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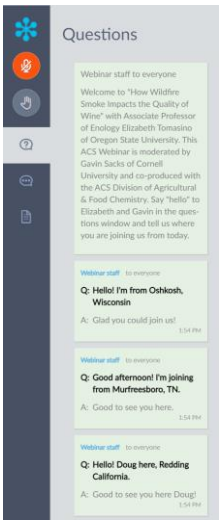

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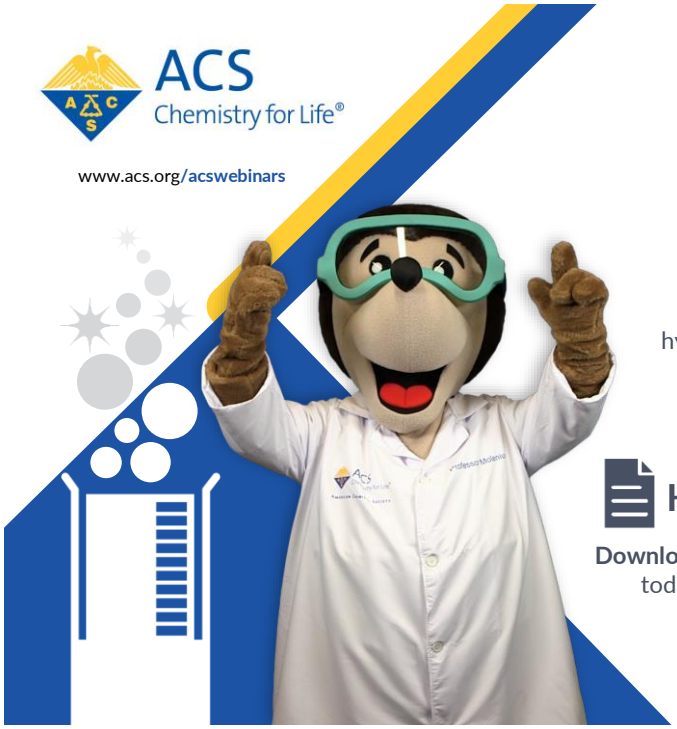
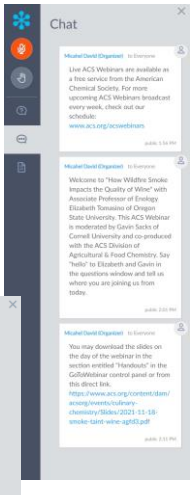


Chat

Announcements and hyperlinks from our team



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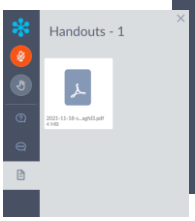

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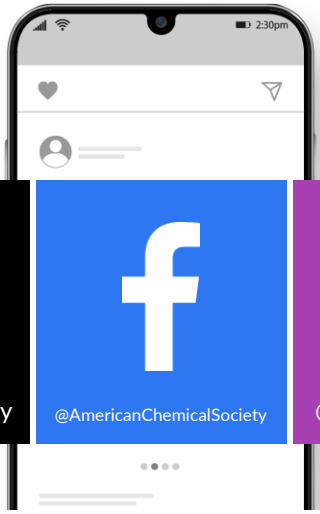

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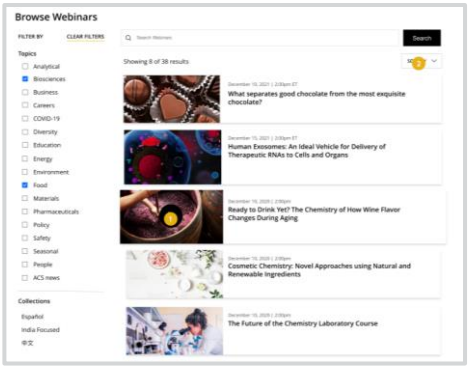

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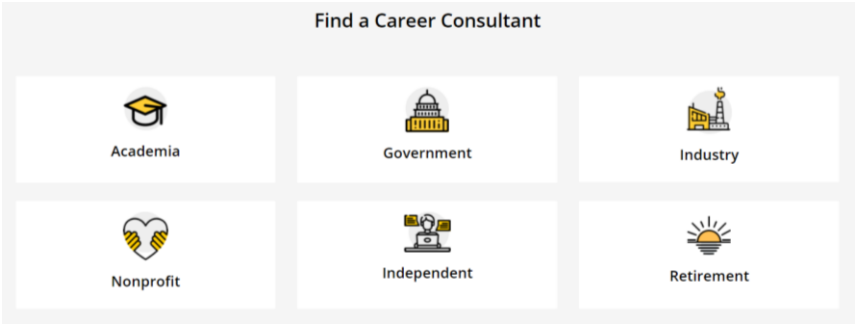
https://chemidp.acs.org

6

6

Career Consultant Directory



- ACS Member-exclusive program that allows you to arrange a one-on-one appointment with a certified ACS Career Consultant.
- Consultants provide personalized career advice to ACS Members.
- Browse our Career Consultant roster and request your one-on-one appointment today!

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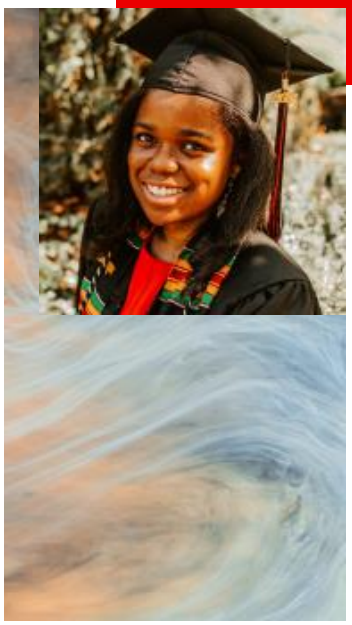
8

8



ACS Scholar Adunoluwa Obisesan

BS, Massachusetts Institute of Technology, June 2021
(Chemical-biological Engineering, Computer Science & Molecular Biology)

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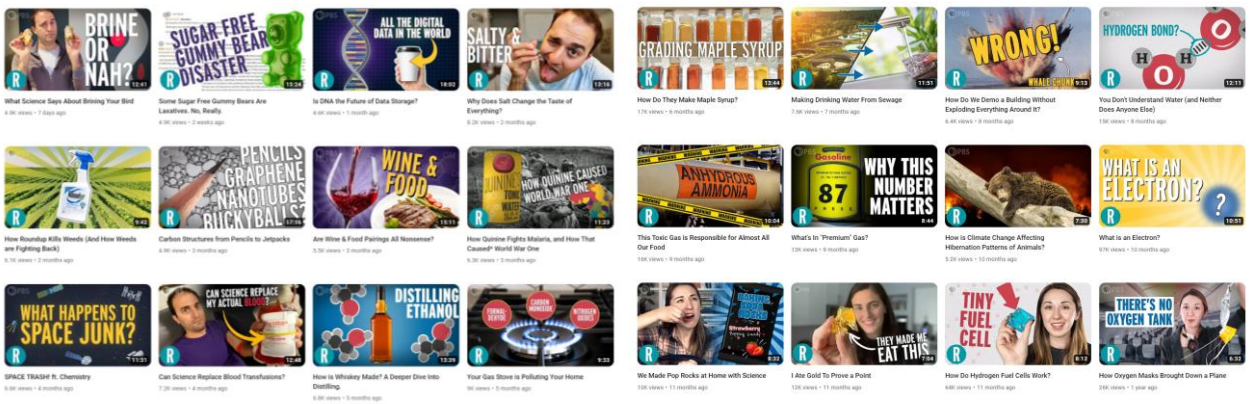
Reactions



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11

11

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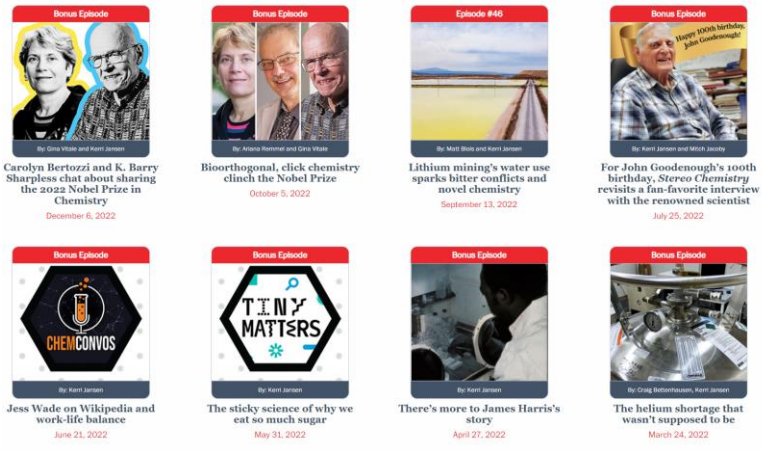

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Preview Content: acs.org/indnl

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ACS ON CAMPUS

14

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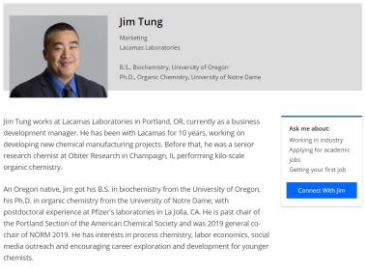
Virtual Office Hours

https://www.acs.org/careerconsulting.html

Personal Career Consultations



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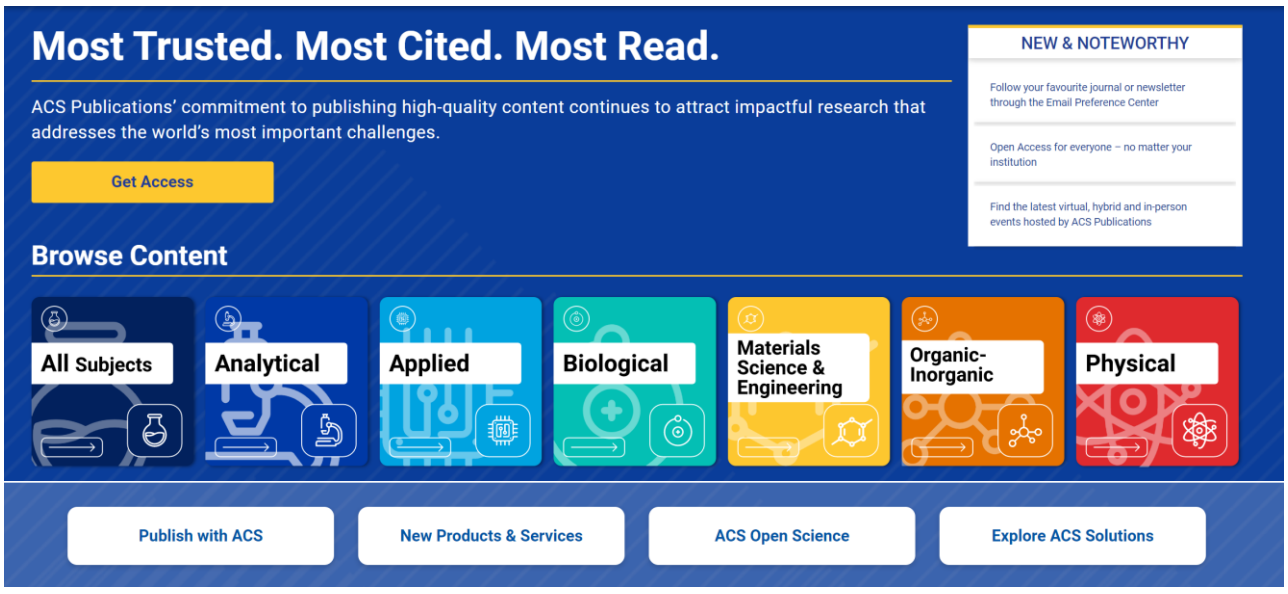

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16

ACS OFFICE OF DEIR

Advancing ACS' Core Value of Diversity, Equity, Inclusion and Respect

Resources

Inclusivity Style Guide
Designed to help staff and members use language and images that respect diversity in all its forms.

ACS Webinars on Diversity
Covering diversity and inclusion at the workplace

ACS Publications DEIR Hub
See what ACS Publications is doing for fostering inclusivity in scholarly publishing

ACS Volunteer and ACS Meetings Code of Conduct
Fostering a positive and welcoming environment for attendees, volunteers and staff.

C&EN Trailblazers
C&EN highlights scientists from different backgrounds who are making an impact in chemistry.

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Quick Guide: Inclusion Moments
Learn more about what Inclusion Moments are and see ideas to host them during your meetings.

Quick Guide: How to host inclusive in-person events
Recommendations and best practices to ensure that your events can accommodate everyone.

Diversity, Equity, Inclusion, and Respect
**Adapted from definitions from the Ford Foundation Center for Social Justice:

Equity**
Seeks to ensure fair treatment, equality of opportunity, and fairness in access to information and resources for all. We believe this is only possible in an environment built on respect and dignity. Equity requires the identification and elimination of barriers that have prevented the full participation of some groups.

Diversity**
The representation of varied identities and differences (race, ethnicity, gender, disability, sexual orientation, gender identity, national origin, tribe, caste, socio-economic status, thinking and communication styles, etc.), collectively and as individuals. ACS seeks to proactively engage, understand, and draw on a variety of perspectives.

Inclusion**
Builds a culture of belonging by actively inviting the contribution and participation of all people. Every person's voice adds value, and ACS strives to create balance in the face of power differences. In addition, no one person can or should be called upon to represent an entire community.

Respect
Ensures that each person is treated with professionalism, integrity, and ethics underpinning all interpersonal interactions.

https://www.acs.org/diversity

17

17

ACS Advocacy

See your influence in action!

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The impact and results of **ACS member advocacy** outreach and efforts by the numbers!

2439+
Members participated In Act4Chemistry
Get Involved

1739+
ACS Advocacy Workshops participants or enrollees
Enroll in a workshop

49
Years of Public Policy Fellows
Become a Fellow

2000
Letters sent to Congress
Take Action

https://www.acs.org/policy

18

ACS Technical Division Chemical Health & Safety (CHAS)

ACS Committee Chemical Safety

A complete listing of ACS Safety Programs and Resources

RAMP UP CHEMICAL SAFETY

Resources to Support Laboratory Safety Education and Practice

Download it for free in the "Projects & Announcements" Section! www.acs.org/ccs

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19

19

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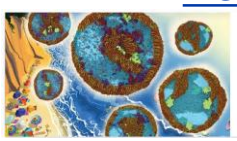

August 2023

How the Chemical Complexity of Aerosols Impacts Climate and Disease

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Artificial Molecular Machine : Going from Solution to Surfaces

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Symposia

- Critical Materials: Perspectives from Industry, Government, and Research Communities
- Elevating Atmospheric Chemistry Measurements and Modeling with Artificial Intelligence

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- ✓ Energy
- ✓ Sustainability
- ✓ Hydraulic Fracturing
- ✓ Forensic Science

Awards

- National Medal of Science
- National Medal of Technology and Innovation
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20

20

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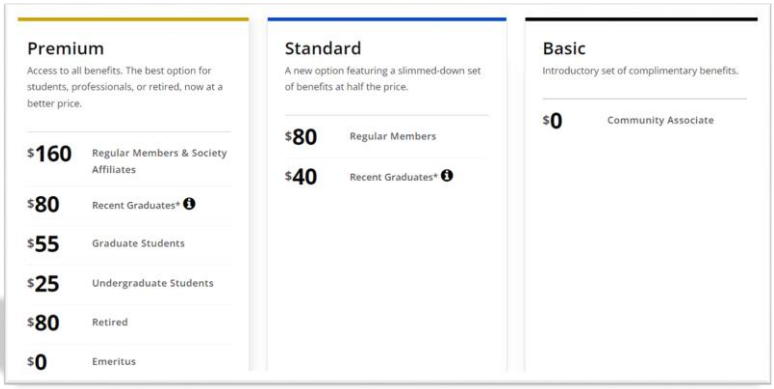

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Thursday, January 25, 2024 | 2-3pm ET

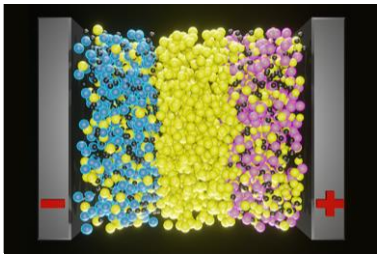
The Formula for Successful Interviews

ACS Division of Business Development and Management and the ACS Division of Professional Relations

Wednesday, January 31, 2024 | 2-3pm ET

How to Make Your Communication Accessible

Co-produced with the ACS Office of Diversity, Equity, Inclusion and Respect



Thursday, February 8, 2024| 2-3:30pm ET

Better Ion Transport Through Polymer Chemistry

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Say hello in the
questions window!
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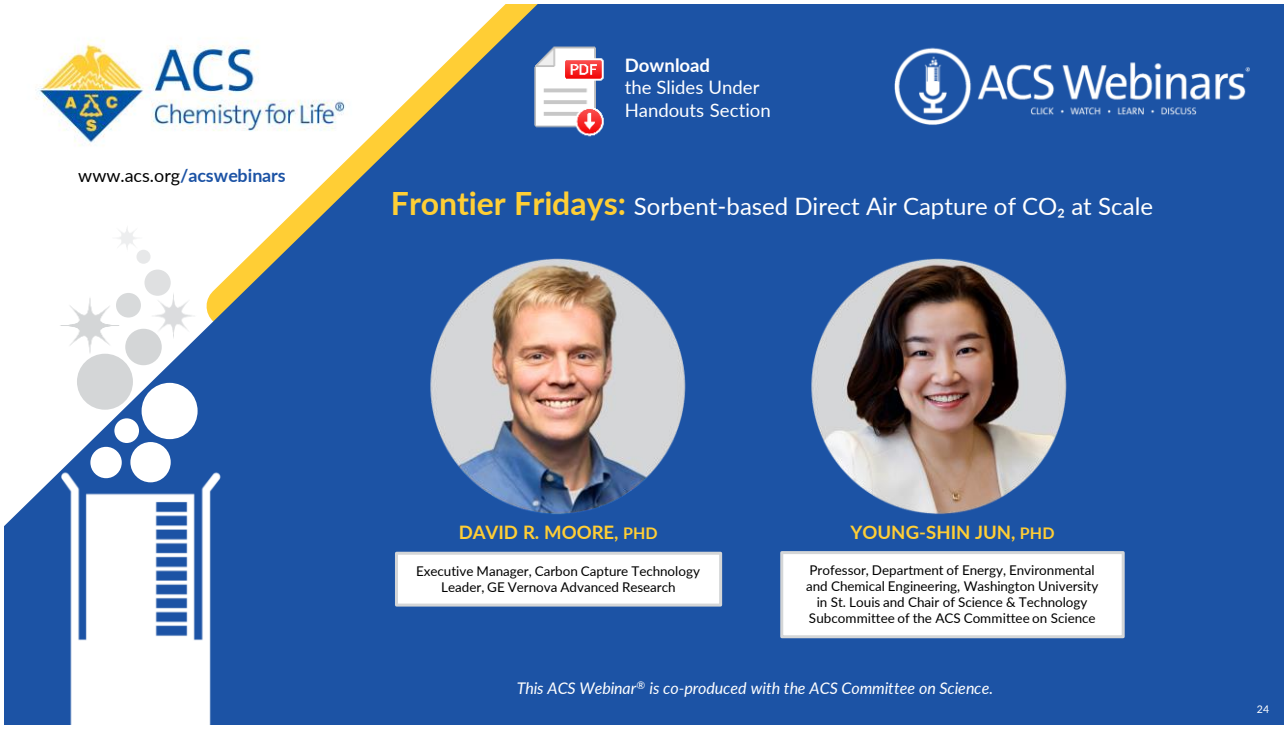
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Frontier Fridays: Sorbent-based Direct Air Capture of CO_2 at Scale
DAVID R. MOORE, PHD
Executive Manager, Carbon Capture Technology
Leader, GE Vernova Advanced Research
YOUNG-SHIN JUN, PHD
Professor, Department of Energy, Environmental
and Chemical Engineering, Washington University
in St. Louis and Chair of Science & Technology
Subcommittee of the ACS Committee on Science
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24

24

GE VERNOVA

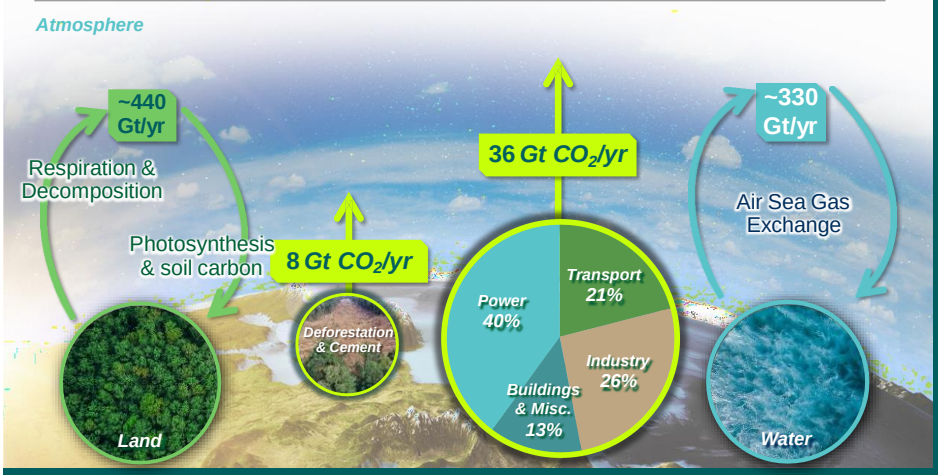
SORBENT-BASED DIRECT AIR CAPTURE OF CO_2 AT SCALE

David R. Moore, Ph.D.
Executive Manager,
Carbon Capture Technology Leader

25

The world's carbon cycle

Limiting warming to **1.5°C (Paris Agreement goal)** implies reaching **net zero CO_2** emissions globally **by 2050**



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ROADMAP TO NET ZERO

- Decarbonize power generation
- Electrify other energy sectors
- Provide carbon free solutions for "hard-to-electrify" sectors

CO_2 REMOVAL TECHNOLOGIES

- Post-combustion Capture (PCC) & Direct air capture (DAC)
- Afforestation & reforestation
- Biomass energy w/ carbon capture & storage (BECCS)
- CO_2 Mineralization
- Biomass storage

Decarbonizing power gen & negative emissions tech critical to net zero CO_2

26

A Question for the Audience

GE VERNOVA

How many acres (km²) of mature trees would be needed to remove 44 Gt CO_2?

A. 18 million acres (73,000 km²)
B. 180 million acres (730,000 km²)
C. 1.8 billion acres (7.3 million km²)
D. 18 billion acres (73 million km²)
E. 180 billion acres (730 million km²)

The Final Jeopardy theme song is now playing in your mind…

27

An Answer for the Audience

GE VERNOVA

How many acres (km²) of mature trees would be needed to remove 44 Gt CO_2?

A. 18 million acres (73,000 km²)
B. 180 million acres (730,000 km²)
C. 1.8 billion acres (7.3 million km²)
D. 18 billion acres (73 million km²)
E. 180 billion acres (730 million km²)

Notes:

- Assumption #1: Each mature tree removes ~25 kg CO_2/year
- Assumption #2: An acre of forest contains ~100 mature trees
- 44 Gt CO_2 per year / 0.025 tonne CO_2 per tree per year = 1.8 trillion trees
- 1.8 trillion trees / 100 trees per acre = **18 billion acres of land needed**
- The continental United States is 1.9 billion acres (7.7 million km²)
- Earth has 32.2 billion acres of land (130 million km²)

Getting to net zero CO_2 requires a multi-pronged strategy of diverse solutions

28

Pathways to minimizing CO_2 emissions

GE VERNOVA

- **Human-generated CO_2 is primarily from combustion activities:**

Hydrocarbon Fuel + Air (i.e., $O_2 + N_2$) → **CO_2** + **H_2O** + Other Gases

- **Three distinct approaches to eliminate CO_2:**

① Do not *do* combustion at all = Ren + Storage, Nuclear, Hydro

② Do not *generate* CO_2 in the first place… **Hydro~~carbon~~** fuel Combustion = H_2 or NH_3 as a fuel

③ Do not *liberate* CO_2 to the atmosphere… **Hydrocarbon** fuel Combustion but take out CO_2 = Carbon Capture & Storage

- **All approaches are not easy and require significant investments to deploy at scale:**
  - All-Renewable/Nuclear/Hydro: *cost, permitting, & supply chain + how to deal with the grid and the intermittent nature of REN*
  - H_2/NH_3 as a fuel: *production cost, transportation network and infrastructure, and long duration storage*
  - CO_2 capture and storage: *capture technology scaleup, transportation network and infrastructure, and permanent storage*

Decarbonization is a balancing act between economics and the "art of possible"

29

Carbon Capture Technology First Principles

GE VERNOVA

Air or Flue Gas → **Material System** → **CO_2 Capture** → **CO_2 Release** → **Utilize/ Compress**

Energy → CO_2 Capture

DAC = 415 ppm, 0.04%
PCC = 45,000 ppm, 4.5%

CO_2 Depleted Air

DAC = Direct Air Capture
PCC = Post-combustion Capture

	MATERIAL		SYSTEM	
DAC Separation Mode	**Enabling Material Component**	**Regeneration Temperature (°C)**	**Heat of Desorption (MWh/t CO_2)**	**System Energetics (MWh/t CO_2)**
Chemical	Liquid Solvent & Aqueous Hydroxides (KOH)	900[i,ii]	1.1[i,ii]	1.5-2.4[i,iii]
Sorption	Solid Sorbent (amine-based supports; MOFs; polymers)	90-200[ii,iii]	0.4[ii]	1.3-2.9[ii,iii]
Pressure-driven/ electrochemical	Bipolar membrane electrodialysis; carbonate electrolysis	ambient	1.1-1.5[iv]	1.6-14.2[iv]

[i] Keith, D. et al., *Joule*, **2018**, *2*, 1573-1594
[ii] NASEM **2019**. *Negative Emissions Technologies and Reliable Sequestration: A Research Agenda.*
[iii] Fasihi et al., *J. Clean. Prod.* **2019**, *224*, 957-980.
[iv] *Ind. Eng. Chem. Res.* **2020**, *59* (15), 7007–7020; *Polymer Journal* **2021**, *53*,111–119; Lattimer et al., *Meet. Abstr.*, **2022**, *MA2022-02*, 1034.

Driving towards the best material + separation process + system energetics

30

Carbon Capture: PCC vs. DAC

PCC = Post-combustion Capture
DAC = Direct Air Capture

GE VERNOVA

Air or Flue Gas → **Capture** → **Release** → **Utilize/ Compress & Store**

CO_2
PCC: 45,000 ppmv, 4.5%
DAC: 415 ppmv, 0.04%

- PCC = 100x higher [CO_2], high flow
- DAC = Low [CO_2], 100x higher flow

Attribute	PCC	DAC
CO_2 Concentration	**4.5%**	**0.04%**
Air Flow Vol (Nm^3 gas/kg CO_2)	**12.5**	**1,930**
Air Flow Rate (kg/s)	**734 (1.3 MM CO_2 tpa)**	**65,760 (1 MM CO_2 tpa)**
Residence Time (sec)	1-3	1-3
Inlet T (ºC)	**40-70**	**-20-40**
Inlet Humidity (%)	**>80%**	**10-95%**
Pressure Drop (Pa)	**1200**	**<100**
Desorption T (ºC)	90-120	90-120
CO_2 Purity (%)	>98%	>98%
CO_2 Pressure (atm)	>80	>80

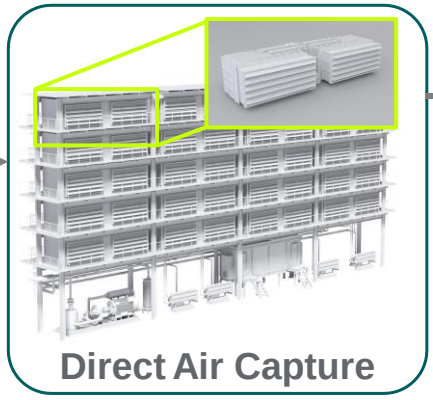
Advancing carbon capture technology solutions across CO_2 concentrations

Decarbonizing the Air … *Solid Sorbents*

GE VERNOVA

Pre-industrial Revolution: ~280 ppm
Today: ~415 ppm
No climate action: >600 ppm by 2100

Air
415
ppm CO_2



Air
~100
ppm CO_2

Direct Air Capture

Direct Air Capture Differentiation

- Solid sorbent technology … maximizing productivity
- Engineered process … coupled to sorbent properties
- Novel system design … achieving better energetics

Net negative technologies required to complete the energy transition

DAC Commercial Piloting

GE VERNOVA

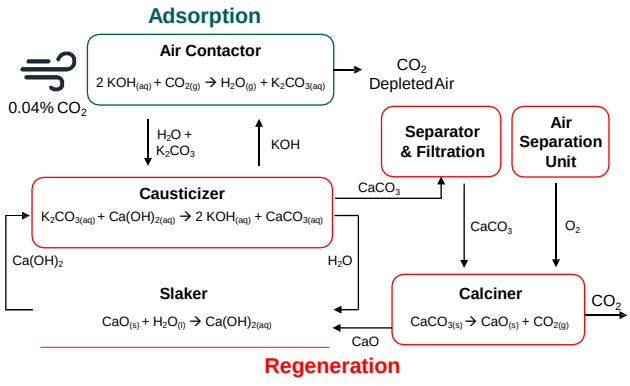
Company	Description	Technology	System Size	Pilots Today
Climeworks	• Founded in 2009; >200 employees; raised $784MM over 8 rounds • With Carbfix, first company to offer CO_2 removal services *(Orca plant)*	Solid Sorbent *(amine-based filter)*	**4,000 tonne CO_2/yr** today **36,000 tonne CO_2/yr** under construction	
Carbon Engineering	• Founded in 2009; >90 employees; raised $82M since '19 • STRATOS - 1PointFive, Oxy & Worley • Synthetic fuels (AIR TO FUELS™)	Liquid Solvent *(Potassium Hydroxide)*	**400 tonne CO_2/yr** today **500,000 tonne CO_2/yr** mid 2025 (STRATOS)	
Global Thermostat	• Founded in 2010; ~45 employees; raised >$90M over 11 rounds • Synthetic Fuels (w/ Sumitomo)	Solid Sorbent *(amine-based monolith)*	**2,000 tonne CO_2/yr** today	
Heirloom	• Founded in 2020; ~35 employees; raised $54MM in Series A • Concrete production (CarbonCure) & CO_2 removal (Microsoft, Frontier)	Solid Sorbent *(Calcium Oxide)*	**1,000 tonne CO_2/yr** today	

DAC companies are mobilizing, partnering and scaling

Decarbonizing Air… *liquid Solvents vs. solid Sorbents*

GE VERNOVA

Aqueous Liquid Solvents (KOH)



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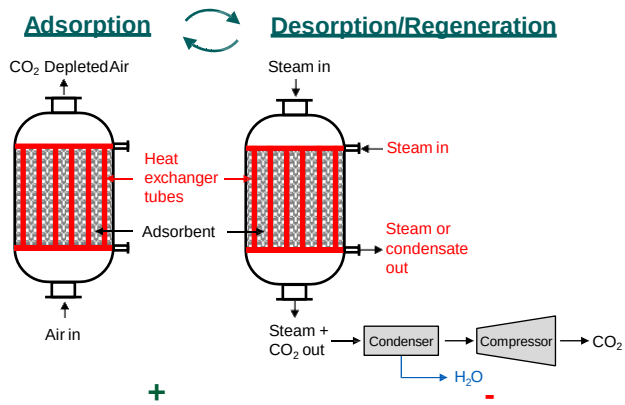
- Low pressure drop operation
- Commercial piloting (TRL 7)

-

- High desorption temps (900 ºC)
- Corrosion = higher CAPEX
- Make-up chemicals required

Solid Sorbents



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- Low ΔP (moving/fluidized bed)
- Low desorption temp (110 ºC)
- Solid state system = lower CAPEX

-

- High ΔP (fixed bed)
- Emerging tech (TRL 4-7)

Solid sorbents and liquid solvents are the most practiced DAC technologies

Solid Sorbents… *what is a sorbent?*

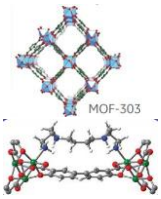
GE VERNOVA

Sorbent = a substance that has the property of collecting particles/molecules of another substance by sorption

Activated carbon

Silica gel, Zeolites, Alkali/ alkaline earth compounds

Metal-organic Frameworks (MOFs)
- Physisorbent
- Chemisorbent



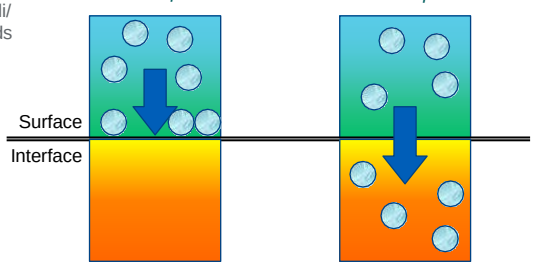
Lewatit® VP OC 1065

Polymeric & ion exchange resins

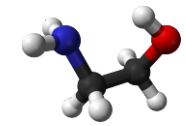
Adsorption vs Absorption

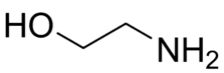
*Particles/molecules **adhere to** the surface of the other phase*

*Particles/molecules **dissolve into** the bulk of the other phase*



Sponge





Amine solvents (e.g., monoethanolamine)

K. An et. al., *J. CO_2 Util*, **2023**, *76*,102587; *Science* **2021**, 374, 454; *Science* **2020**, 369, 392; *J Am. Chem. Soc.*, **2008**, *130*, 10870.

Sorbent form, fit & function drive system performance

Solid Sorbent Systems

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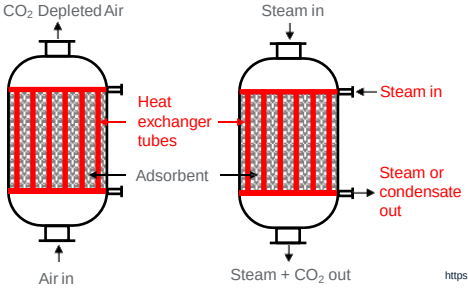
Dhoke, et. al., *Ind. Eng. Chem. Res.* **2021** *60* (10), 3779-3798.

Fixed Bed

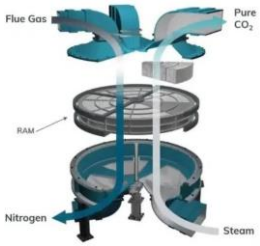
- Conventional Packed Bed
- Structured (e.g., monoliths, laminates)



+ Plug flow: max CO_2 capture
+ Sorbent mechanical stability
- Packed Bed: high ΔP; poor mass & heat transfer
- Structured: costs & scale-up

Moving Bed

- Conventional
- Rotating



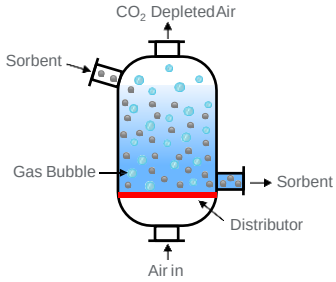
Rotary Adsorption Machine (RAM)

https://carboncredits.com/ge-and-svante-join-hands-to-develop-carbon-capture-tech/

+ Steady state ops; lower ΔP
+ Rotating: lower cycle times
- Conventional: complexity; sorbent mechanical stability
- Rotating: sealing mechanisms

Fluidized Bed

- One stage or multi-stage
- Transient Reactor



+ Stead state ops; lower ΔP
+ Good heat transfer & mixing
- CO_2 removal efficiencies
- Sorbent mechanical stability

Sorbent form, fit & function drive system performance

Solid Sorbents… *what makes an ideal sorbent?*

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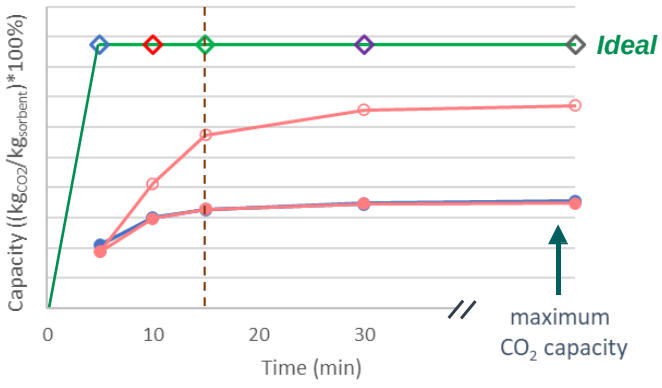
Sorbent Properties:
CO_2 Adsorption Capacity vs. Time



Capacity is a key driver for CAPEX & energy use

$$Capacity = \frac{mass\ CO_2\ (kg)\ adsorbed}{mass\ sorbent\ (kg)}$$

$$Sorbent\ Productivity = \frac{Capacity}{\boldsymbol{CO_2\ adsorption\ time\ (hr)}}$$

Fast kinetics drive lower cycle times

Sorbent adsorption & desorption properties are critical system cost drivers

CAGE Lab… *a preeminent sorbent R&D lab*

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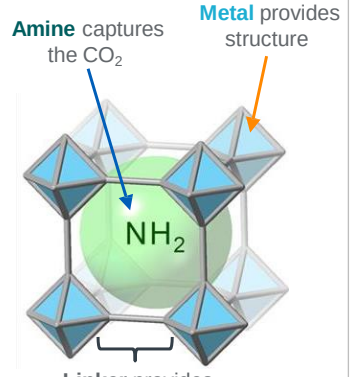
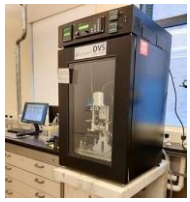
Solid Sorbent Structure ⟷ **Sorbent & Film Properties** ⟷ **Dynamic System Performance**





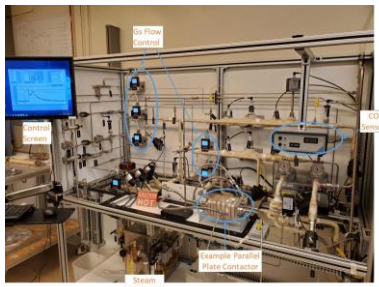
Thermodynamics & Kinetics

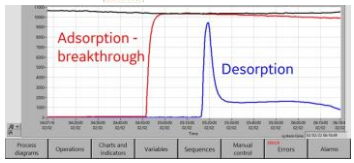
Data Analytics Dashboard

Establishing the Metrics for Success

Scorecard Metrics

- Productivity= $SorbCO_2Prod_{ads}$
- Sorbent Life
- Film Productivity Ratio = FK_{CO2}
- CO2 Desorb Energy = ΔH_{CO2}^{ads}
- H2O Desorb Energy = ΔH_{H2O}^{ads}
- H2O/CO2 Productivity = $\frac{SorbH_2OProd_{ads}}{SorbCO_2Prod_{ads}}$
- Parasitic Desorb Energy = $\frac{SorbH_2OProd_{ads}}{SorbCO_2Prod_{ads}} \times Fr_{H2O} \times \Delta H_{H2O}^{des}$





Structure-property-performance fundamentals accelerate innovation & enable scaling

Sorbent Capture & Release Processes

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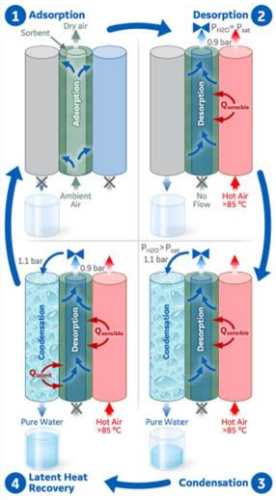
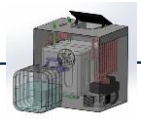
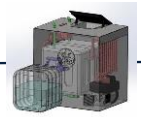
AIR2WATER: Atmospheric Water Extraction as an illustrative example



1 Adsorption

Ambient Air →  → Moisture-depleted Air

2 Desorption

Heat In (TSA)
Vacuum (VSA)
Sweep Gas (PSA)
→  → Water Vapor

TSA = Temperature Swing Adsorption; VSA = Vacuum Swing Adsorption; PSA = Pressure Swing Adsorption

3 Condensation

Heat Out
Pressure
→ Water Vapor → 

Key Energetic Drivers (gains, losses)

- Isosteric Heat of Adsorption (Q_{st})
- Electric Power (Fans)

- Isosteric Heat of Adsorption (Q_{st})
- Sensible Heat ($Q_{sensible}$)
- Electric Power

4 Latent Heat of Condensation (Q_{latent})
- Electric Power (Fans, Compressors)

Energy reduction requires optimal sorption processes + heat recovery

Tech Differentiation… *Sorbent + Process + System*

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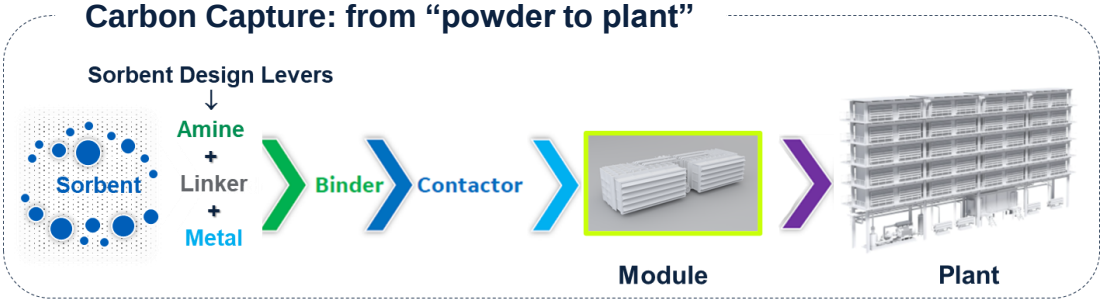
Carbon Capture: from "powder to plant"

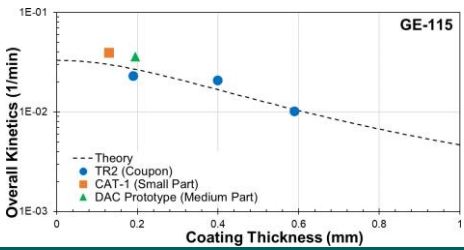


Key Metrics for System Competitiveness

1. CO_2 Productivity
   - Capacity [kg_{CO2}/kg_{sorb}]
   - Kinetics [hr^{-1}]
2. H_2O/CO_2 Ratio
3. Sorbent Life [years]

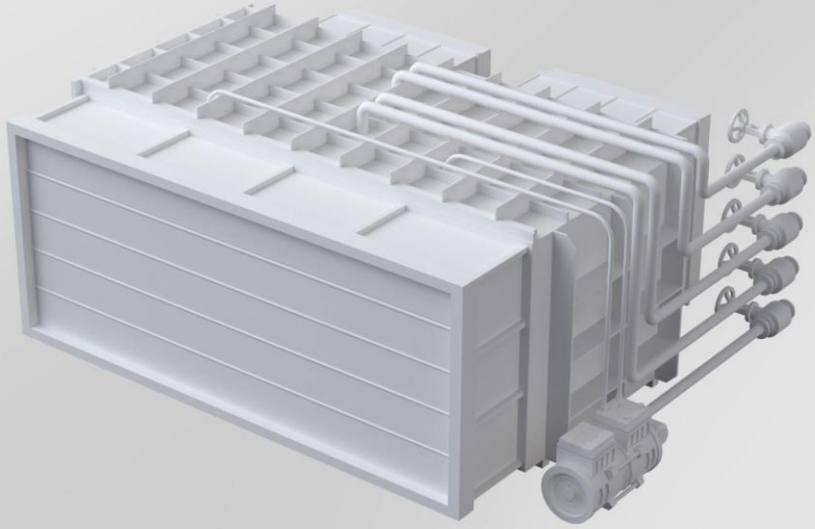
Direction of Goodness

↑ ↑ ↑ ↓ ↑



Continuous performance & process improvement enable scale and energy & cost reduction

The process of capturing and releasing CO_2



17

41

AIR2$$$... *Atmospheric Water Extraction & CO_2 Capture*

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DARPA AIR2WATER
(4-yr, $14.3 MM)

Develop a sorbent-integrated prototype powered by fuel for 150-500 L/day potable water production

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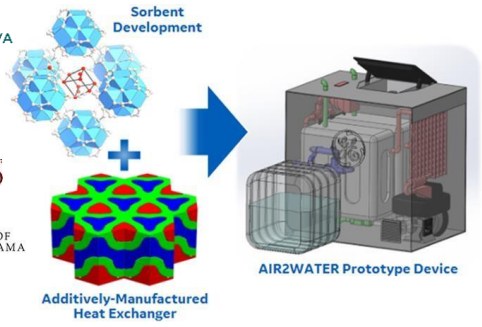
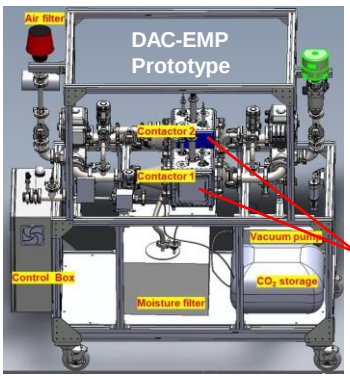
Berkeley
THE UNIVERSITY OF CHICAGO
UNIVERSITY OF SOUTH ALABAMA



AIR2CO2
($14 MM)

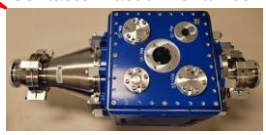
- ✓ DOE AIR2CO2 Contactor
- ✓ DOE PLASTIC4CO2
- ✓ DAC Hubs – 1 M t_{CO2}/yr
- ✓ DOE AIR2MeOH
- ✓ **ARPA-E DAC + Biofuels**

Demonstrate a bench-scale, sorbent-integrated process to produce butanol directly from air-captured CO_2



Sorbent-coated Contactor

Contactor Vacuum Chamber



Leveraging government partnerships to accelerate technology development

18

42

Carbon Capture: Technology to Demonstration

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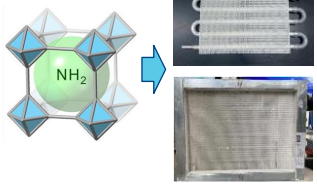
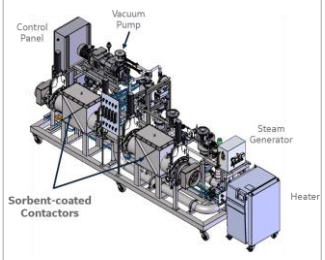
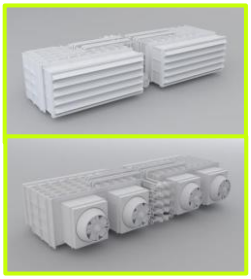
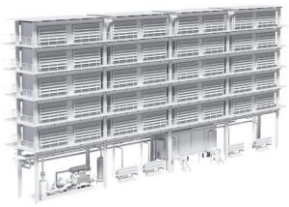
2021-2022	2023-2024	2025-2028	2029-2030+
Solid Sorbent Fabrication Sorbent-coated Contactor			









Sorbent & Contactor Pilot Design

- Sorbent life and productivity
- Contactor selection & coating
- Novel system designs to reduce energy requirements

Pilot Demonstration

- Large-scale sorbent production
- Coated contactor mfg @ scale
- Strategic partnerships and project downselection

Commercial Piloting

- System energetics & cost reductions
- Meet CO_2 sequestration requirements

Commercial Operation

- **DAC:** \$300/t CO_2 → <\$150/t CO_2
- **PCC:** \$70/t CO_2 → \$40/t CO_2

Partnerships critical to accelerate commercialization of carbon capture solutions

Carbon Capture and Hydrogen (H_2) Utilization

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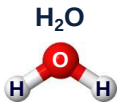
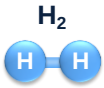
Hydrogen as a fuel… Burn it



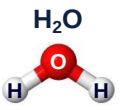
Power

Electrolysis



***Flexible*, Decarbonized Gas Power**

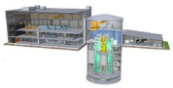
Hydrogen as a feedstock… Utilize it with CO_2



+

CO_2

Nuclear Power & Heat



Electrolysis (SOCC)

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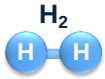
H_2



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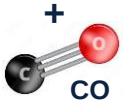

CO

Syn-gas

Sustainable Fuels Petrochemicals (Methanol) New Materials

CO_2 and hydrogen utilization converts historical waste streams to value products

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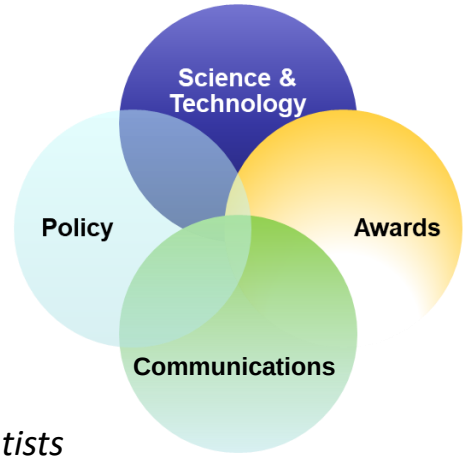

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46

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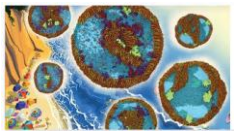

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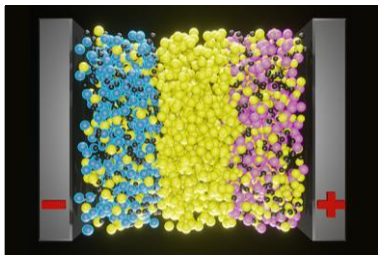

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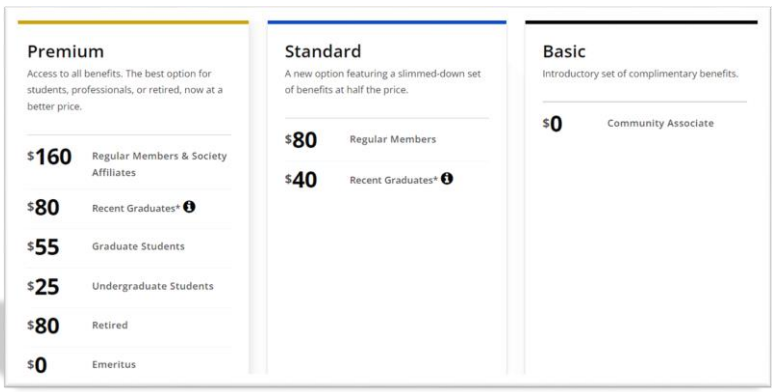

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