June 2024

# Net-zero Flexible Power: High Capture Rate

# Project Review Meeting

U.S. DEPARTMENT OF ENERGY

Fossil Energy and Carbon Management

# Carbon Capture Program…Evolution

## 1st and 2nd Generation Technologies

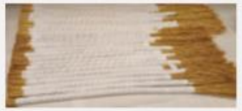
2025: $40/tonne $CO_2$

**2008 -**

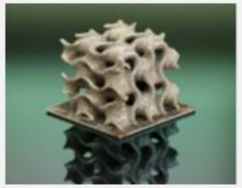
- ✓ Lower CAPEX/OPEX
- ✓ Reduced regeneration energy
- ✓ Increased working capacity

## Transformational Technologies

2030: $30/tonne $CO_2$



Hollow Fibers



3D Print

Biphasic Solvent

**2015 -**

- ✓ Water Lean Solvents
- ✓ Adv. Membranes
- ✓ Hybrid Systems
- ✓ Process Intensification

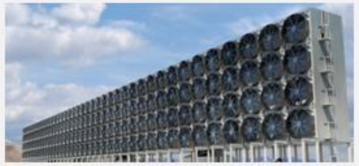
## Scale-up

TCM

**2018 -**

- ✓ Engineering Scale testing
- ✓ FEED studies

## Industrial, NG,CDR & CCS Demos



Carbon Engineering, DAC

Ethanol Plant

**2020 -**

- ✓ CDR: DAC & BiCRS
- ✓ Industrial, NG
- ✓ CCS Demos



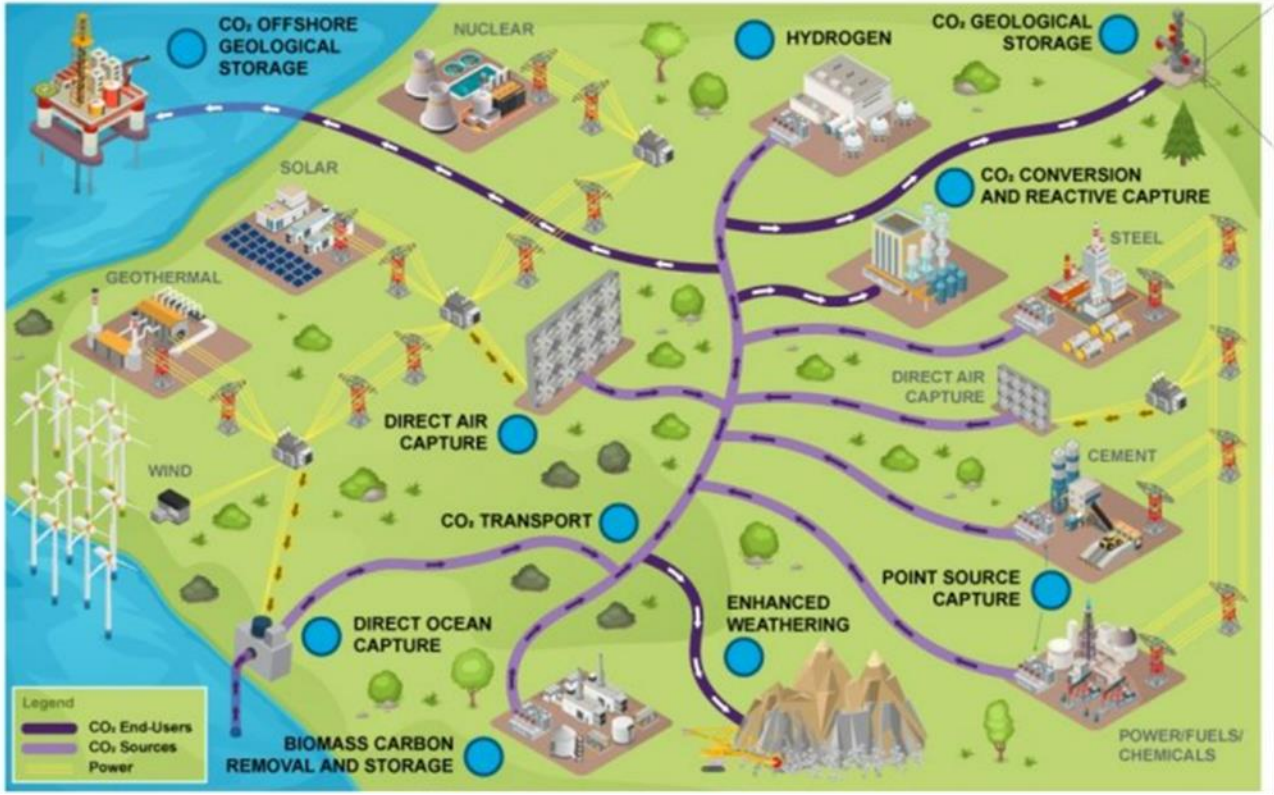
**Reduce cost and risk to enable wider, strategic commercial deployment**

# Carbon management: BIL & IRA funding

*Carbon Transport and Storage*

- $CO_2$ transportation loan support
- $CO_2$ transportation engineering studies

- Expanding storage capacity: CarbonSAFE




*Carbon Capture & Industrial Decarb*

- Commercial CCS Demos
- Carbon Capture Pilots

- $H_2$ Hubs
- Industrial Decarbonization

*Carbon Dioxide Removal*

- DAC Hubs

*Carbon Dioxide Conversion*

- Utilization Procurement Grants & $CO_2$ Conversion

**BIL**: Bipartisan Infrastructure Law; **IRA**: Inflation Reduction Act

# DOE Point Source Carbon Capture Portfolio

| | Components | Small Pilots | Large Pilots | Demo |
|---|---|---|---|---|
| |  Testing novel materials & processes with simulated exhaust |  Bench- and Pilot-scale technology testing with real flue gas |  Engineering scale for integrated capture system<br>No storage |  Unit-wide<br>Carbon transport & storage |
| **ARPA-E** | ✓ FLECCS | ✓ FLECCS | | |
| **FECM** | ✓ ✓ | ✓ ✓ | ✓ MTR, UIC, TCM | |
| **IEDO** | ✓ | ✓ | | |
| **OCED** | | | BIL Funded: ✓ 25 MW ✓ 75 KTA | BIL Funded: ✓ unit ✓ 300+ KTA |

✓ Industrial
✓ Power

**ARPA-E:** Advanced Research Program Agency – Energy
**OCED**: Office of Clean Energy Demonstration

**FECM**: Fossil Energy and Carbon Management;
**IEDO**: Industrial Efficiency & Decarbonization Office

# Commercial, licensing deals

**chevron invests in carbon capture and removal technology company, ION clean energy**

XB100 — Svante — 2023 Honoree

Svante Recognized as One of the World's Top 100 Private Deep Tech Companies by XPRIZE | XB100

Svante has been recognized as one of The World's Top 100 Private

READ MORE

Svante 3M

3M and Svante Announce Joint Development Agreement to Develop and Produce CO2 Removal Products

The companies will work together to identify and deploy projects which can

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SK INC. AND ION CLEAN ENERGY ENTER NEW PARTNERSHIP TO COMMERCIALIZE ION'S INDUSTRY-LEADING CARBON CAPTURE TECHNOLOGY

SLB Announces Agreement to Acquire Majority Ownership in Aker Carbon Capture

Honeywell

Honeywell Collaborates With The University Of Texas At Austin For Innovative Carbon Capture And Storage Technology

ExxonMobil

ExxonMobil, Mitsubishi Heavy Industries form carbon capture technology alliance

Schlumberger and RTI International Partner to Accelerate the Industrialization of Innovative Carbon Capture Technology

**chevron invests in carbon capture and removal technology company, svante**

HOUSTON/VANCOUVER, Dec. 15, 2022 – Chevron New Energies (CNE), a division of Chevron U.S.A. Inc., and Svante announced that Chevron is the lead investor in Svante's Series E fundraising round, which raised $318 million that will be used to accelerate the manufacturing of Svante's carbon capture

SRI International

Baker Hughes acquires exclusive license from SRI International for Mixed Salt Process technology for carbon capture

Baker Hughes

Baker Hughes Acquires Mosaic Materials to Advance Next-Generation Carbon Dioxide Capture Technology

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KOCH ENGINEERED SOLUTIONS ANNOUNCES STRATEGIC PARTNERSHIP WITH ION CLEAN ENERGY

KOCH ENGINEERED SOLUTIONS

October 18, 2022

**Technip Energies and Shell Catalysts & Technologies Strengthen Strategic Alliance on CANSOLV Technology to Address Growing Carbon Capture and Storage Demand**

Lafarge Canada Collaborates with Svante and Dimensional Energy to Begin Utilization of CO2 Captured at Richmond Cement Plant

May 15, 2023 Press Release

Dimensional Svante Lafarge

**Linde Signs Agreement with ExxonMobil for Carbon Dioxide Off-Take**

Baker Hughes

**Baker Hughes Partners with NET Power Zero-Emissions Power Plants**

**Exxon Mobil buys Denbury, pipeline company with carbon capture expertise, for $5 billion**

LG&E and KU, EPRI, University of Kentucky, begin industry-leading research

CHART Cooler By Design.

Chart Industries Acquires Sustainable Energy Solutions, Inc.

GE and Svante Announce Collaboration to Develop Carbon Capture Technology for Power Generation

# FOA 2614 Round 6: NOI

## Notice of Intent No.: DE-FOA-0003397

*AOI-1F. Reactive Carbon Capture Approaches for Point Source Capture or Atmospheric Capture with Integrated Conversion to Useful Products*

*AOI-3F. Engineering-Scale Testing of Transformational Carbon Capture Technologies for Natural Gas Combined Cycle (NGCC) Power Plants*

*AOI-3G. Engineering-Scale Testing of Transformational Carbon Capture Technologies in Portable Systems at Industrial Plants*

*AOI-3H-a. Preliminary Front-End Engineering Design Studies (Pre-FEED) for Carbon Capture Systems at Existing (Retrofit) Domestic NGCC Power Plants*

*AOI-3H-b. Preliminary Front-End Engineering Design Studies (Pre-FEED) for Carbon Capture Systems at Hydrogen Production Facilities Using Coal, Mixed Coal/Biomass, or Natural Gas Feedstock*

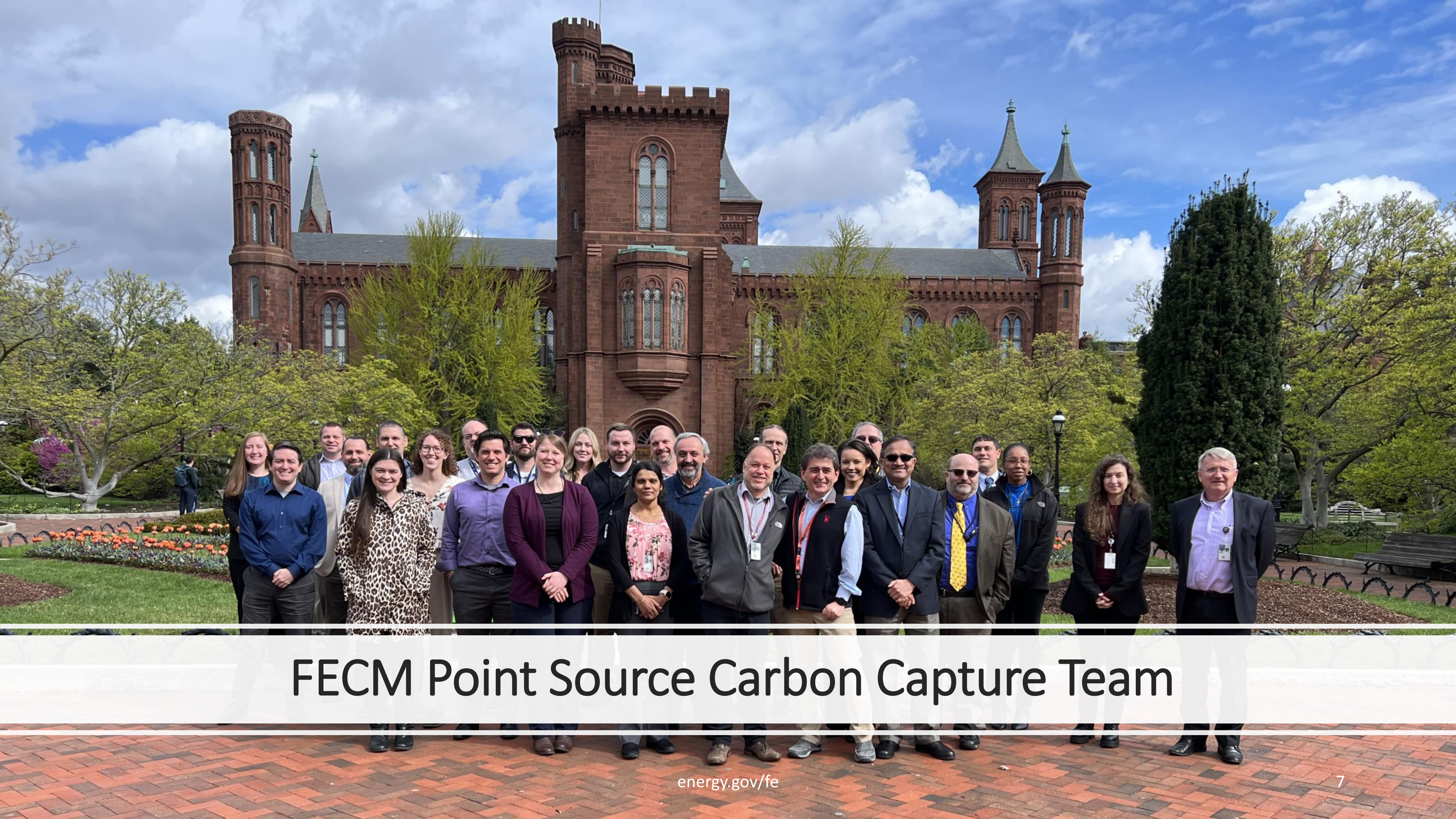
FedConnect: Opportunity Summary

**AOI-1. Carbon Conversion Technology**
The objective of AOI-1 is to support R&D investigating the conversion of carbon dioxide ($CO_2$) into environmentally responsible and economically feasible products.

**AOI-2. Carbon Dioxide Removal Technology**
The objective of AOI-2 is to solicit applications that develop carbon dioxide removal (CDR) technologies (e.g., direct air capture with durable storage,
biomass carbon removal and storage, enhanced mineralization, ocean-based CDR, terrestrial sequestration) to support progress towards achieving the U.S. Department of Energy's Carbon Negative Shot target

**AOI-3. Point Source Carbon Capture**
The objective of AOI-3 is to solicit applications that are specifically focused on developing lower cost, highly-efficient, technologies for point source capture from fossil fuel power plants and industrial point sources.

**AOI-4. Carbon Storage Technology**
AOI-4 aims to support resource assessments to securely store large amounts of CO2.

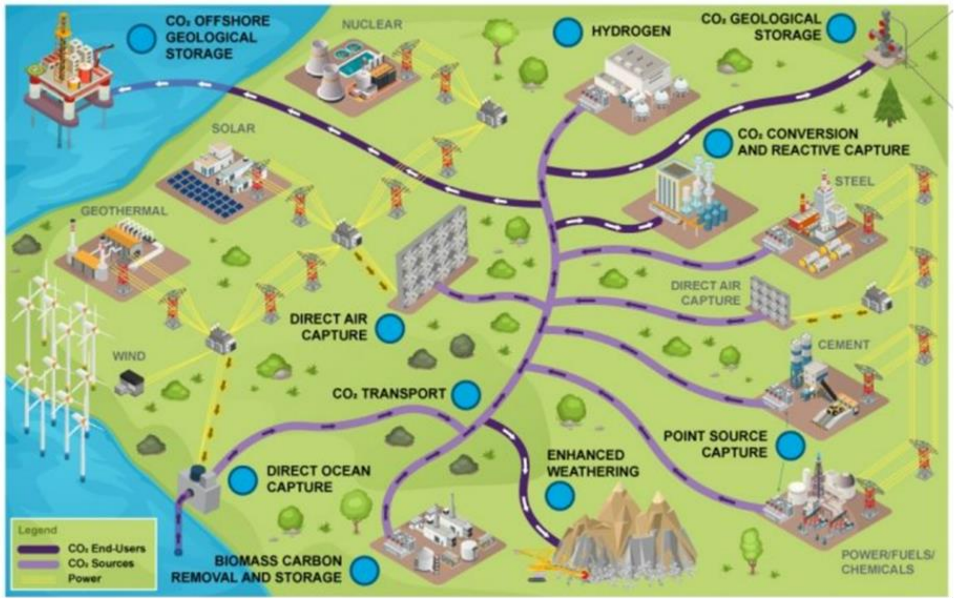


# FECM Point Source Carbon Capture Team

# PSC Strategic Vision

Support demonstration of first-of-a-kind carbon capture on power and industrial sectors coupled to dedicated and reliable carbon storage, that will lead to commercially viable carbon hub opportunities for widescale deployment and facilitate a carbon-free economy by 2050, emphasizing robust analysis of life cycle impacts, and understanding air/water quality impacts.

Secure Carbon Storage




Carbon Dioxide Removal & Low C Electricity and Heat

Low C Industry & Flexible Power + PSC

$CO_2$ Conversion into durable Products

*Focus Area 1: Support Power Retrofit Demos*

- Enabling technologies

*Focus Area 2: Net Zero, Flex Power*

- Technology development to support flexible CCS with high capture efficiency
- FEEDs to seed the formation of Carbon Hubs.

*Focus Area 3: Support Industrial Retrofit Demos*

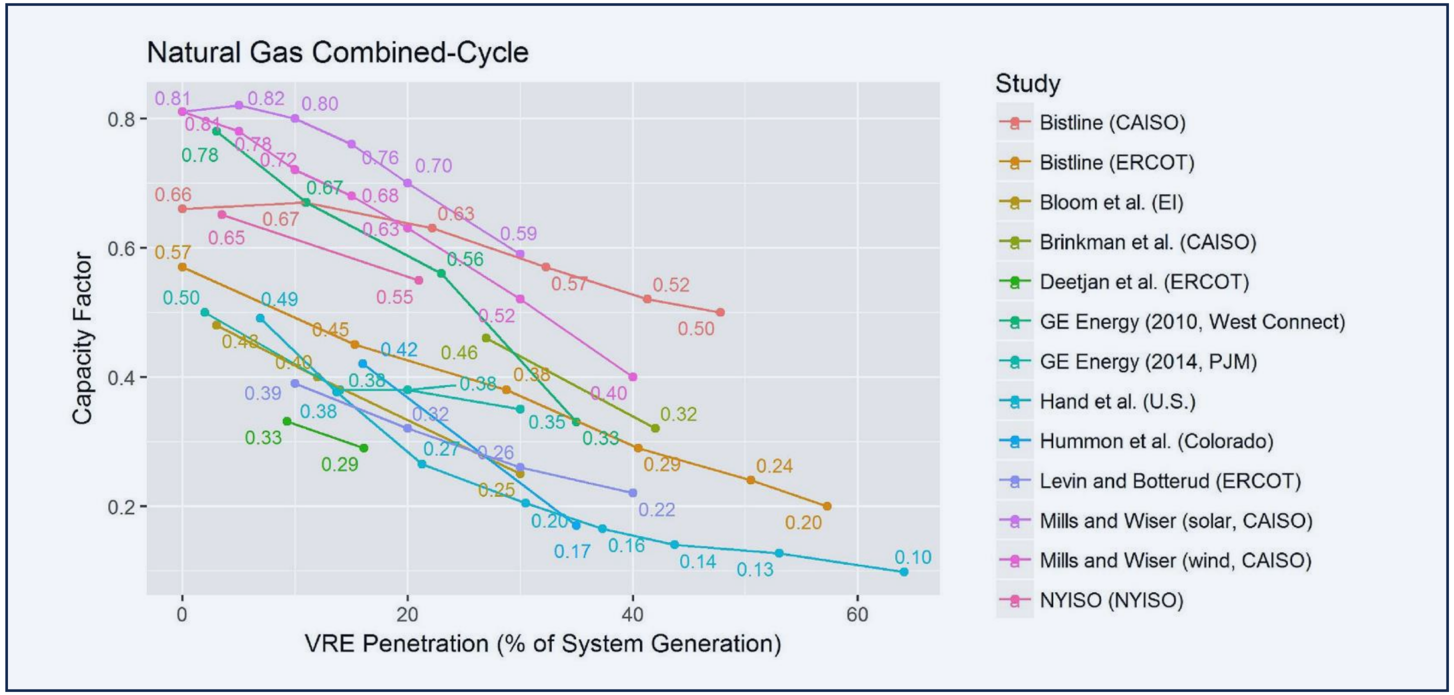
- Enabling technologies

*Focus Area 4: Integrated decarbonized industrial + CCS*

- Technology development for integrated decarbonized industrial processes coupled with transformational CCS
- FEEDs to seed the formation of Carbon Hubs.

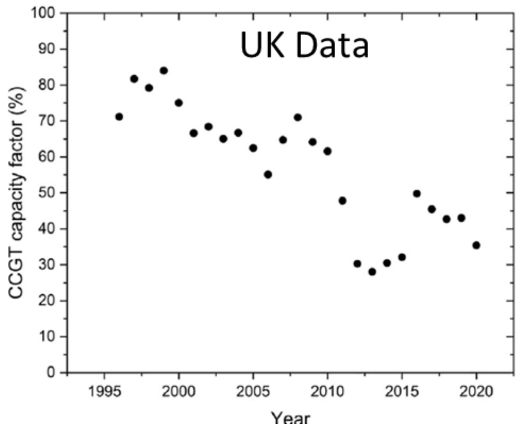
# Motivation

As penetration of intermittent renewables in the grid increases, the **capacity factor of NGCC will decrease** and **frequency of start-up and shut-down events of power plants with CCS will increase**




Mills, Andrew D., et al. "Impacts of variable renewable energy on wholesale markets and generating assets in the United States: A review of expectations and evidence." Renewable and Sustainable Energy Reviews 120 (2020)

- *The existing paradigm that CCS is a technology intended for steady state operation is being challenged for both electric generation and industrial applications.*



# Degree of Capture $_{\text{Duty Cycle}}$ = f (Capture Rate$_{\text{steady state}}$, Flexibility)

- Distinguish between the instantaneous Degree of Capture (DoC) and the Integrated Degree of Capture (IDoC)

$$DoC = 100.\left(\frac{CO_2^{Generated} - CO_2^{Emitted}}{CO_2^{Generated}}\right)$$

$$IDoC = \int_{t_0}^{t_f} DoC\,dt$$

- High capture rates under steady state operations could offset CO2 emitted during transient operations and enable to reach carbon intensity goals under flexible operations

Mac Dowell et al. "Optimization of post-combustion CO2 capture for flexible operation." Energy Procedia (2014)

# Could we achieve high capture?..

| Capture Tech | 90% $CO_2$ Capture | 99% $CO_2$ Capture | Comments |
|---|---|---|---|
| Chemical absorption | + | + | |
| Physical absorption | + | + | |
| Solid sorbent – chemical | + | + | |
| Solid sorbents – physical | + | +/- | Trade off with $CO_2$ purity<br>Process design optimization |
| Chemical looping | + | + | |
| Polymeric membranes* | + | - | Trade-off with $CO_2$ purity<br>High compression/low vacuum needed |
| Metal membranes ($H_2$) | + | + | |
| Ion transport membranes ($O_2$) | + | + | |
| Ceramic membranes | + | + | |
| Refrigeration | + | +/- | Higher capture rates achievable with $CO_2$-solid formation; purity issues with liquid formation |

(+) achievable, (-) not achievable

*technically achievable with higher selectivity



IEAGHG. *"Towards zero emissions CCS in power plants using high capture rates or biomass"* (2019)

# At what cost?

- Evaluated maximum limit of feasible $CO_2$ capture rate for a power and industrial sources of $CO_2$ (solvent PCC)
- CR> 98% economically unfeasible (more effectively addressed by CDR) for dilute $CO_2$ point sources (<4%). Marginal cost varies with $CO_2$ concentration with low concentration streams being systemically more costly

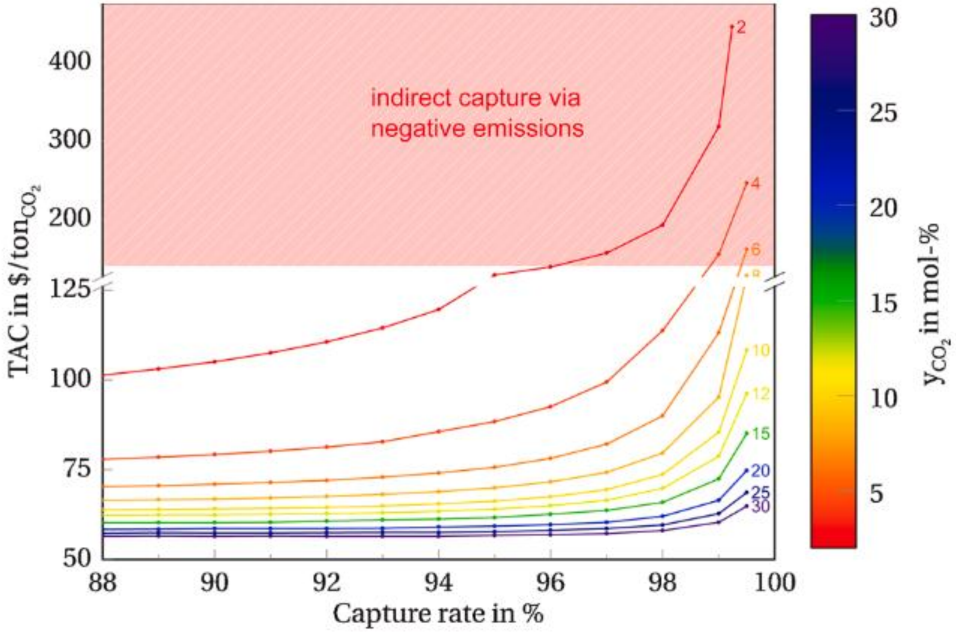



**Fig. 15.** Total annualised cost *TAC* plotted over capture rate. Same data as

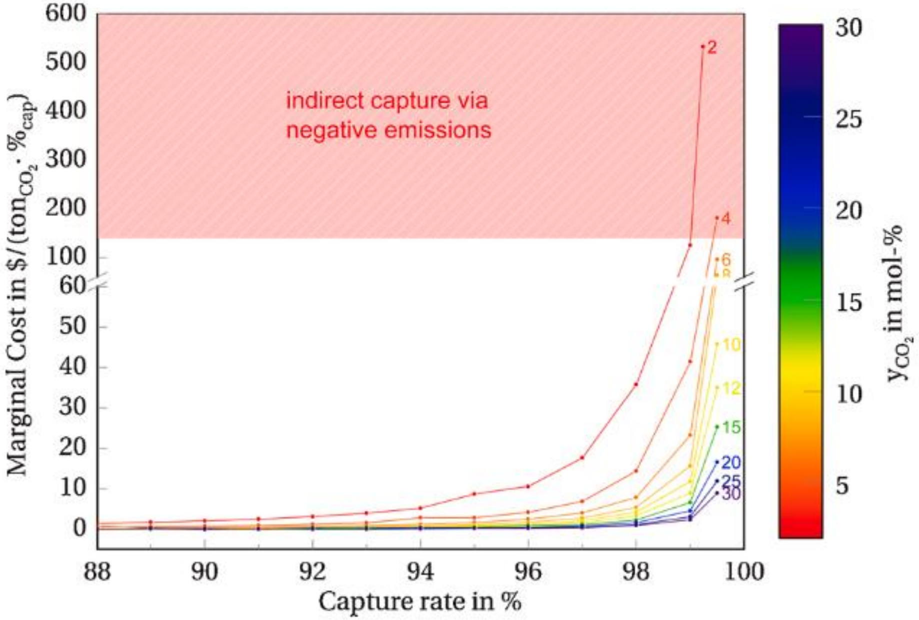
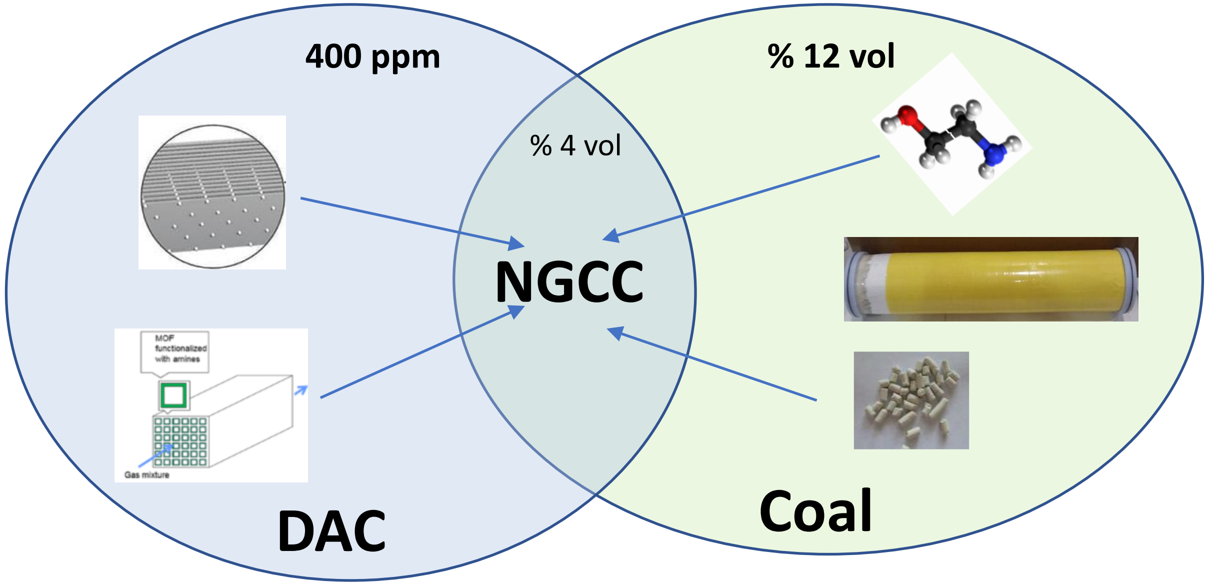



**Fig. 16.** Marginal cost defined as the derivative of the total annualised costs (see Eq. (2)) with regard to the capture rate as a function of $CO_2$ concentration (colour).



Brandl et al. *Beyond 90% capture: Possible, but at what cost?* International Journal of Greenhouse Gas Control 105 (2021)

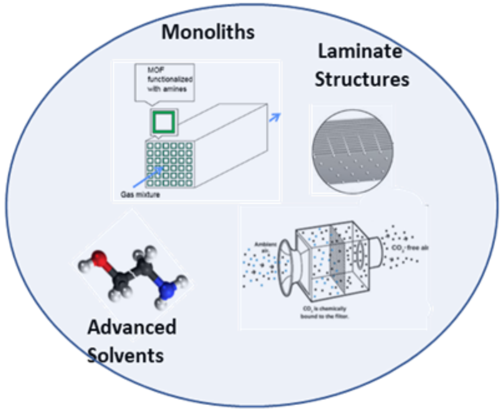
# 95+% NGCC Solution.. Leverage both PSC & DAC developments?



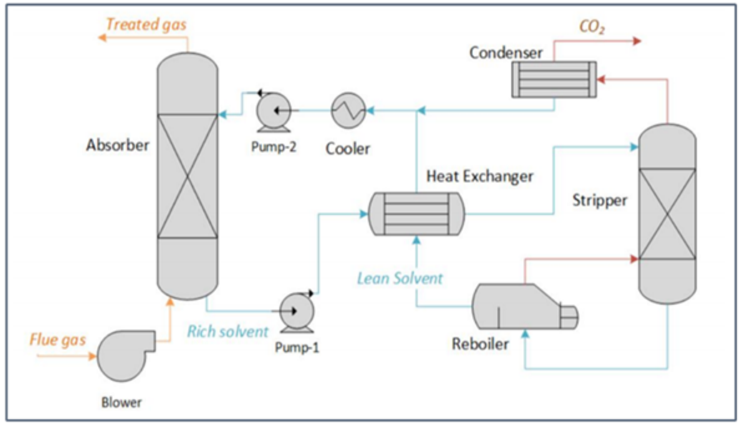
# FOA 2515 (2021-2022)

## AOI 1: *Bench-Scale Testing of Highly-Efficient Components and Processes for NGCC Plants*

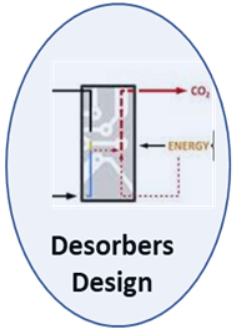
AOI1a: Components: Simulated Exhaust / Bench Scale, Batch Testing
AOI1b: Integrated Process: Simulated or Real Exhaust / Bench Scale, Continuous Testing




Components (AOI1a)




Integrated Process (AOI1b)




Components (AOI1a)

### Inputs

Carbon Capture Materials (TRL 2)* or Components/ Processes (TRL 3)**

- Material Systems Advanced Solvents (no aq. Amines)
- Hybrid/novel processes**
- No membranes

### Research Objectives (Targets)

- Improve stability for hydrothermal & oxidative degradation
- Increase vol. productivity (300 mol $CO_2$/l h)
- Reduce pressure drop (<150 Pa)
- Lower Heat Duty (<2 GJ/ton)

### Success Criteria

- 95+% Carbon capture efficiency
- 1 month steady-state operation**
- Progress towards 20% reduction in cost
- TRL 3*, TRL 4**
- Cost = f (% capture efficiency)
- Pathways to Net zero C

* AOI1a
** AOI 1b

# FOA 2515/ Round 1

| | Prime | Sub-recipients | Material | Innovation to achieve 95% | Prior / Related Work |
|---|---|---|---|---|---|
| 1A | GE | TDA Research, Inc., University of California Berkeley, and University of South Alabama | TEPA, Covalent organic framework (COF) | Plastic, tri-furcated structure, rotating contactor with indirect heating | DOE AIR2CO2 (DE-FE0031956) |
| 1A | SRI International | OLI Systems Inc.; Trimeric Corporation; Baker Hughes | Ammonia Mixed Salt Process (MSP) | Ultra-lean regenerator coupled with 2-absorber system to achieve 95% capture efficiency & produce almost dry, pressurized CO2. | 0.5 MWe scale for coal application is underway (DE-FE0031588) |
| 1B | UK University of Kentucky | EPRI, Louisville Gas & Electric and Kentucky Utilities | Dual Solvent System: Water-lean amines (bulk removal) + KOH-based electrochemical system (polishing step) | Coupled water-lean solvent with KOH polishing step to achieve up to 99% capture efficiency | Award selection (FOA 2402): development of KOH based electrochemical DAC system |
| 1B | TDA Research | Membrane Technology Research, Schlumberger, Dr. Ashok Rao | Polymer laminates of functionalized mixed matrix polymer (MMP) sheets: TEPA, PMA, PES | Microwave assisted temperature swing adsorption (MTSA) & vacuum desorption | MMP & VCSA (Coal): DE-SC0018682<br>MMP & MTSA (DAC): DE-SC0020848 |
| 1B | Cormetech Reliability. Delivered. | Global Thermostat, Middle River Power, Southern Company, Zero Carbon Partners | Extruded silica monolith with amine functionality (PEI) | Vacuum-free desorption,<br>Multi-brick contactor design (~ SCR installations), with no inlet air dilution | DAC with PPI monolith: 2402<br>DAC continuous process: FE0031957 |

polymethacrylate (PMA) tetraethylenepentamine (TEPA) polyether sulfone (PES) polymer

# FOA 2515/ Round 2

| Prime | Sub-recipients | Carbon Capture Technology |
| --- | --- | --- |
| Gas Technology Institute | University of Buffalo | Nano-confined ionic liquid (NCIL) membrane combined with a dehydration membrane |
| Susteon Inc. | University of Wyoming | Amino acid/MDEA based solvent and ionic liquid catalyst (ILC) |
| University of Kentucky Research Foundation | Electric Power Research Institute | Novel carbon capture materials and absorber reactor components that contribute to increased $CO_2$ mass transfer through increased turbulent gas-liquid interface and improved solvent wetting |
| Research Triangle Institute | Pacific Northwest National Lab<br>Partner: Schlumberger | Next generation non-aqueous solvent technology (GEN2NAS) in smaller footprint capture plants with rotating packed bed absorbers |

# Summary of Meeting Objectives

1. Review current FECM projects targeting high $CO_2$ capture rates as well as summarize ARPA-E FLECCS.
2. Identify **promising approaches** to achieve high $CO_2$ capture rates from point sources
3. Identify **challenges and R&D needs** to achieve high $CO_2$ capture rates and flexible operation
4. Identify **challenges and R&D needs** to maintain high capture rates over entire power duty cycles **in future grid scenarios**
5. Determine **economic trade-offs of achieving high capture rates**
6. Identify opportunities to **co-deploy point source capture and direct air capture** to reach net-zero

# Meeting Structure

- **Full workshop agenda:** [Net-zero Flexible Power: High Capture Rate Project Review Meeting | netl.doe.gov]
    - ***3 panel discussions:*** perspectives from technology developers, OEMs and utilities
    - ***2 sessions current FECM projects report-out***: 9 projects
    - ***3 talks***: research findings on feasibility of high capture rates and flexible operation
    - ***Report out from ARPA-E FLECCS program***
    - ***Breakout sessions:*** 3 topics to cover
- **Summary report** will follow the meeting