College of Engineering

Institute for Decarbonization and Energy Advancement

# Negative-Emissions Enabled Direct Air Capture with Coupled Electro-Production of Hydrogen at a 5 kg-per-hour Scale

(DE-FE0032255)

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University of Kentucky

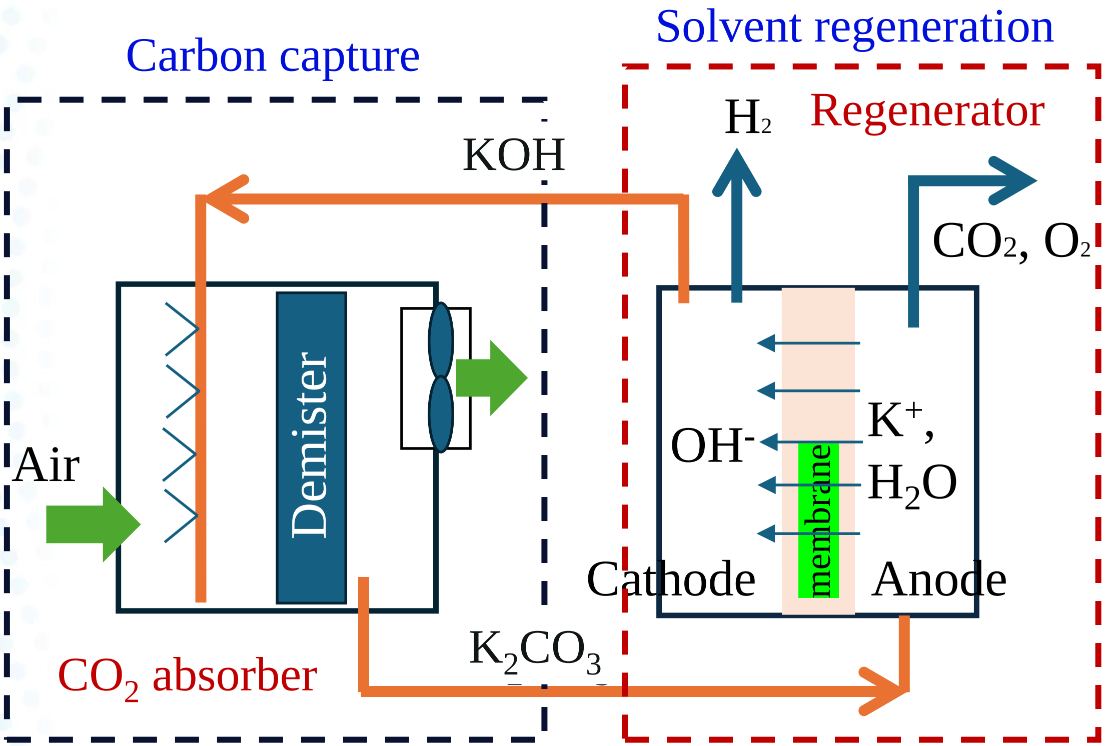
August 5th, 2024

# Project Overview

| | |
|---|---|
| **Project Title** | Negative-Emissions Enabled Direct Air Capture with Coupled Electro-Production of Hydrogen at a 5 kg-per-hour Scale |
| **Award #** | DE-FE0032255 |
| **Project Goals** | Develop an intensified and simplified DAC process at a TRL 5 scale that simultaneously produces $H_2$ to offset the process cost. |
| **Funding** | DOE: $2,999,681 Cost-Share: $749,943 |
| **Duration** | 08/1/2023 – 7/31/2026 , 3 Budget Periods |
| **Project Participants** | UKy, EPRI, PPL Corporation, and TotalEnergies |

# Solvent-Based Technology Applied to DAC

## Process Sketch for DE-FE0032255



Carbon capture

Solvent regeneration

Regenerator

$H_2$

KOH

$CO_2$, $O_2$

Demister

Air

$OH^-$

$K^+$, $H_2O$

membrane

Cathode

Anode

$CO_2$ absorber

$K_2CO_3$

**$CO_2$ capture**

$CO_2 + 2OH^- \rightarrow CO_3^{2-} + H_2O$

**Alkaline water electrolysis**

$2H_2O \rightarrow O_2 + 4H^+ + \text{electrons}$

$2H_2O + \text{electrons} \rightarrow H_2 + 2OH^-$

**$CO_2$ release**

$H^+ + CO_3^{2-} \rightarrow HCO_3^-$

$H^+ + HCO_3^- \rightarrow CO_2 + H_2O$

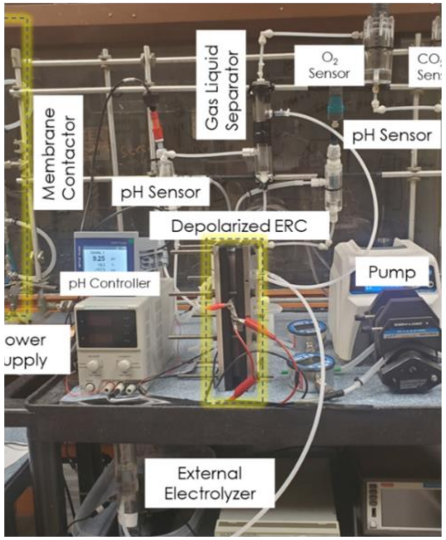
**Solvent regeneration**

$K^+ + OH^- \rightarrow KOH$

Feature: producing $H_2$ for sale, offsetting DAC operating cost

# History of DAC and $H_2$ Production Research

**DAC 1.0**, proof-of-concept



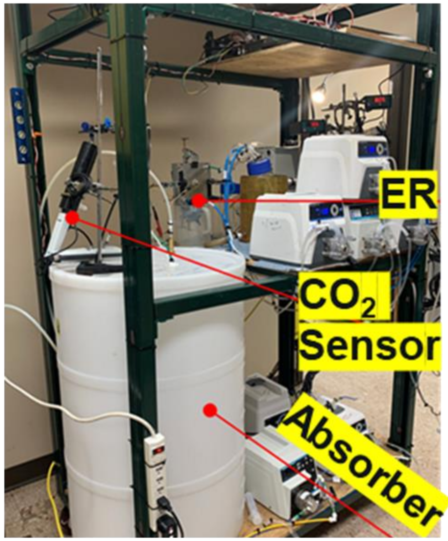
**2020 - 2021**

- 30 W regenerator
- 2 L $min^{-1}$ air contactor
- <1 kg $yr^{-1}$ $CO_2$ capture process
- <1 kg $yr^{-1}$ $H_2$ production

- Standard operation and explored depolarized operation

DE-FE0031962

**DAC 2.0**, size up



**2021 - 2023**

- 210 W regenerator
- 10 cfm air contactor
- 200 kg $yr^{-1}$ $CO_2$ capture
- 10 kg $yr^{-1}$ $H_2$

- Zero-gap cell design, electrode material selection
- ~500 kJ $mol^{-1}$ regeneration energy

DE-FE0032125

**DAC 2.5**, point-source integration

**2022 - 2023**

- 600 W regenerator
- 14 cfm gas with 4,000 ppm $CO_2$ contactor
- Negative Emissions, Integrated with point source capture (3-5% $CO_2$) as polisher
- Carbon polisher, 1700 kg $yr^{-1}$ process
- $H_2$ production at 77 kg $yr^{-1}$

**Our publication**

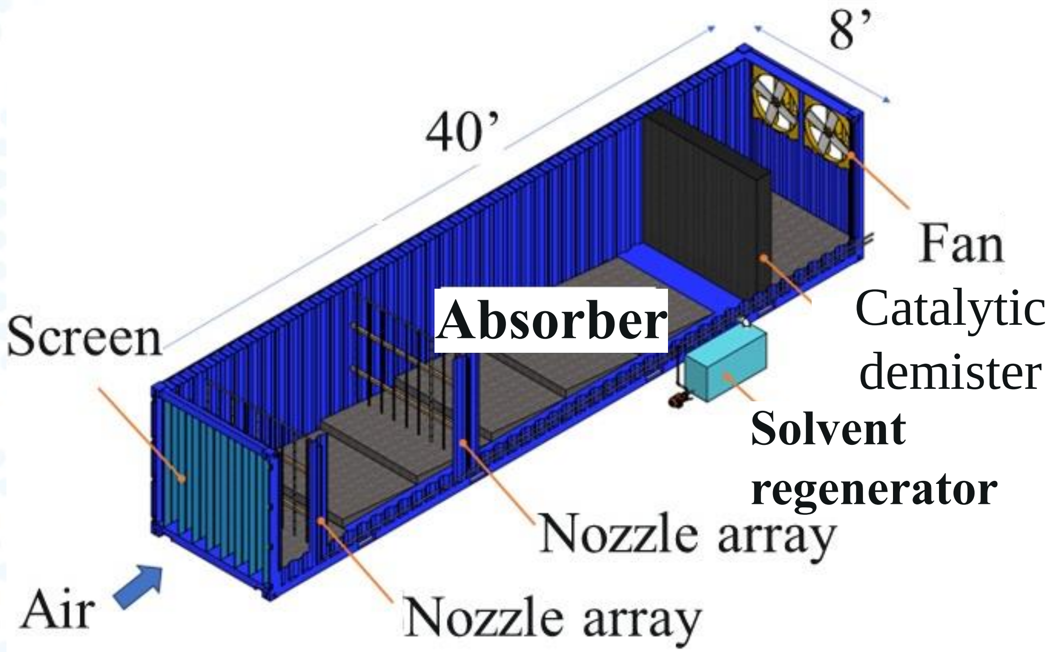
Journal of the Electrochemical Society 169 (4), 044527
ECS Advances 3 (2), 024501
International Journal of Applied Ceramic Technology 20 (5), 3014-3026
US 11857914B2

# 2023-2026: DAC 3.0

## Packing assisted cross-flow absorber and stacking solvent regenerator

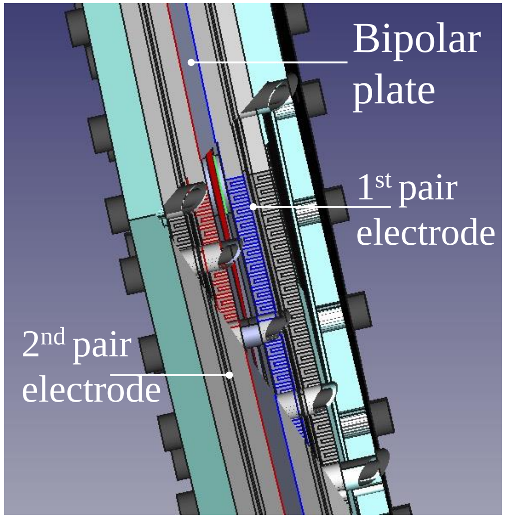
Equipment Sketch for DE-FE0032255

Capturing kiloton of $CO_2$ $year^{-1}$ from air



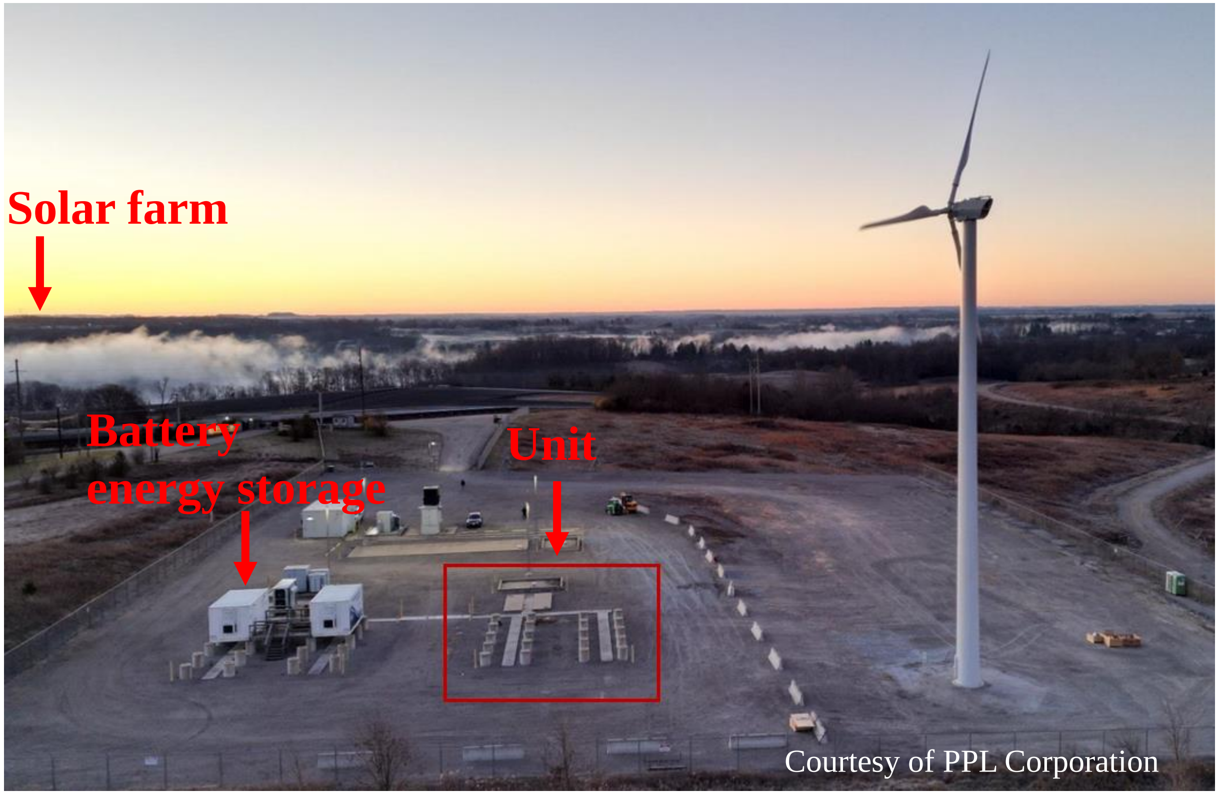
*Packing structure is not shown.

Solvent regenerator:
- Bipolar plate



# Project Goal

## Renewable powered DAC and $H_2$ production at PPL testing site



Courtesy of PPL Corporation

- The unit will be installed at the E.W. Brown Power Generation Plant affiliated with PPL Corporation.
- The unit will be powered by renewable energy coupled with battery energy storage, facilitating life cycle assessment.

# Motivation of Tasks 2 and 3 in BP 1

## Reduce energy needed for solvent regeneration

## Catalytic Demister for carbon capture (Task 2)

**Conventional**

$CO_2$ Release:

$H^+ + CO_3^{2-} \rightarrow HCO_3^-$
$H^+ + HCO_3^- \rightarrow CO_2 + H_2O$

2 $H^+$ process
requires 2 electrons

Through
catalyst
doping

**Performance Enhancement**

$CO_2$ Release:

$H^+ + HCO_3^- \rightarrow CO_2 + H_2O$

1 $H^+$ process
requires 1 electron

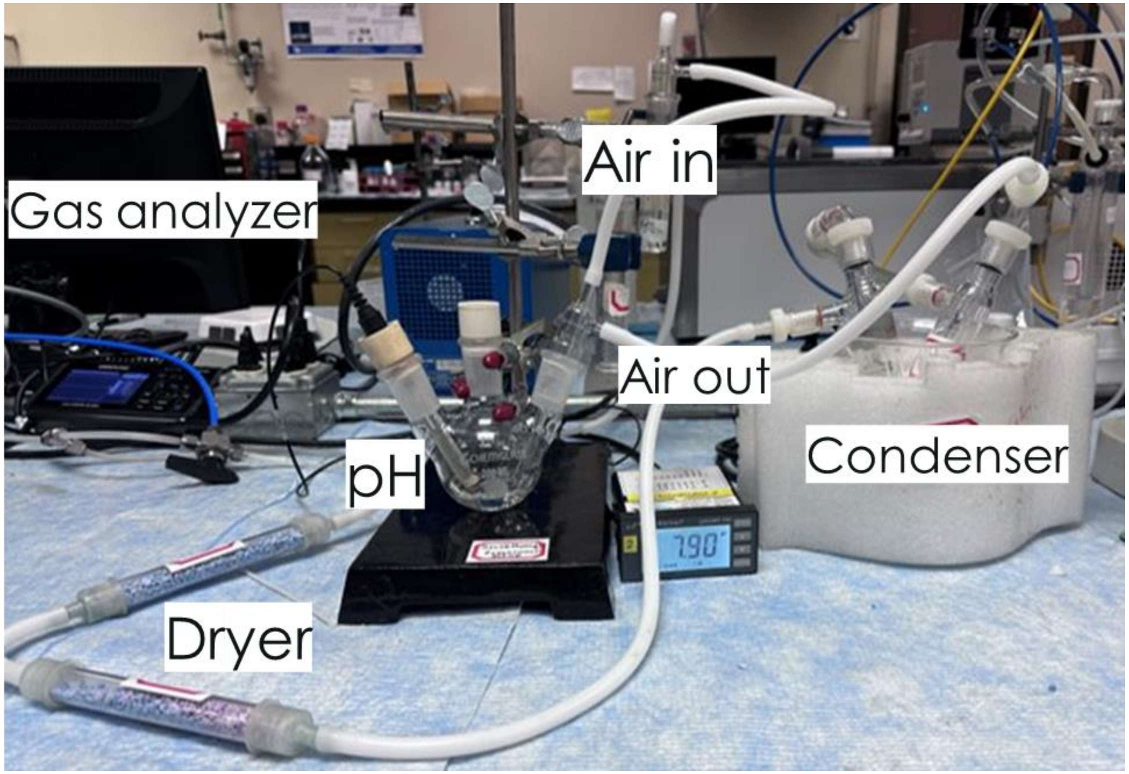
- Due to the small partial pressure of $CO_2$ in air, $CO_3^{2-}$ is the major product.
- Using a catalyst to promote $HCO_3^-$ formation, therefore reducing the number of electrons (electricity) for $H^+$ production.

## Catalytic electrode for solvent regeneration (Task 3)

- Using a catalytic material to minimize overpotential of water electrolysis or gas evolution reactions.

# Catalyst Development (Task 2)

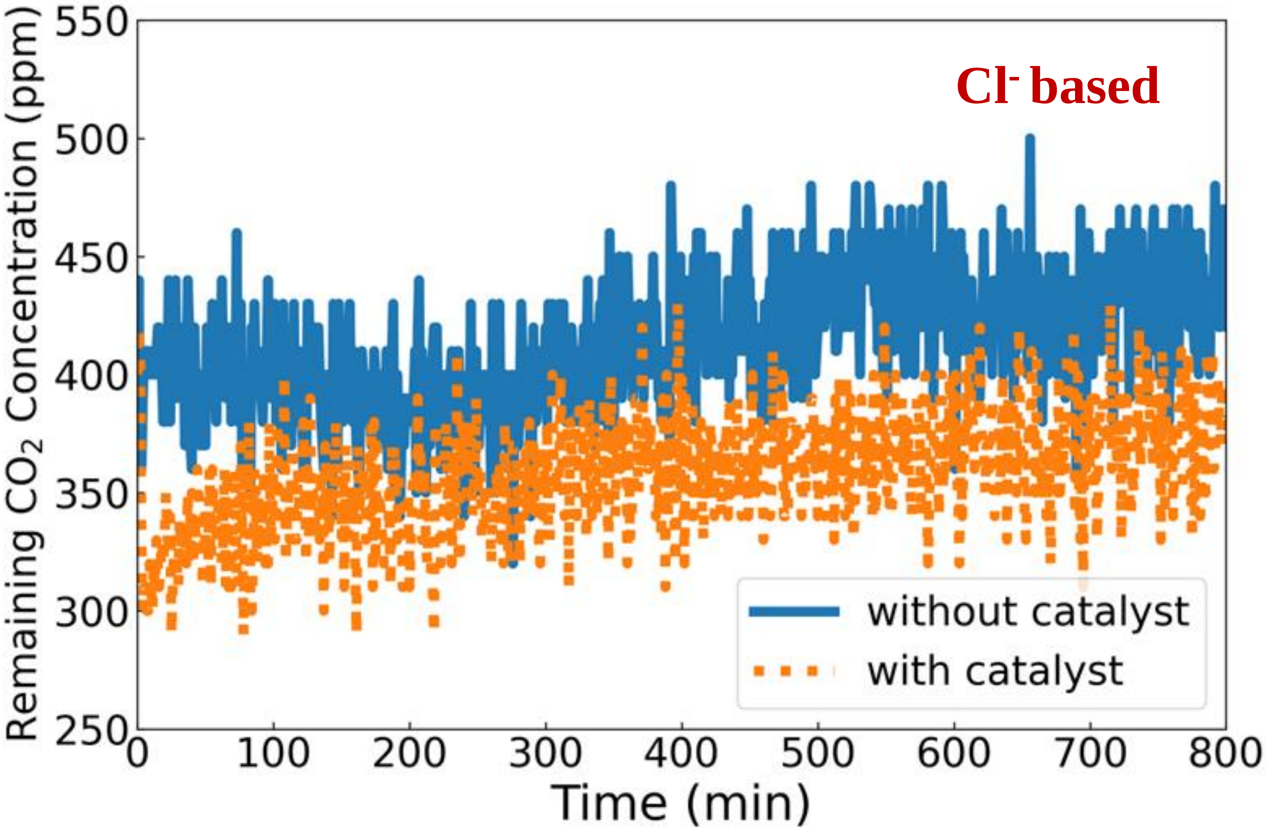
## Experimental



- Conditions: 0.5 L min$^{-1}$ of air, 5 mM catalyst in 1 M $K_2CO_3$ for air capture, Vaisala $CO_2$ gas analyzer
- Measured: remaining $CO_2$ concentration
- Goal: calculate carbon capture rate

# Catalyst Development

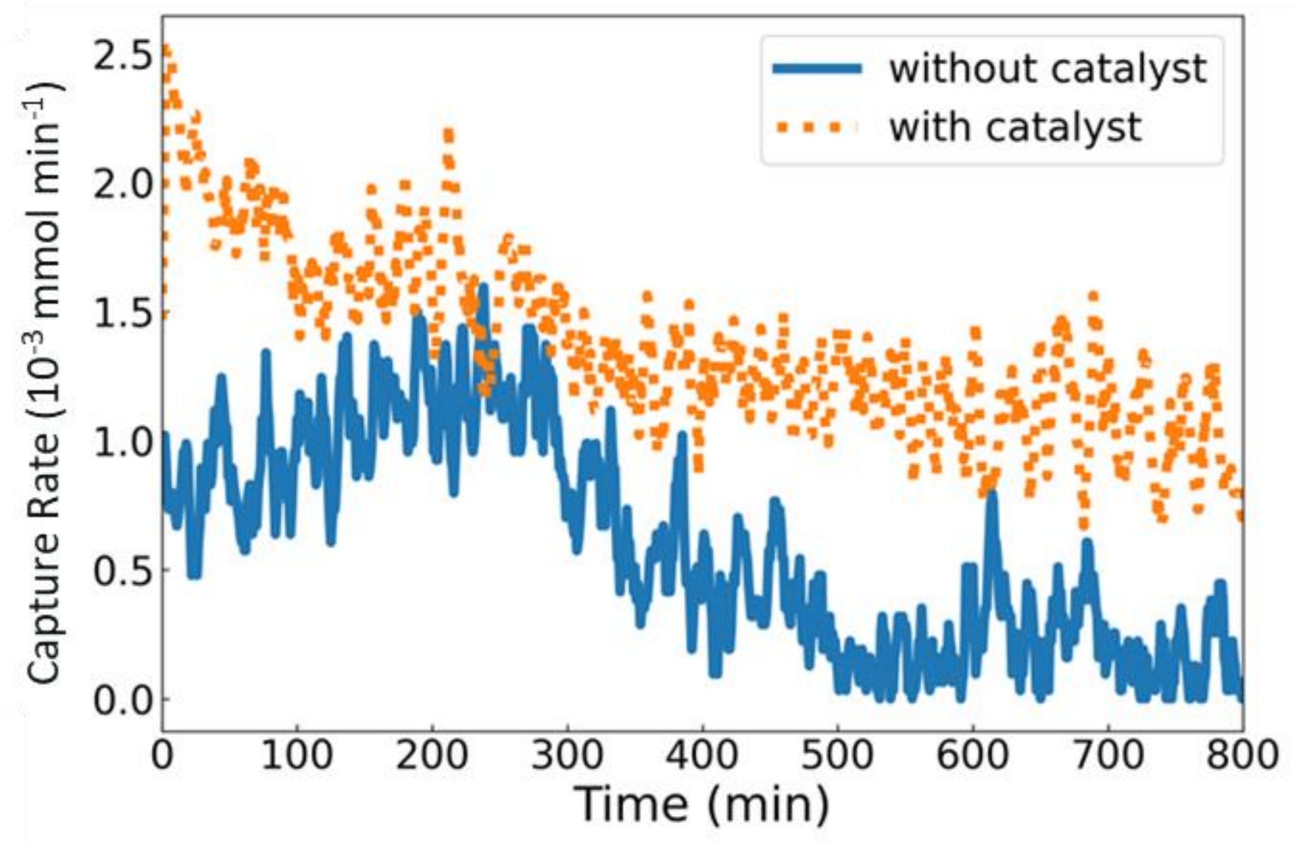
## $CO_2$ capture performance



- $BF_4^-$ based and $Cl^-$ based catalysts have been synthesized.
- CA mimic shows the enhanced carbon capture performance at high pH, due to its enhanced surface charge, facilitating $CO_2$ reacting with $CO_3^{2-}$ to produce $HCO_3^-$.

# Catalyst Development

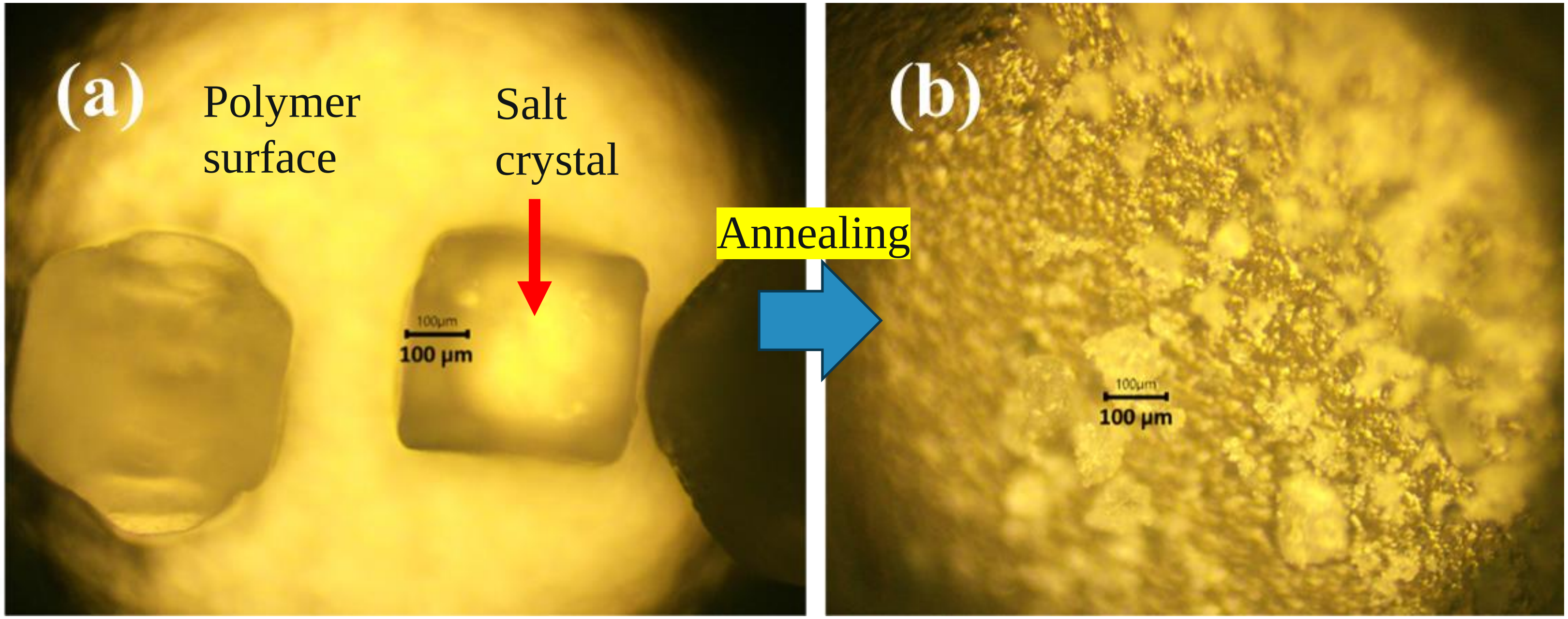
## Substantial increases in capture rate



- At 800 min, the rate without catalyst is almost diminished while the rate with catalyst is still measurable.

# Catalyst Development

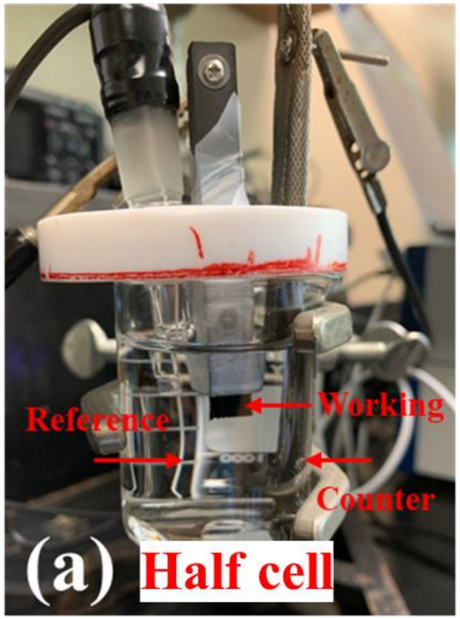
## Immobilization of non-soluble catalyst on demister

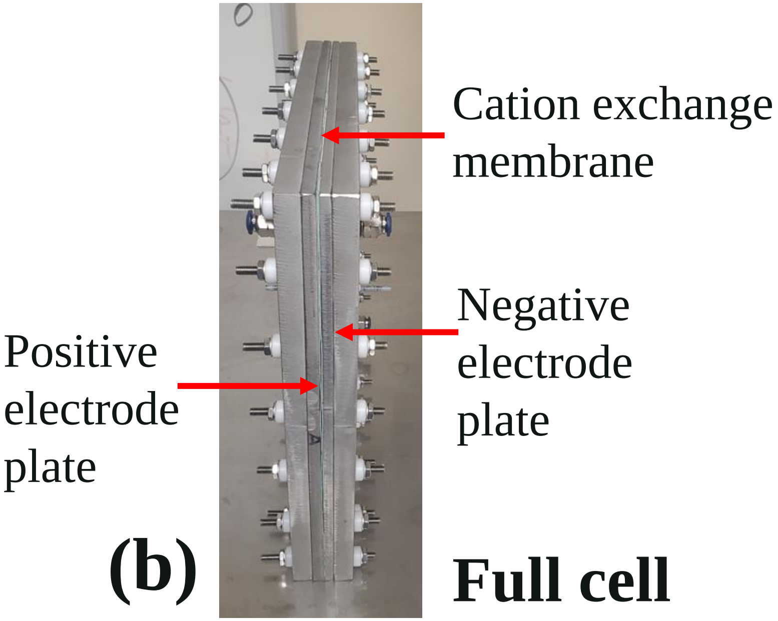


- Roughen surface of demister.
- Using water-soluble salt particles to induce surface pits on a demister through annealing, thereby establishing host sites for a catalyst.

# Catalyst Electrode Selection (Task 3)

## Experimental

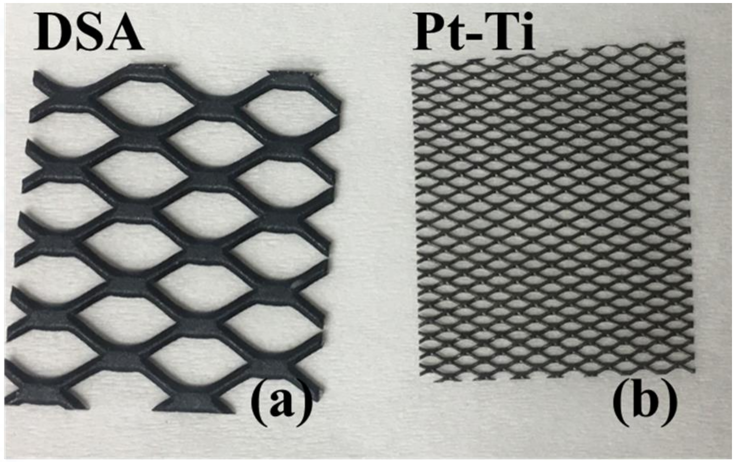


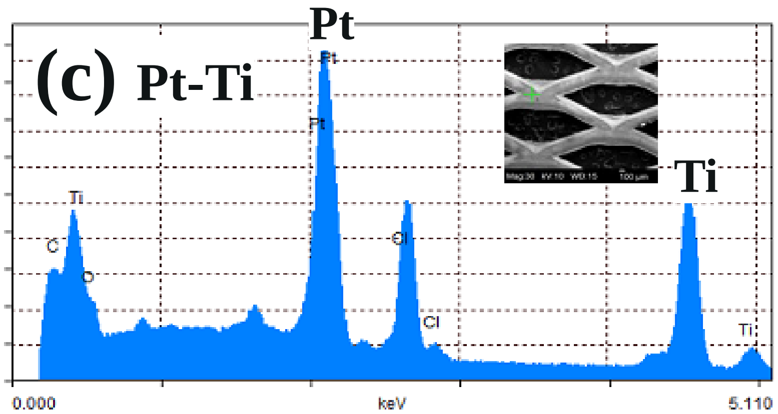


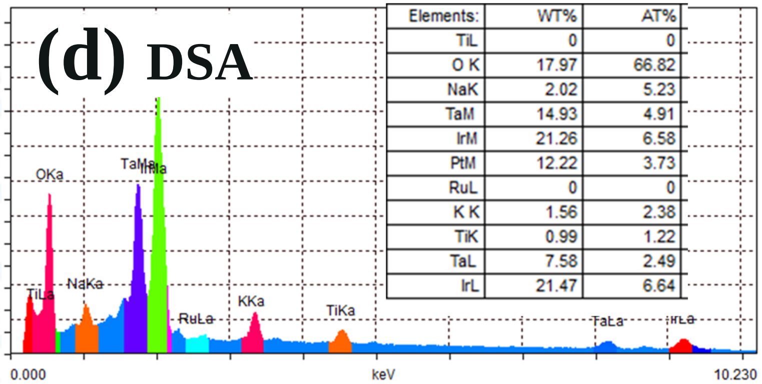
Half-cell: 3-electrode cell, cycling voltammetry, 100 mV $s^{-1}$, 1 – 1.5 M $K_2CO_3$
Full-cell: 400 $cm^2$ plate cell, constant current charging, varied charging currents, up to 2-6 M $K^+$.
Measured: current vs voltage
Goal: examine catalytic material stability under alkaline conditions

# Catalyst Electrode Selection

## Catalytic electrode: DSA vs Pt-Ti







| Elements: | WT% | AT% |
|---|---|---|
| TiL | 0 | 0 |
| O K | 17.97 | 66.82 |
| NaK | 2.02 | 5.23 |
| TaM | 14.93 | 4.91 |
| IrM | 21.26 | 6.58 |
| PtM | 12.22 | 3.73 |
| RuL | 0 | 0 |
| K K | 1.56 | 2.38 |
| TiK | 0.99 | 1.22 |
| TaL | 7.58 | 2.49 |
| IrL | 21.47 | 6.64 |

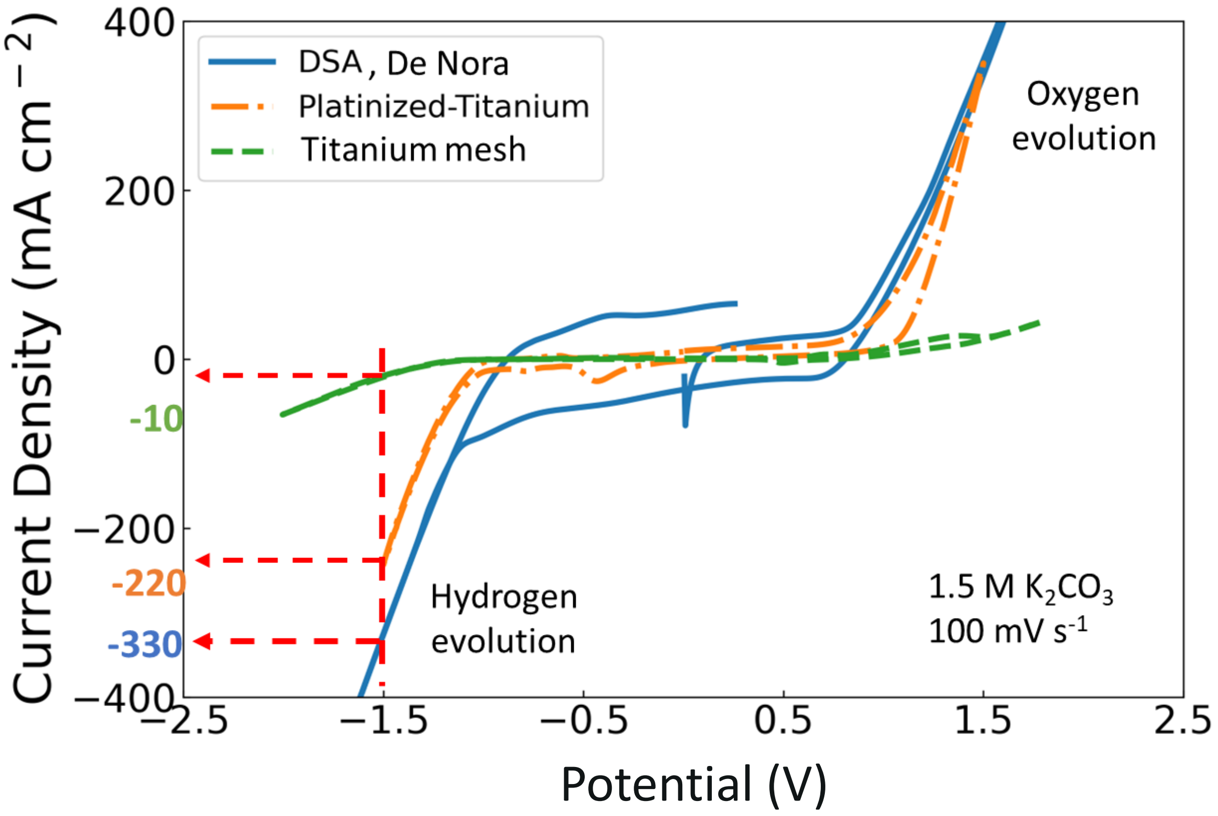
- Dimensional stable anode (DSA): a titanium mesh coated with Ir, Pt, etc
- Platinized titanium (Pt-Ti): a titanium mesh coated with Pt black.
- Both electrodes can catalyze gas evolution reactions.

https://www.denora.com/our-brands/DSA.html

https://www.denora.com/our-products/Anodes-for-Oxygen-Evolution/platinized-anodes.html

# Catalyst Electrode Selection

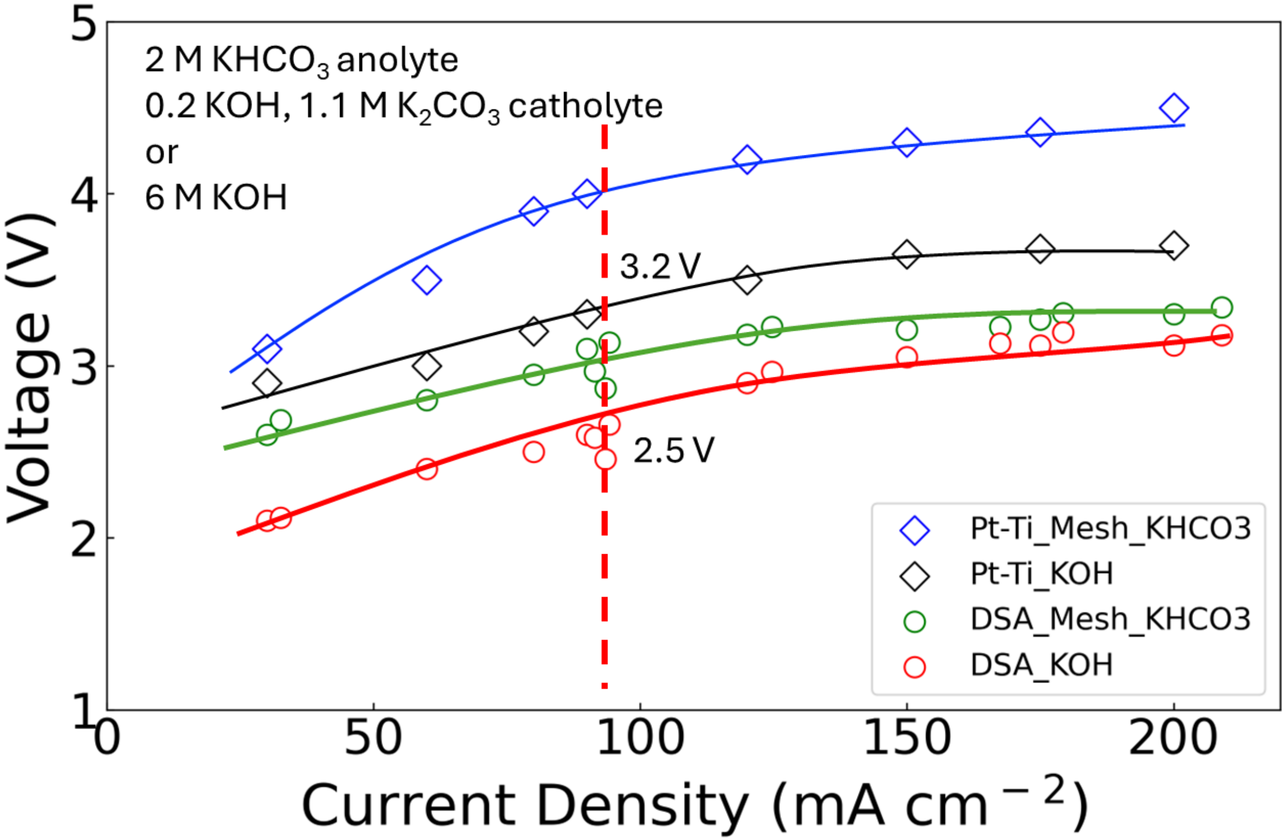
## Catalytic effect in half-cell: DSA > Pt-Ti



- DSA exhibits a more robust current response compared to Pt-Ti, indicating a potentially faster kinetic for gas evolution reactions.

# Catalyst Electrode Selection

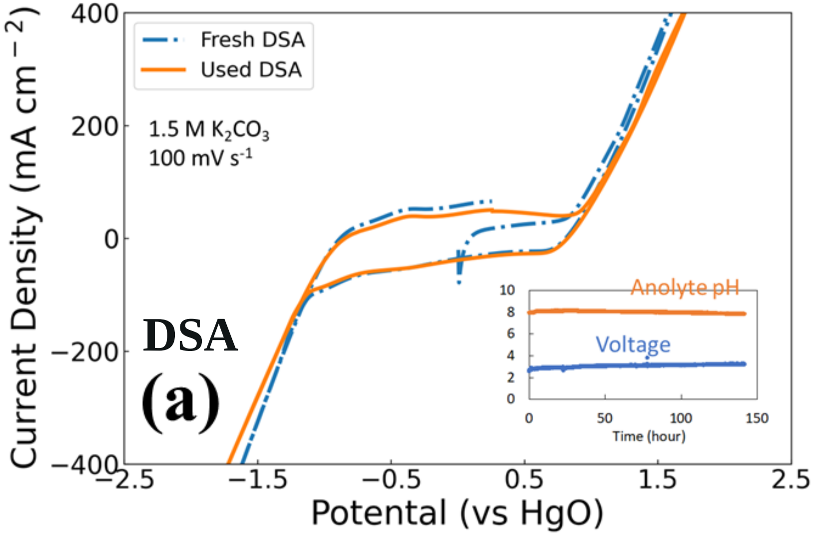
## Operating voltage of a full cell: DSA < Pt-Ti

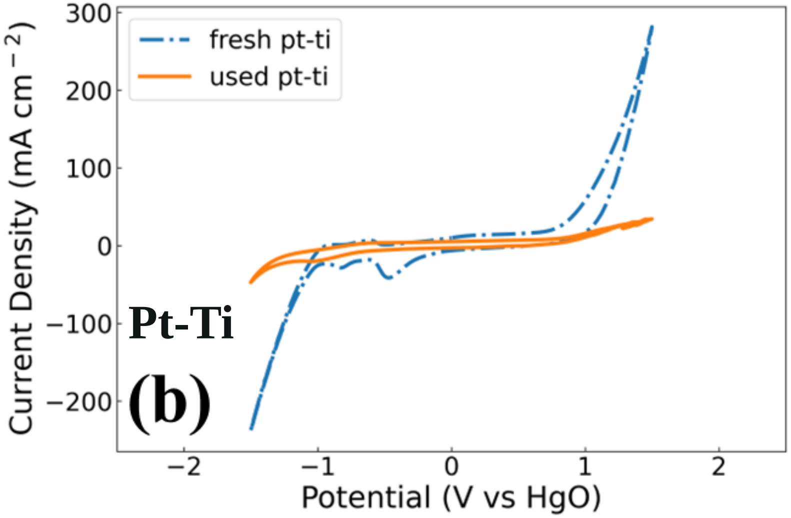


- DSA exhibits a lower voltage compared to Pt-Ti, consist with the results from the half-cell studies.

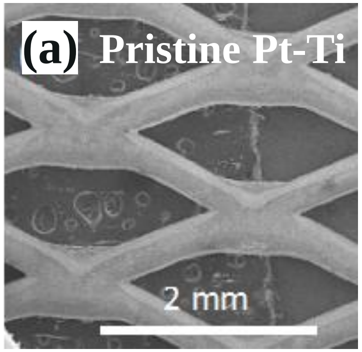
# Catalyst Electrode Selection

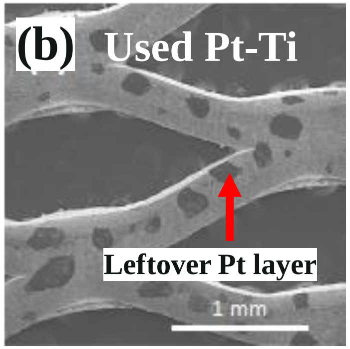
## Electrode stability: DAS > Pt-Ti





- Following a full-cell long-term test, half-cell tests for used anodes were repeated.
- DSA demonstrates greater electrochemical stability when it comes to gas evolution reactions.
- The decline in current behavior observed in Pt-Ti is attributed to the loss of the Pt catalytic layer.
- Select DSA as the catalytic electrode.

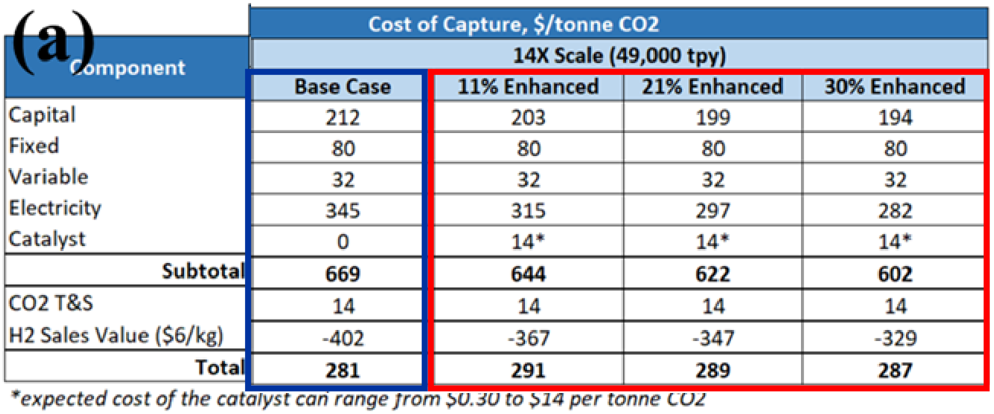




# Preliminary Techno-Economic Analysis (Task 4)

## Impact of catalyst on DAC cost

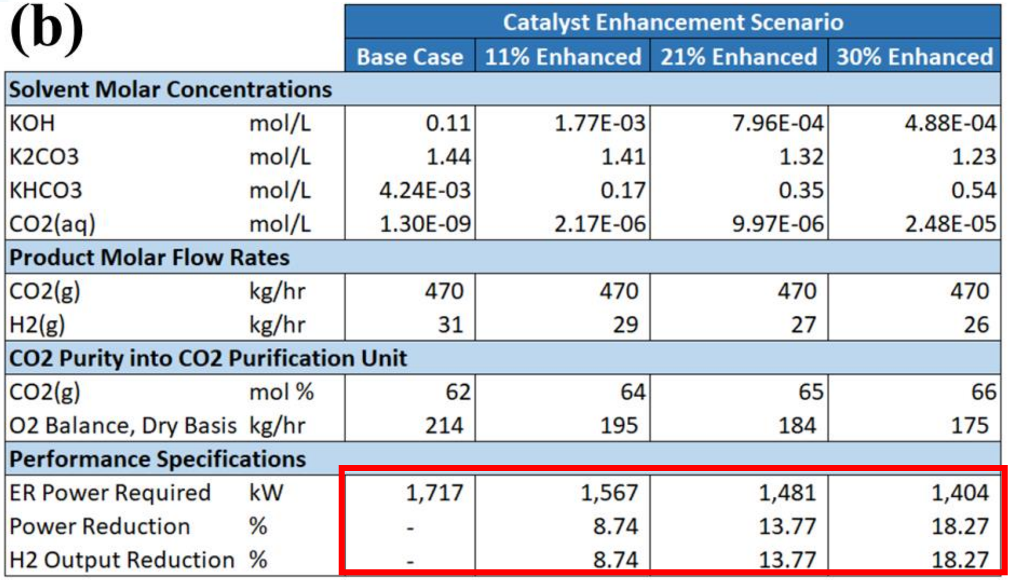
**(a)**



| Component | Cost of Capture, $/tonne CO2 | | | |
|---|---|---|---|---|
| | 14X Scale (49,000 tpy) | | | |
| | Base Case | 11% Enhanced | 21% Enhanced | 30% Enhanced |
| Capital | 212 | 203 | 199 | 194 |
| Fixed | 80 | 80 | 80 | 80 |
| Variable | 32 | 32 | 32 | 32 |
| Electricity | 345 | 315 | 297 | 282 |
| Catalyst | 0 | 14* | 14* | 14* |
| **Subtotal** | **669** | **644** | **622** | **602** |
| CO2 T&S | 14 | 14 | 14 | 14 |
| H2 Sales Value ($6/kg) | -402 | -367 | -347 | -329 |
| **Total** | **281** | **291** | **289** | **287** |

**expected cost of the catalyst can range from $0.30 to $14 per tonne CO2*

**(b)**



| | | Catalyst Enhancement Scenario | | | |
|---|---|---|---|---|---|
| | | Base Case | 11% Enhanced | 21% Enhanced | 30% Enhanced |
| **Solvent Molar Concentrations** | | | | | |
| KOH | mol/L | 0.11 | 1.77E-03 | 7.96E-04 | 4.88E-04 |
| K2CO3 | mol/L | 1.44 | 1.41 | 1.32 | 1.23 |
| KHCO3 | mol/L | 4.24E-03 | 0.17 | 0.35 | 0.54 |
| CO2(aq) | mol/L | 1.30E-09 | 2.17E-06 | 9.97E-06 | 2.48E-05 |
| **Product Molar Flow Rates** | | | | | |
| CO2(g) | kg/hr | 470 | 470 | 470 | 470 |
| H2(g) | kg/hr | 31 | 29 | 27 | 26 |
| **CO2 Purity into CO2 Purification Unit** | | | | | |
| CO2(g) | mol % | 62 | 64 | 65 | 66 |
| O2 Balance, Dry Basis | kg/hr | 214 | 195 | 184 | 175 |
| **Performance Specifications** | | | | | |
| ER Power Required | kW | 1,717 | 1,567 | 1,481 | 1,404 |
| Power Reduction | % | - | 8.74 | 13.77 | 18.27 |
| H2 Output Reduction | % | - | 8.74 | 13.77 | 18.27 |

- The base case show the cost of carbon capture is $281 tonne $CO_2$.
- Created 3 catalyst enhanced carbon capture scenarios at catalyst cost of $14 tonne$^{-1}$.
- DAC cost with catalyst > base case.
  - High cost of making catalyst
  - Reduction in $H_2$ production
- The use of catalyst reduce the power consumption of solvent regeneration.

# Community Benefits in BP 1

- We have students and interns working on the tasks of (1) catalyst immobilization and (2) classroom teaching materials of decarbonization.
  - Students have learned decarbonation technologies, e.g., point source carbon capture, DAC, and green hydrogen production.
- The teaching materials will be disseminated to the students at UKy college of engineering in the Fall semester 2024.

| Activity | Metrics and Data |
|---|---|
| Recruit student(s), BP1 | • 1 student recruited to participate in project |
| Collaborate with community stakeholders to develop educational content, BP2 | • 2 topics to be in the course materials. |
| Provide access to developed content, including online posting, classroom instruction, and/or outreaches, BP3 | • 2 topics developed for instructional purposes will be shared on the UK-IDEA website<br>• At least 1 presentation from a recruited student |

# Work Plan in BP 2 (August 2024 – July 2025)

Task 5 in BP 2

- Step 0: polish P&ID and 3-D CAD design
  - Finalizing mass chart and equipment selection.
- Step 1: procurement, balance of plant, fabrication
  - $CO_2$ absorber and solvent regenerator
- Step 2: process monitoring and control
  - Sensors (pH, conductivity, etc), datalogger, etc
  - HAZOP study
- Step 3: startup and commissioning
  - Testing unit at UK-IDEA
- Step 4: integration with solar power

# Lessons Learned

## Carbon Capture

- The duration of droplet suspension time is a critical factor in achieving efficient $CO_2$ capture.

## Solvent Regeneration

- The membrane seal, which prevents mixing between the catholyte and anolyte, is vital in the solvent regeneration process as it enables $CO_2$ recovery through pH swings.

# Summary

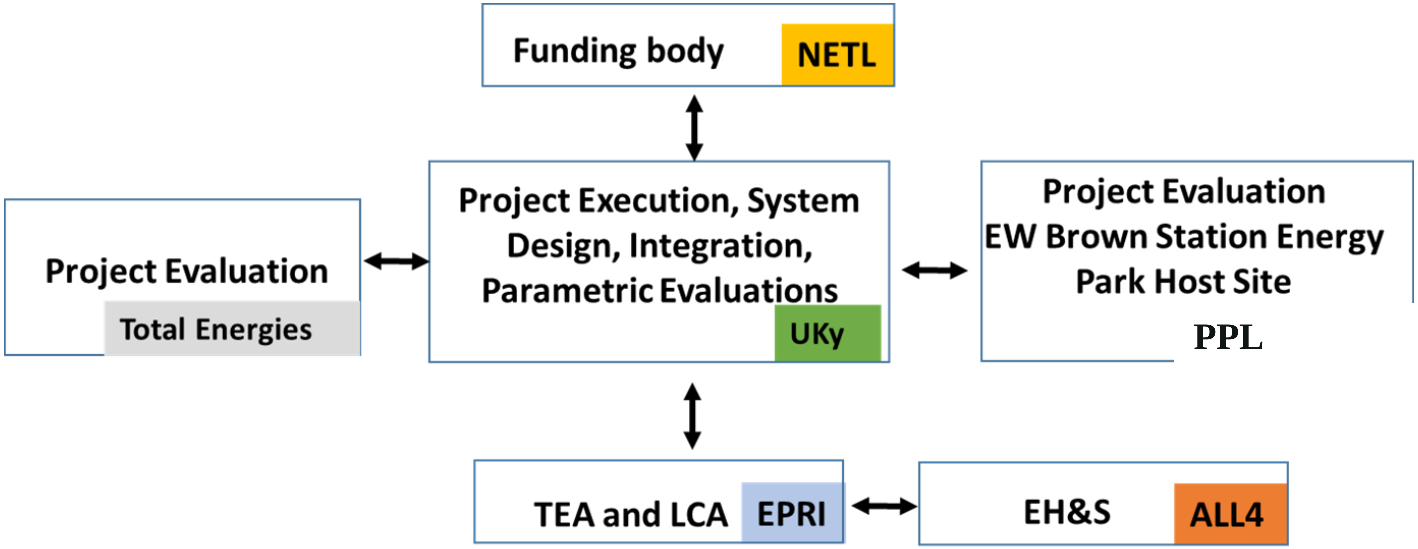
- We have developed 2 catalytic materials, **catalytic 3-D demister** and **stable catalytic electrode**, to reduce the energy consumption for solvent regeneration.

- Preliminary TEA indicates that the expense of capturing 1 ton of $CO_2$ may fall **below $300** when factoring in proceeds from $H_2$ sales (@ $6/kg) and catalyst cost.

# Acknowledgements

- **DOE-NETL**: Elliot Roth, Patricia Rawls, and Andrew Jones
- **EPRI**: Adam Berger and Kianna Marquez
- **PPL**: Aron Patrick, Chad Alkire, and Samuel Kelty
- **TotalEnergies**: Jeffrey Parkey and Phuc-Tien Thierry
- **UK-IDEA**: Jinwen Wang, Pom Kharel, Su Shi, Steve Summers, Matt Button, Priyabrata Biswal, Siza Chaudhary, Lisa Richburg, Moushumi Sarma; **Student and Intern**: Emily Liu, Jenna Roseman, Maya Rao, Jesse Okorafor, Emmanuel Ohiomuba, Siza Chaudhary, Patrick Adoba

# Project Team and Division of Responsibility



Funding body **NETL**

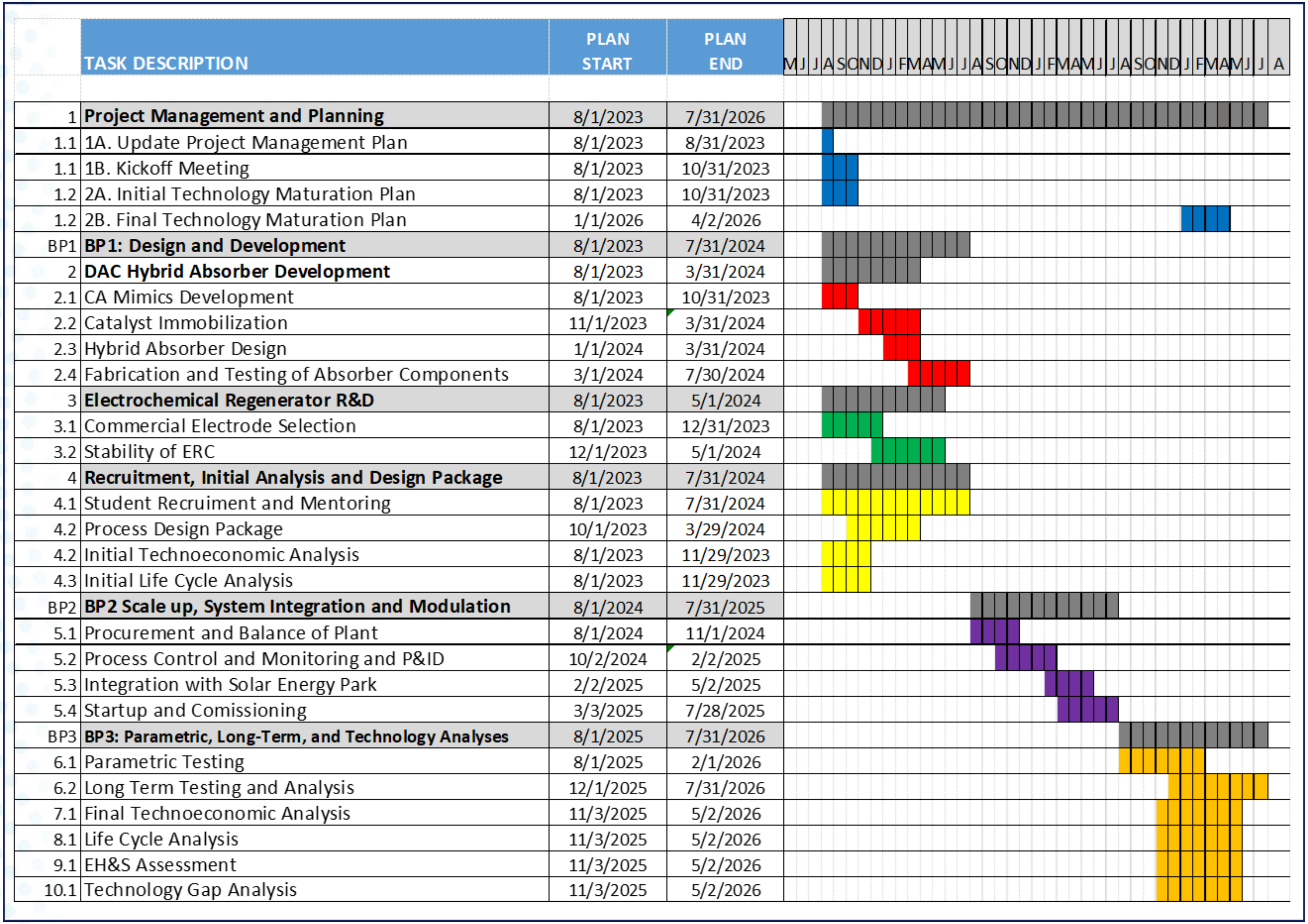
Project Execution, System Design, Integration, Parametric Evaluations **UKy**

Project Evaluation **Total Energies**

Project Evaluation EW Brown Station Energy Park Host Site **PPL**

TEA and LCA **EPRI**

EH&S **ALL4**



| | TASK DESCRIPTION | PLAN START | PLAN END |
|---|---|---|---|
| 1 | **Project Management and Planning** | 8/1/2023 | 7/31/2026 |
| 1.1 | 1A. Update Project Management Plan | 8/1/2023 | 8/31/2023 |
| 1.1 | 1B. Kickoff Meeting | 8/1/2023 | 10/31/2023 |
| 1.2 | 2A. Initial Technology Maturation Plan | 8/1/2023 | 10/31/2023 |
| 1.2 | 2B. Final Technology Maturation Plan | 1/1/2026 | 4/2/2026 |
| BP1 | **BP1: Design and Development** | 8/1/2023 | 7/31/2024 |
| 2 | **DAC Hybrid Absorber Development** | 8/1/2023 | 3/31/2024 |
| 2.1 | CA Mimics Development | 8/1/2023 | 10/31/2023 |
| 2.2 | Catalyst Immobilization | 11/1/2023 | 3/31/2024 |
| 2.3 | Hybrid Absorber Design | 1/1/2024 | 3/31/2024 |
| 2.4 | Fabrication and Testing of Absorber Components | 3/1/2024 | 7/30/2024 |
| 3 | **Electrochemical Regenerator R&D** | 8/1/2023 | 5/1/2024 |
| 3.1 | Commercial Electrode Selection | 8/1/2023 | 12/31/2023 |
| 3.2 | Stability of ERC | 12/1/2023 | 5/1/2024 |
| 4 | **Recruitment, Initial Analysis and Design Package** | 8/1/2023 | 7/31/2024 |
| 4.1 | Student Recruiment and Mentoring | 8/1/2023 | 7/31/2024 |
| 4.2 | Process Design Package | 10/1/2023 | 3/29/2024 |
| 4.2 | Initial Technoeconomic Analysis | 8/1/2023 | 11/29/2023 |
| 4.3 | Initial Life Cycle Analysis | 8/1/2023 | 11/29/2023 |
| BP2 | **BP2 Scale up, System Integration and Modulation** | 8/1/2024 | 7/31/2025 |
| 5.1 | Procurement and Balance of Plant | 8/1/2024 | 11/1/2024 |
| 5.2 | Process Control and Monitoring and P&ID | 10/2/2024 | 2/2/2025 |
| 5.3 | Integration with Solar Energy Park | 2/2/2025 | 5/2/2025 |
| 5.4 | Startup and Comissioning | 3/3/2025 | 7/28/2025 |
| BP3 | **BP3: Parametric, Long-Term, and Technology Analyses** | 8/1/2025 | 7/31/2026 |
| 6.1 | Parametric Testing | 8/1/2025 | 2/1/2026 |
| 6.2 | Long Term Testing and Analysis | 12/1/2025 | 7/31/2026 |
| 7.1 | Final Technoeconomic Analysis | 11/3/2025 | 5/2/2026 |
| 8.1 | Life Cycle Analysis | 11/3/2025 | 5/2/2026 |
| 9.1 | EH&S Assessment | 11/3/2025 | 5/2/2026 |
| 10.1 | Technology Gap Analysis | 11/3/2025 | 5/2/2026 |