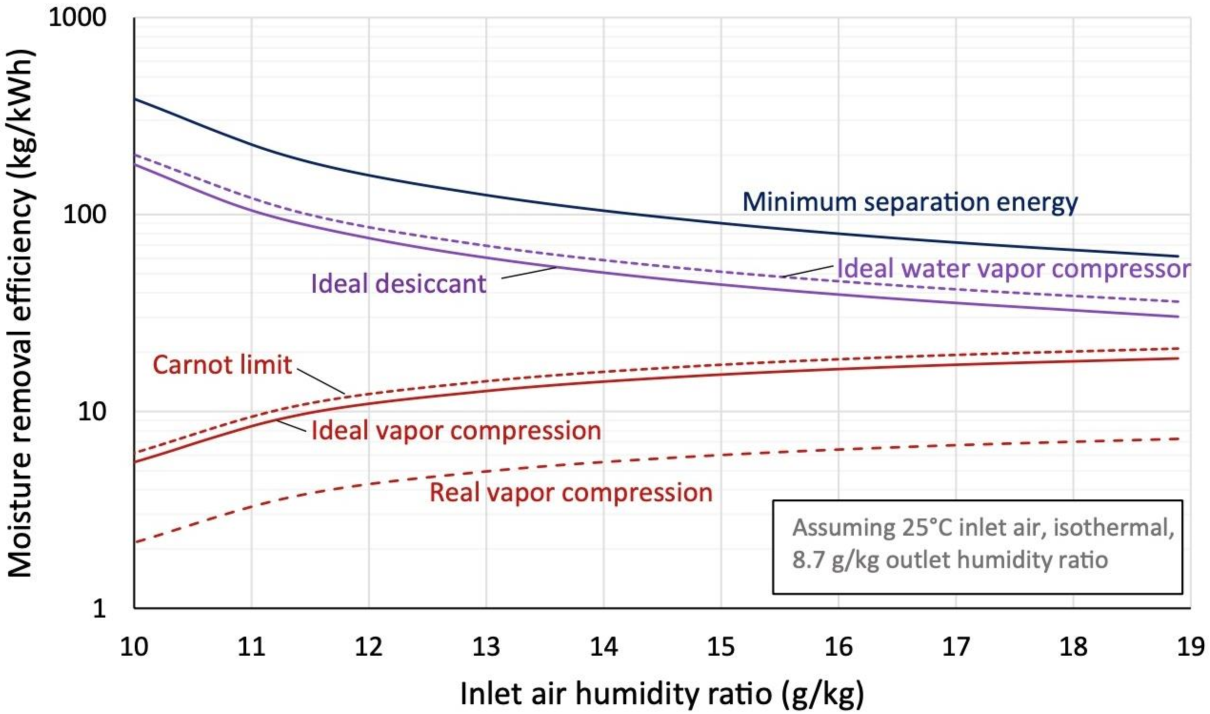




Sources: Goetzler W, Zogg R, Young J, Johnson C. Alternatives to vapor-compression HVAC technology. Ashrae Journal. 2014 Oct 1;56(10):12.; O.M. Zaki, R.H. Mohammed, O. Abdelaziz, Energy Conversion and Management 256 (2022) 115380.; J.D. Batukray, Zenodo (2019).

10x moisture removal efficiency improvement w/ new separation processes

Temperature loads – Improved cooling efficiency can also be expected

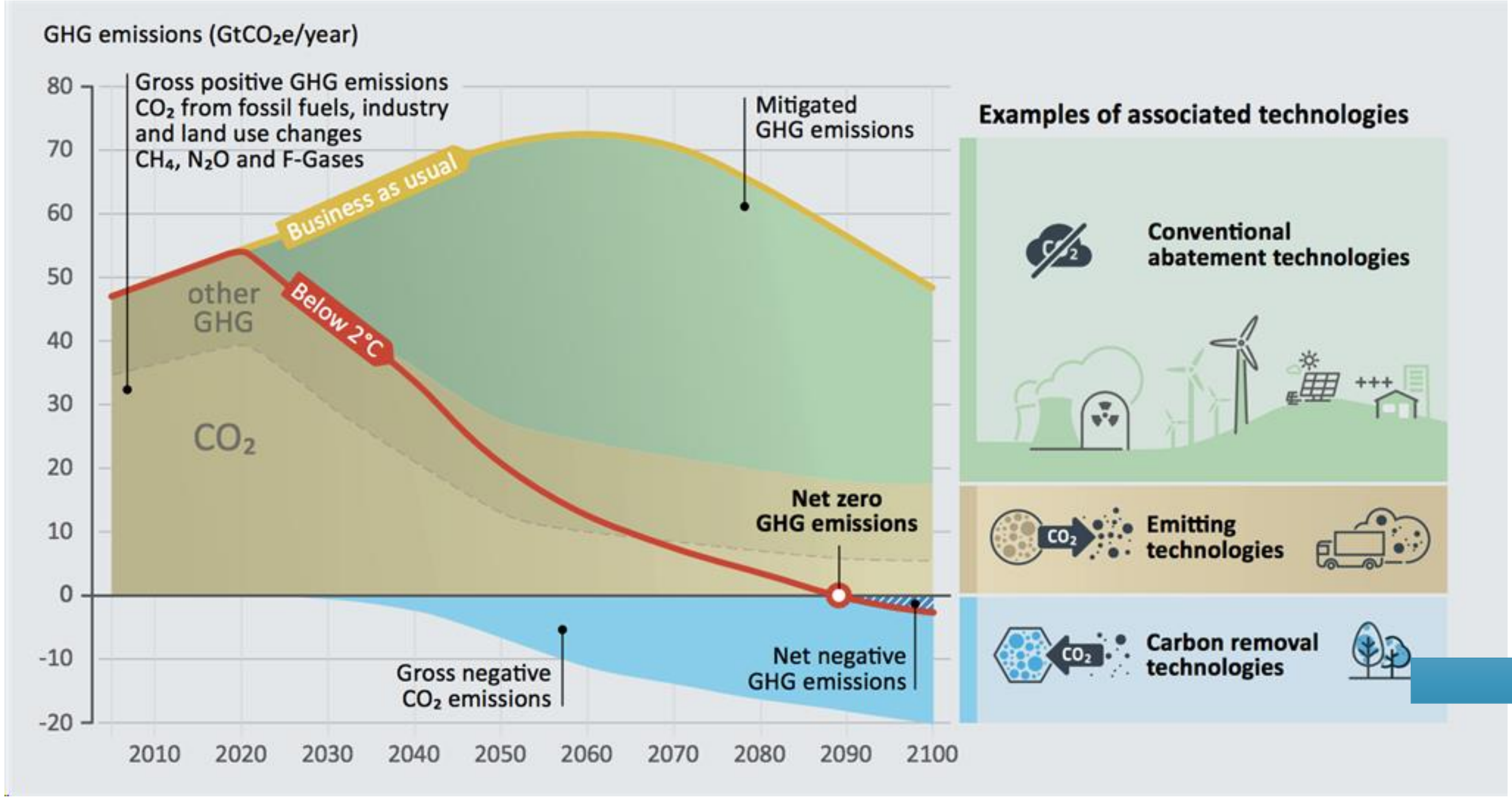


Sources: S. Garimella, K. Lockyear, D. Pharis, O. El Chawa, M.T. Hughes, G. Kini, Joule 6 (2022) 956–971.

CHANGING WHAT'S POSSIBLE

Expanding Carbon Utilization Approaches

Gton Carbon Removal Capacity Will be Necessary



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

arpa·e
CHANGING WHAT'S POSSIBLE

Opportunity for Buildings?

Number of strategies for servicing a negative emissions industry

Biological

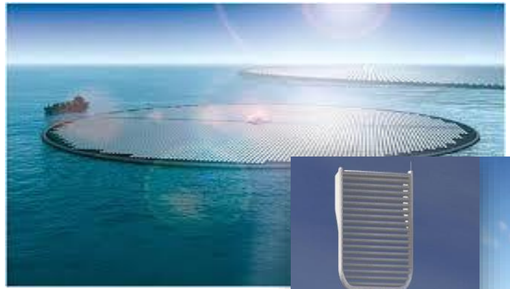
Coastal Blue Carbon and Aquatic Systems

Forest and Land Management

Soil Carbon Sequestration

Soil Amendments & Nutrient Management

Engineered



DOC

DAC

Utilized Functional Storage

Enhanced Weathering and Mineralization

Hybrid

New Carbon Buildings

BECCS

Biochar

Energy requirements for DAC need to be considered

Climeworks DAC (1 module)	
Face area	20 m^2
(Vol) Flow rate	2.86 m^3/s
Face velocity	0.183 m/s
Capture rate	~130 kg/day
Capture efficiency (est.)	70%
Fan and system energy	300 kWh/tCO_2
Regeneration energy	2000 kWh/tCO_2
Compression energy (est.)	100 kWh/tCO_2
DAC pressure (est.)	~300 Pa
Total energy	2400 kWh/tCO_2

Climeworks

*Assuming running 24 hours per day and system efficiency of ~50%

$$\text{Power (W)} = \frac{\text{flow rate}\left(\frac{\mathrm{m}^3}{\mathrm{s}}\right) \cdot \boldsymbol{\Delta P}(\mathbf{Pa})}{\eta_{\text{fan}}}$$

In 2021, the average annual electricity consumption for a U.S. residential utility customer was 10,632 kWh, an average of about 886 kWh per month.

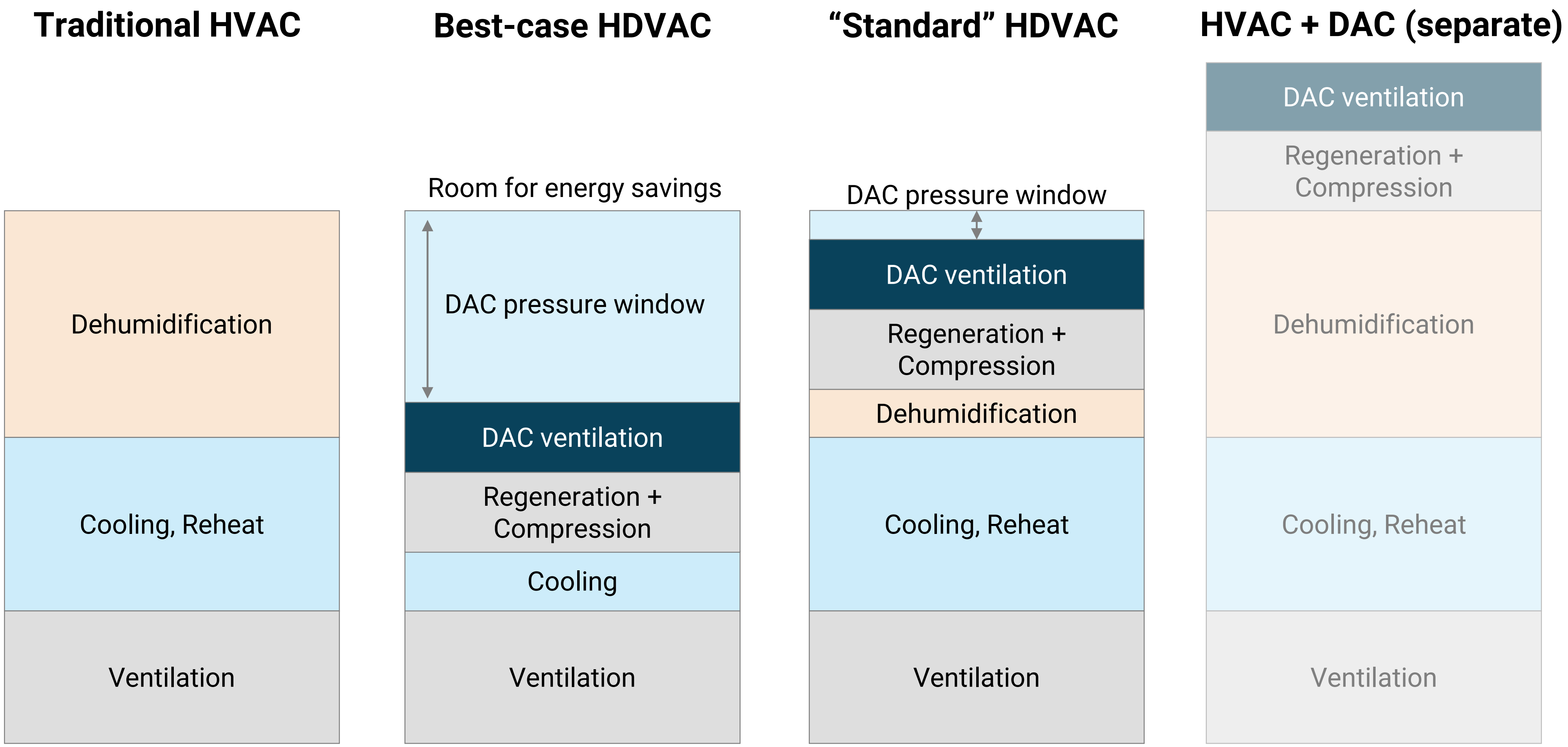
Workshop Vision

Transform our buildings HVAC operations:

- *lower energy requirements for small, modular DAC*
- *expand SSL approaches & improve energy performance of HVAC systems*

CHANGING WHAT'S POSSIBLE

Starting framework



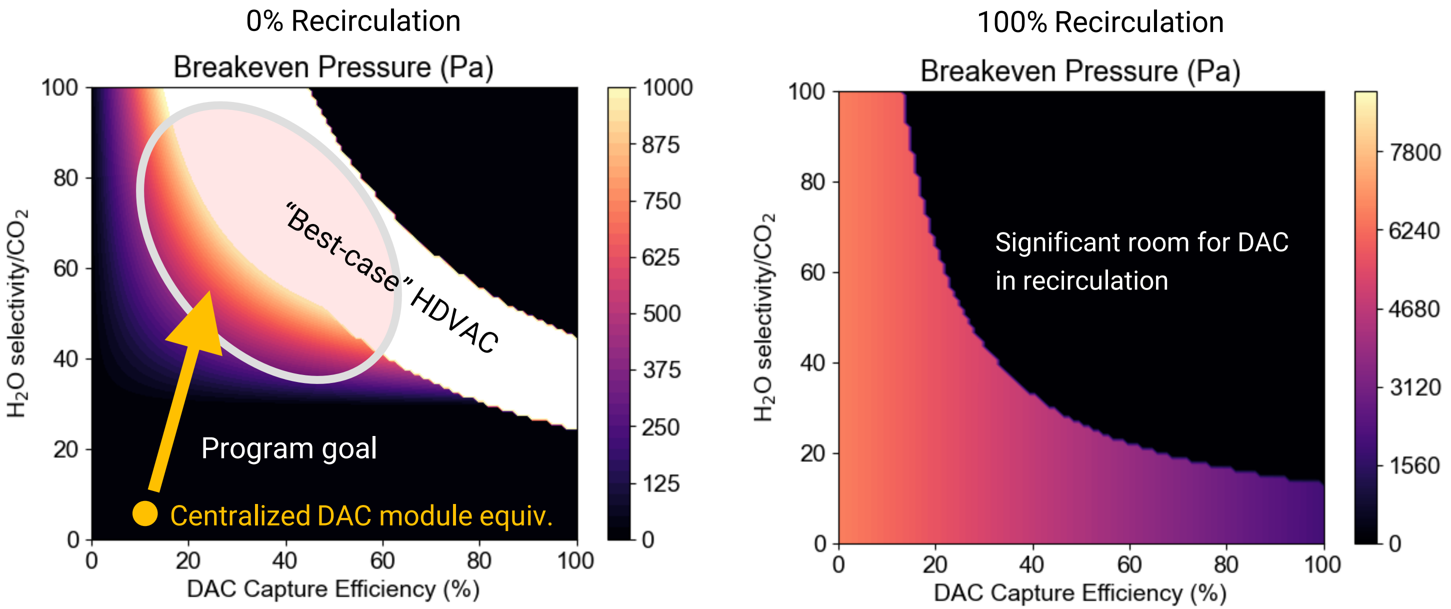
Proposed HDVAC Target

Objective	Category	Target
System efficiency ($kW_{HDVAC}/kW_{HVAC\text{-}intake}$)	Energy usage	0.5

$HVAC_{intake}$ (kW) = Dehumidification + Cooling + (Reheat) + Ventilation

HDVAC (kW) = Cooling (↓) + Total ventilation (↑) + DAC energies

Comparing HDVAC to HVAC cooling outside air (power not energy)



* Starting conditions of 26°C/70% RH to 20°C/20-55% RH

CHANGING WHAT'S POSSIBLE

Developing Potential Program Metrics

- **Objectives:**
  - Strike balance between achieving **capture efficiency & overall system performance**
  - Employ relevant metrics for **tomorrow's HVAC systems**
  - Consider **path to market** (residential vs. commercial, new construction vs. retrofit)
- **Challenges:**
  - Performance requirements are **building-type, climate-zone specific**
  - Adoption dependent on **installation and maintenance**
  - Maintenance of acceptable/improved **indoor air quality**

Developing Potential Metrics

Objective	Category	Target
Indoor air quality (CO_2) (during occupancy)	Health	< 600 ppm CO_2
Indoor air quality (TVOC) (during occupancy)	Health	< 0.3 mg/m^3
System efficiency ($kW_{HDVAC}/kW_{HVAC\text{-}intake}$)	Energy usage	0.5
DAC quality factor (−ln(penetration)/ΔP) *e.g.*, 70% DAC @ 1 kPa = −ln(0.3)/1 = 1.2	CO_2 capture	> 6 kPa^{-1}
CO_2 capture rate (metric tons/year)	CO_2 capture	> 1.5 × AC tons (mt/year)
Sorbent useful lifetime ($kg_{CO2}/kg_{sorbent}$)	Maintenance	1000
Manual service (Sorbent change, CO_2 collection, filters, *etc.*)	Maintenance	< 3× per year
Form factor increase ($FF_{HDVAC}/FF_{Original\text{-}HVAC}$)	Engineering limits	1.2
Payback (HVAC savings only, no carbon credit)	Capital	< 2 years

arpa·e
CHANGING WHAT'S POSSIBLE

Identifying viable pathways for carbon utilization

Life-cycle and cost implications need to be considered:

- On-site vs. off-site use?
- Storage, transportation and associated logistics?
- Potential on-site uses?

Path to Market: Efficiency Standards & Test Procedures

eeCompass

YOUR GUIDE TO APPLIANCE ENERGY CONSERVATION

Appliance and Equipment Standards Program

The Appliance and Equipment Standards Program's 3-part Mission is to:

While Important, Not in Scope for This Potential Effort

- Development/expansion of **carbon markets**
- Updates to/adoption of current/future **HVAC system efficiency standards**
- Development of new **testing specifications**
- Innovations in **manufacturing methods and practices**
- Adoption of new **carbon utilization infrastructure and policies**

First Breakout Sessions: System Design

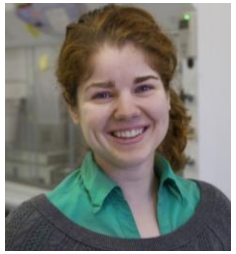
Intake

Facilitator:
Peter
Debock

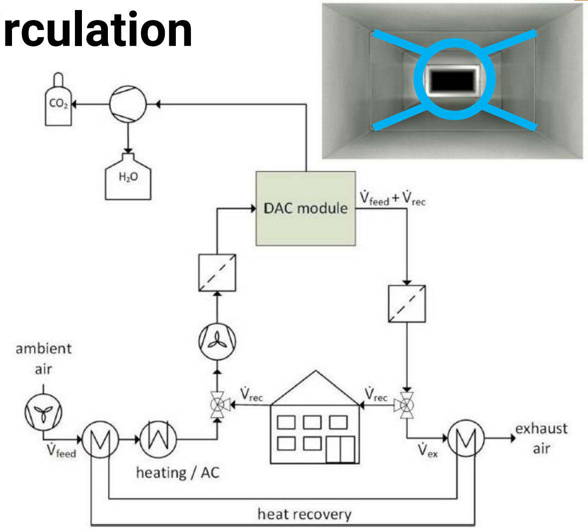
Notetaker:
Daniel
Garcia

Recirculation

Facilitator:
Laurent
Pilon



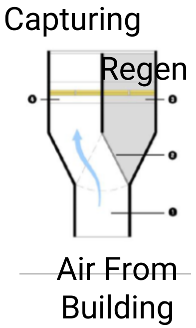
Notetaker:
Kate
Pitman

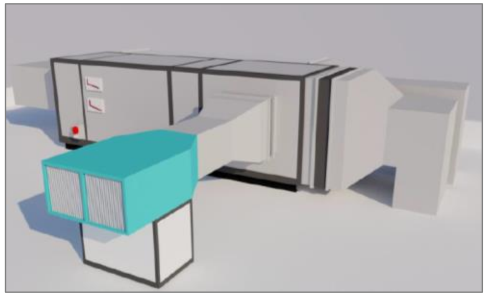


Exhaust Air

Facilitator:
Tony
Bouza

Notetaker:
Sade
Ruffin

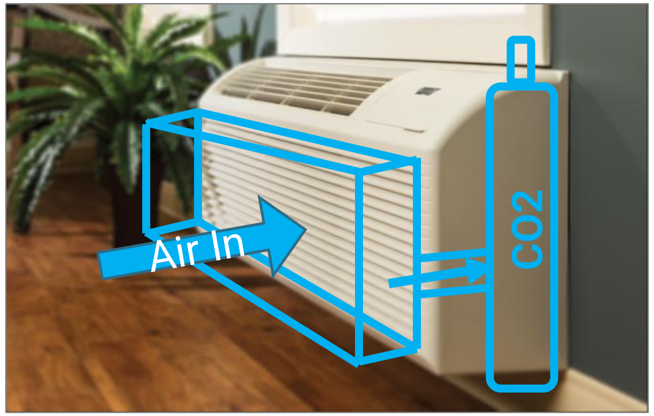




Modular

Facilitator:
Jenifer
Shafer

Notetaker:
Kalena
Stovall



Second Breakout Sessions: Metrics

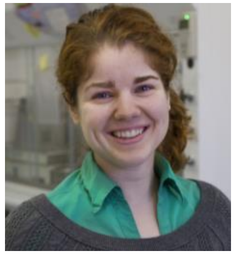
System Configuration

Facilitator:
Peter
Debock

Notetaker:
Daniel
Garcia

Climate Zone

Facilitator:
Laurent
Pilon



Notetaker:
Kate
Pitman

Installation & Maintenance

Facilitator:
Tony
Bouza

Notetaker:
Sade
Ruffin

Building Type

Facilitator:
Jenifer
Shafer

Notetaker:
Kalena
Stovall

What We Want from You Today and Tomorrow

- **Shape potential program structure:**
  - Establish the **most impactful categorization** to achieve both emission reduction & carbon removal goals
  - Identify any **critical technologies/pathways** that are missing
  - Prioritize **key metrics** that are ambitious, yet achievable for success (R&D needs)

- **Stakeholder Outreach:**
  - Spread the word for potential interest in this area!
  - Identify critical expertise not currently on our radar

- **Networking/Team Building:**
  - Facilitate connections across the technology development pipeline for potential project teaming

Be bold and think big!

Rest of Day 1 Agenda – Objective: Establishing a Framework

9:20 – 10:05 AM	**Participant Introductions**	
10:05 – 10:20 AM	**Break**	
10:20 – 10:50 AM	**Future of HVAC Technologies: Challenges & Opportunities** *Tony Bouza, Buildings Technologies Office, U.S. Department of Energy*	
10:50 – 11:20 AM	**Future of DAC Technologies: Challenges & Opportunities** *Katherine Hornbostel, University of Pittsburgh*	
11:20 – 11:30 AM	**Breakout Logistics**	
11:30 – 12:30 PM	**Lunch**	
12:30 – 1:45 PM	**Breakout Sessions** *System Design*	
1:45 – 2:00 PM	**Break**	
2:00 – 3:25 PM	**Technology Approaches to HDVAC** *Harvey Bryan, Arizona State University* *Kashif Nawaz, Oak Ridge National Lab* *Udi Meirav, enVerid* *Petri Laakso, Soletair*	   
3:25 – 3:30 PM	**Metrics Breakout Overview**	
3:30 – 5:00 PM	**Breakout Sessions** *Metrics*	

Day 2 Agenda Preview - Objective: Deployment Strategies

8:30 – 8:45 AM	**Day 1 Summary and Day 2 Objectives** *Marina Sofos, ARPA-E*
8:45 – 9:45 AM	**Fireside Chat on Commercialization Requirements and Barriers** *Moderator: Ken Pulido, ARPA-E*
9:45 – 10:00 AM	**Potential Factors Impacting HDVAC Deployment** *Ken Pulido, ARPA-E*
10:00 – 10:15 AM	**Break**
10:15 – 11:45 AM	**Breakout Sessions**
11:45 – 12:00 PM	**Wrap-up/Adjourn**

THANK YOU!

Marina Sofos, Ken Pulido
Advanced Research Projects Agency-Energy

Mervin Chao, Daniel Garcia, Kate Pitman
Booz Allen Hamilton

15 min. meeting slots available with ARPA-E team for this Friday 1-4 pm ET; Sign-up sheets will be made available after this morning's session

CHANGING WHAT'S POSSIBLE

Technologies for Transforming Building Materials into Carbon Sinks

Marina Sofos, Ph.D.
Program Director @ ARPA-E

ARPA-E Carbon Negative Building Materials Workshop - Day 2

March 25, 2021

Day 1 Recap – Themes in What We Heard from You

- Performance Advantage
- Durability and Service Life
- Multifunctional Materials
- Transparency
- Uncertainty

CHANGING WHAT'S POSSIBLE

Day 1 Recap – Some Ways We're Thinking Now…

- **Categorization:**
  - Flooring assembly that meets specific structural requirements over a given span
  - Materials that meet both structural and insulating property requirements
  - Enabling multifunctionality

- **Metrics:**
  - Emphasize reproducibility over final deliverable size

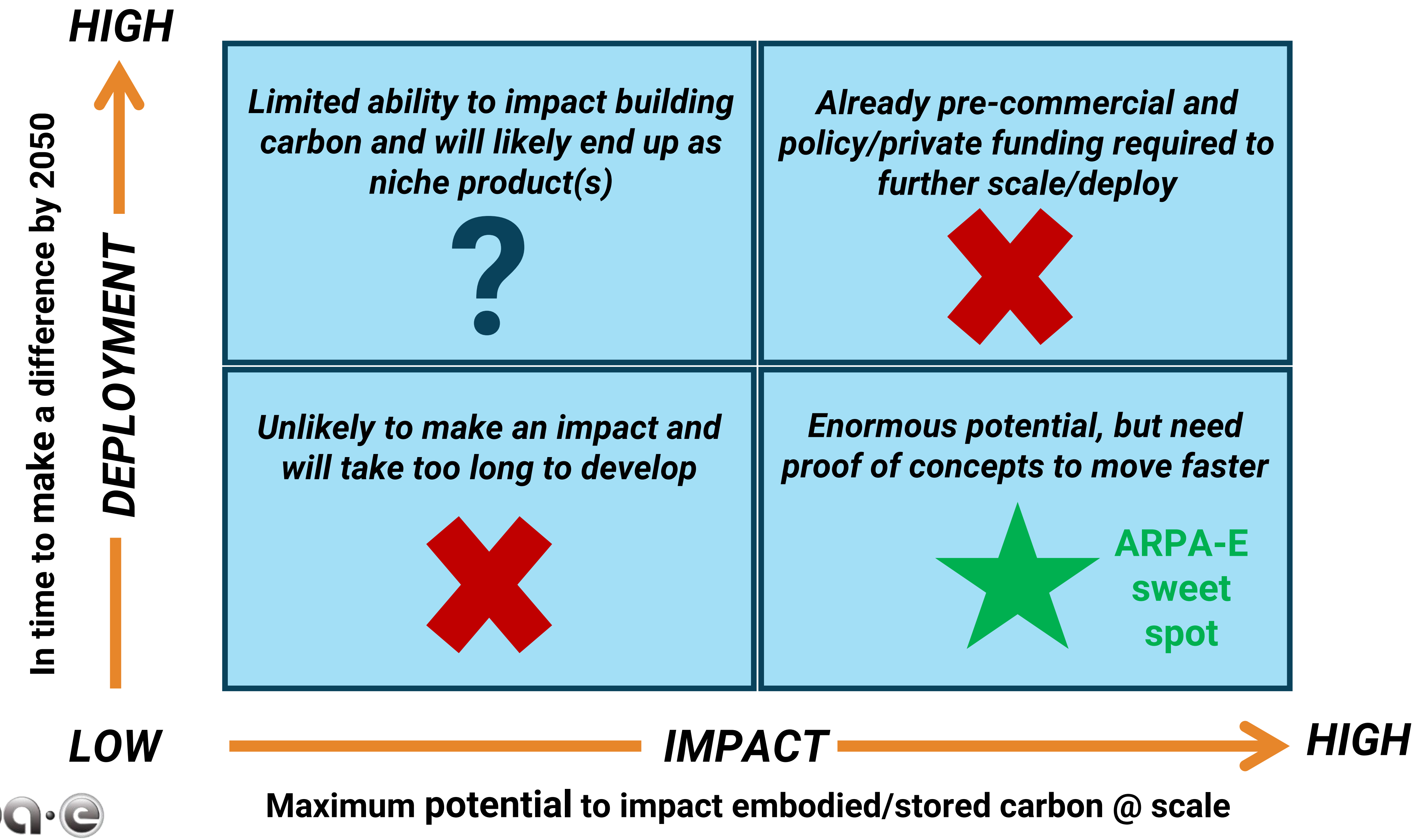
- **LCA:**
  - Achieve performance first and then quantify LCA
  - BUT the LCA then needs to cover the full life, not just A1-A3

- **Markets & Drivers:**
  - Institutional buildings may be good first market
  - Can't have equivalent replacements: products must be better than incumbent

Updates to Materials Metrics

	Revised
Categorization	• Building Elements • Assemblies: Flooring, Walls, etc. • Performance / Purpose (ex. Structural) ***Multiple Options***
Performance Metrics	1. Min 200% carbon storage (LCA A1-A3) (100% for cementitious materials) 2. Durability testing – accelerated aging / wear 3. Code-based standard performance 4. Fire safety rating 5. Health / toxicity assessment (in service and production) 6. Cradle-to-grave LCA *Optional:* region-based testing included (ex. meet seismic performance for CA)
Sample Requirements	• Large enough samples for required test specimen count per test • Samples made on different days to test performance repeatability

Framework for Materials Under Consideration



Today’s Objectives

- Evaluate proposed **material categories** based on ARPA-E framework (i.e. likelihood of deployment vs. potential impact)
- Prioritize greatest **technical challenges** within a selected category
- Identify any **critical technologies/pathways** that are missing

Truly Neutral Concrete

- **Problem:** Concrete is the biggest contributor to CO_2 emissions in the built environment.
- **Opportunity:** With the high volume of concrete, a carbon storing alternative would be impactful.
- **Question:** Where could ARPA-E funding have a meaningful impact?
  - Synthetic aggregates? Biological routes? Something else?

Photo: Pascal Meier, Unsplash

arpa·e
CHANGING WHAT'S POSSIBLE

Mass Timber on the Rise

nature sustainability

PERSPECTIVE

https://doi.org/10.1038/s41893-019-0462-4

Buildings as a global carbon sink

Galina Churkina[1,2]*, Alan Organschi[3,4], Christopher P. O. Reyer[2], Andrew Ruff[3], Kira Vinke[2], Zhu Liu[5], Barbara K. Reck[1], T. E. Graedel[1] and Hans Joachim Schellnhuber[2]

- **Opportunity:** Mass timber is at the heart of thinking about buildings as a carbon sink.

- **Questions:**
  – Are technical advances needed in mass timber?
  – Where else are innovations in forestry products emerging?

CHANGING WHAT'S POSSIBLE

Other Uses for Agriculture Residues

- **Opportunity:** From Chris Magwood: using just the straw waste in the country would offset all transportation emissions

- **Questions:**
  - Building materials and techniques using agricultural residues exist but are seldom implemented. What are the barriers?
  - How can we merge the carbon benefits of using agricultural residues with the convenience and comfort of modern materials?


Photo: Neringa, Unsplash

New Uses for Carbon

- **Problems:**
  - Long-term carbon storage is needed.
  - Methane pyrolysis may result in large amounts of solid carbon.

- **Opportunity:** Emerging technologies in carbon materials from greenhouse gasses could produce high carbon density storage.

- **Questions:** Can these materials be produced cheaply enough to find application in building materials?

Resins, Adhesives, and Matrix: the Connecting Thread

- **Problem:** Making materials from many of these sources require high-emissions resins, adhesives, or matrix.

- **Opportunity:** Focused effort in this area could benefit many different classes of materials.

- **Questions:**
  - What is already being done?
  - Where are new solutions most needed?

Photo: Santonii, Unsplash

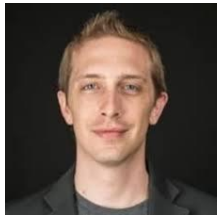
Polymers

- **Problem:** Polymers have become ubiquitous in buildings and are almost exclusively petroleum derived.
- **Opportunity:** Increasing awareness and demand for better products.
- **Questions:**
  - Is there a less toxic alternative to PVC?
  - Can bioderived and recycled products compete?


Photo: Jason Krieger, FreeImages


Photo: Eric McLean, Unsplash

Day 2 Agenda

12:00 – 12:20 PM	**Day 1 Summary and Day 2 Objectives** *Marina Sofos, ARPA-E*	
12:20 – 12:30 PM	**Introduction to ARPA-E Tech-to-Market** *Madhav Acharya, ARPA-E*	
12:30 – 1:30 PM	**Products to Market Panel** *Moderator: Josh Agenbroad, Rocky Mountain Institute* *Ryan Spies, Saint-Gobain* *Jerry Uhland, CalPlant* *Michael Dosier, bioMASON* *Kaustubh Pandya, Brick & Mortar Ventures*	    
1:30 – 1:40 PM	**Break**	
1:40 – 2:00 PM	**Uses of Agricultural and Forestry Products in Thermosetting Polymers** *Dean Webster, North Dakota State University*	
2:00 – 2:20 PM	**Lignin-Based Carbon Materials – Potential High Value and High Volume Applications** *Zhiyong Cai, USDA Forest Products Laboratory*	

Day 2 Agenda (cont.)

2:20 – 2:40 PM	**Mycotecture: shaping the built environment with mycelium** *Christopher Maurer, redhouse*	
2:40 – 3:00 PM	**Reduce and Recapture CO2: Sustainable Approach for Macro- and Nano-Scale Carbon in Building Materials** *Anna Douglas, SkyNano* *Hicham Ghossein, Endeavor Composites*	 
3:00 – 3:15 PM	**Break**	
3:15 – 4:30 PM	**Breakout Sessions Day 2**	
4:30 – 5:00 PM	**Report out and Closing Remarks** *Marina Sofos, ARPA-E*	

Today's Breakouts

Other Materials

Facilitator: Doug Wicks

Notetaker: Kalena Stovall

Moderator: Christina Chang

Wood/Purpose Grown Materials

Facilitator: Marc von Keitz

Notetaker: Dave Lee

Moderator: Emily Yedinak

Carbon Materials

Facilitator: Scott Litzelman

Notetaker: Rose Cox-Galhotra

Moderator: Ian Robinson

Agricultural Residues

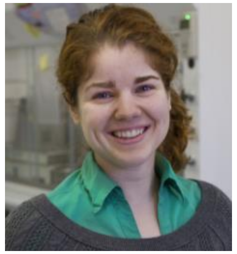
Facilitator: Dave Babson

Notetaker: Laura Demetrion

Moderator: Elizabeth Schoenfelt-Troein

Concrete/Concrete Replacements

Facilitator: Joe King



Notetaker: Kate Pitman

Moderator: Grace Ryan

More opportunities to engage with us

- ***RFI just issued (closing on April 21 @ 5 pm ET), share with your networks!***

  https://arpa-e-foa.energy.gov/

- ***For ideas not covered here, check out OPEN FOA***

  https://arpa-e.energy.gov/open-2021

- ***Virtual ARPA-E Summit May 24-27, 2021***

  https://www.arpae-summit.com/Home

- ***Subscribe to the ARPA-E Newsletter***

  https://arpa-e.energy.gov/news-and-media/newsletter

“We shape our buildings;
thereafter, our buildings shape us.”

-Winston Churchill

THANK YOU!

Marina Sofos, Madhav Acharya
Advanced Research Projects Agency-Energy

Kate Pitman, Kalena Stovall
Booz Allen Hamilton

CHANGING WHAT'S POSSIBLE