DOE Bioenergy Technologies Office (BETO) 2023 Project Peer Review

PEM CO_2 Electrolyzer Scaleup to Enable MW-scale Electrochemical Modules

Dr. Sadia Kabir[#], Dr. Theodore Gao,
Dr. Kathryn Corp, Dr. Sichao Ma, Dr. Kendra Kuhl (PI)

twelve
carbon transformation
for a climate positive world

April 7, 2023 | Carbon Dioxide Utilization

Twelve: Utilizing Biogenic CO_2

Enabling the sustainable use of domestic biomass and waste resources for the <u>production of biofuels and bioproducts</u>

Antarctica, January 13, 2020: World's first CO_2-based sunglasses reach the South Pole

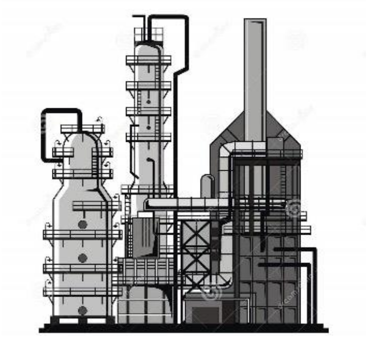
Twelve: Overview

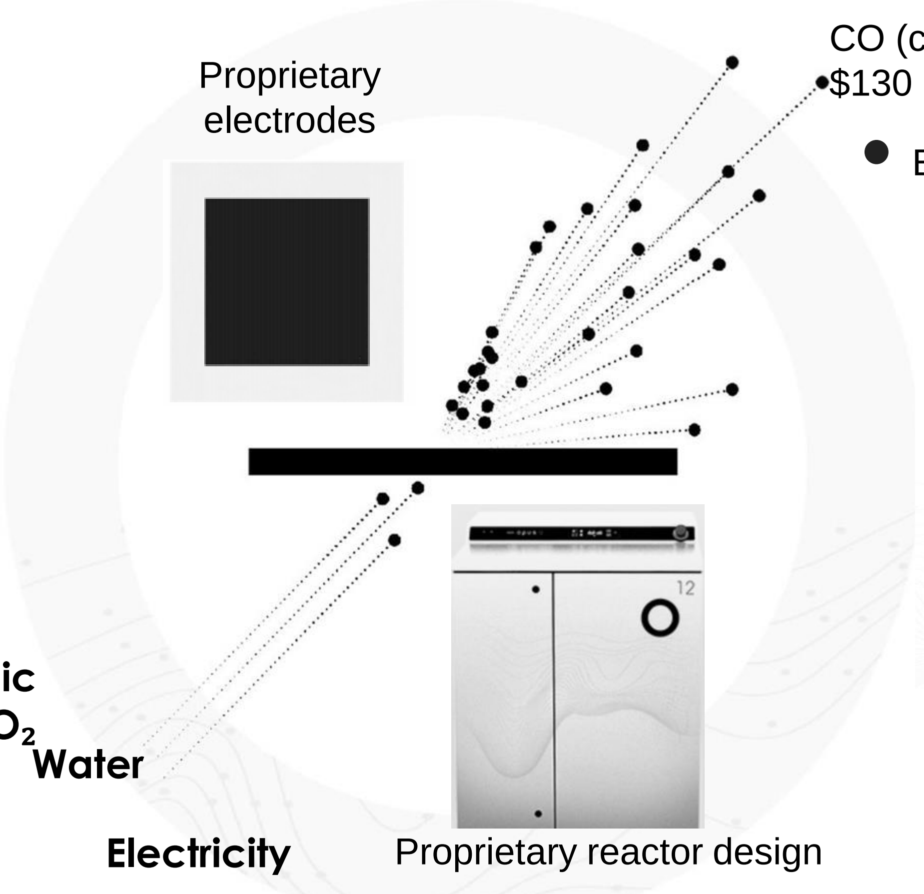
Developing and scaling a platform for a reactor that electrochemically transforms biogenic CO_2 to chemicals and fuels

1 **INPUTS: CO_2, WATER, ELECTRICITY**

2 **ELECTROCHEMICAL REDUCTION OF CO_2**

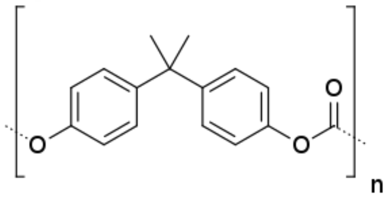
3 **OUTPUTS: PRODUCTS THAT DROP INTO EXISTING SUPPLY CHAINS**

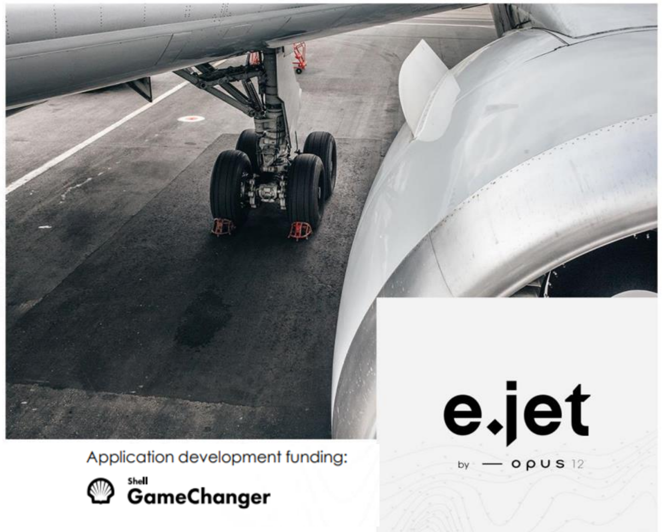




CO (chemicals \$80 billion; jet fuel: \$130 billion, 2025)

- Ethylene (\$250 billion TAM, 2025)
- Biogas (\$25 billion TAM, 2025)
- Oxygen





World first CO_2 derived polycarbonate

Roadmap: Biogenic CO_2 Conversion to Products at Scale

1

2020:
1-5 kg/ day CO_2

2

Currently:
100 kg per day CO_2

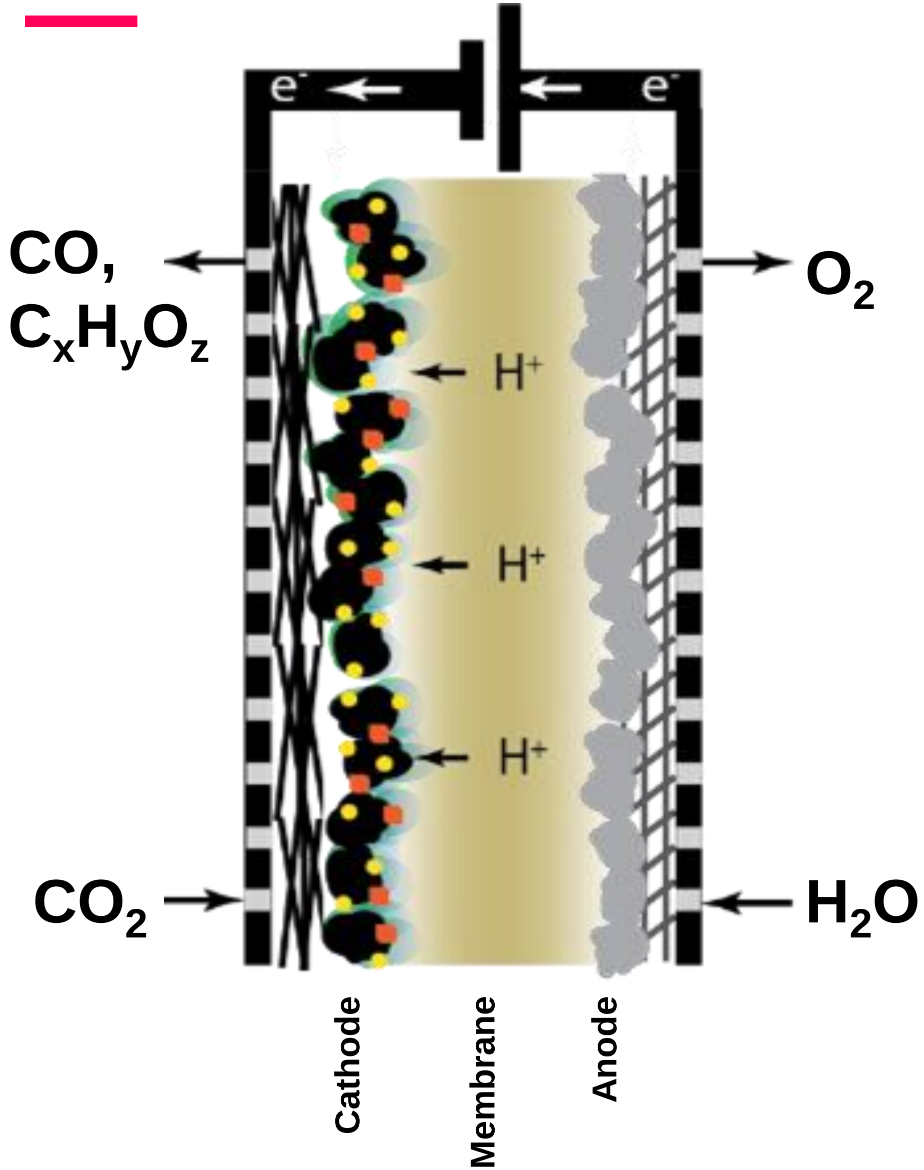
3

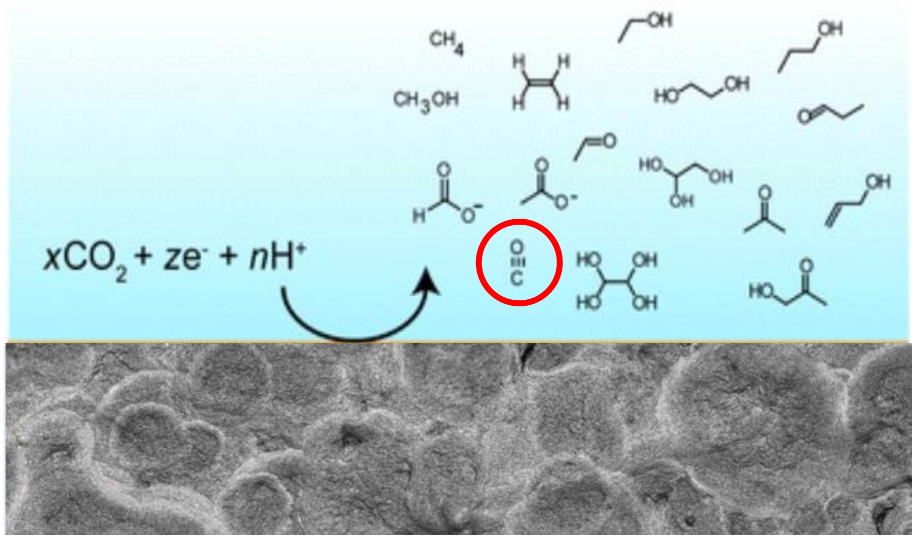
2023: 1-10 tonnes
per day CO_2

Approach

- Technical approach
- Go/no-go milestones
- Project management and risk analysis

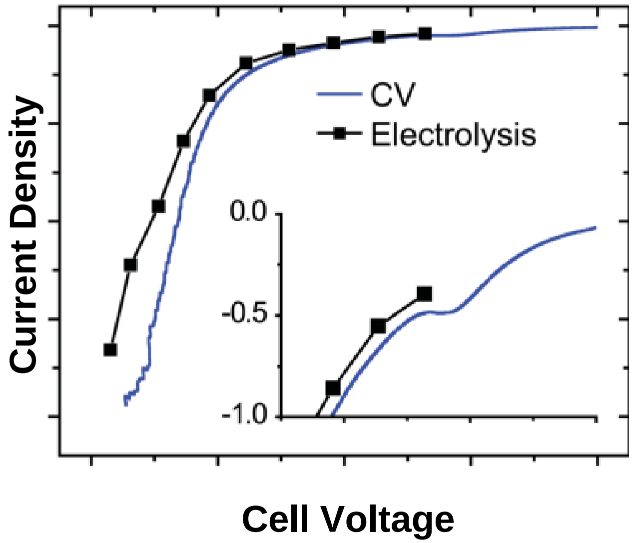
Technical Approach: Twelve's core innovation is a membrane electrode assembly (MEA) that enables CO_2 electrolysis



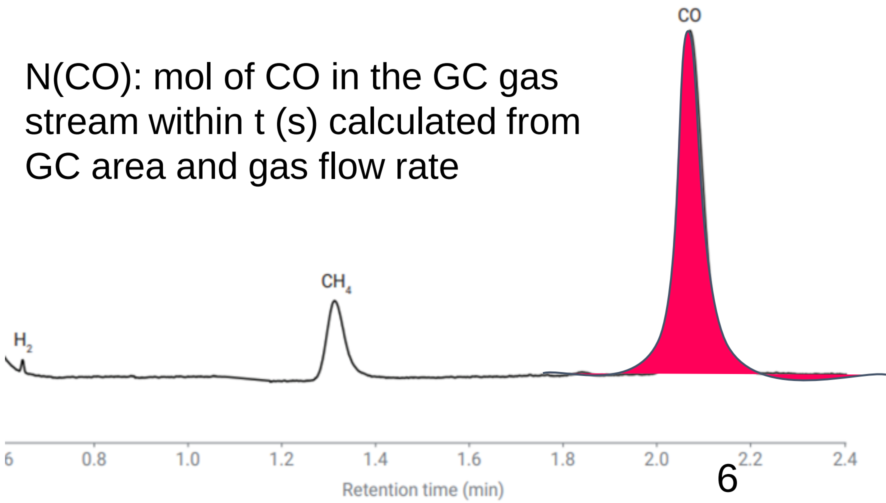


Faradaic Yield (CO) = n x N(CO) x F / Q

- n = no. of electrons transferred for CO_2 conversion
- N(CO) = moles of CO
- F = Faraday constant
- Q = Charge

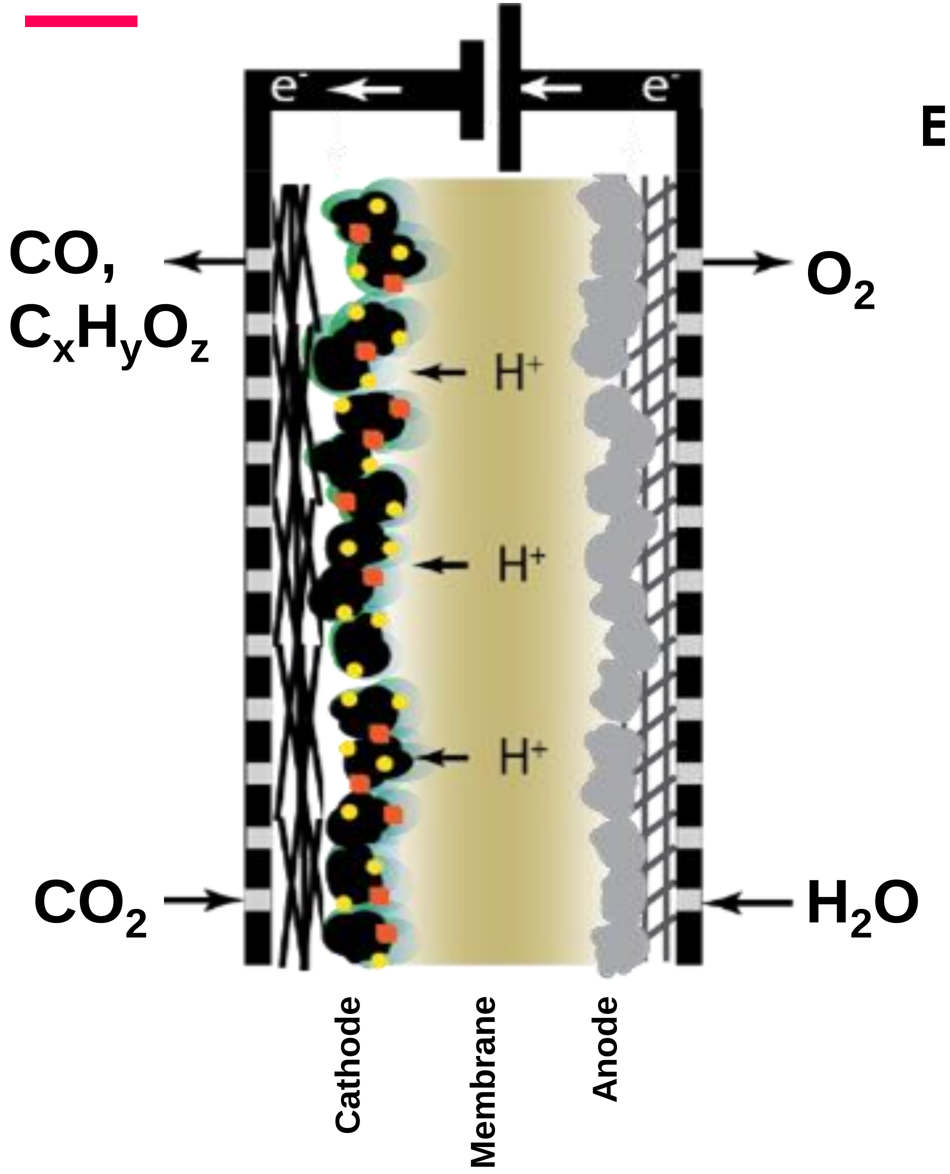


N(CO): mol of CO in the GC gas stream within t (s) calculated from GC area and gas flow rate



Energy Environ. Sci., 2012,**5**, 7050-7059

Technical Approach: Twelve's core innovation is a membrane electrode assembly (MEA) that enables CO_2 electrolysis



Energy Efficiency = Faradaic Yield x Voltage Efficiency

THE METRICS THAT MATTER FOR COST-EFFECTIVE CO_2 ELECTROLYSIS

1. FARADAIC YIELD

The percent of the electrical current through the system that goes to producing the desired product.

2. VOLTAGE EFFICIENCY

The thermodynamic minimum voltage divided by the actual voltage.

3. CURRENT DENSITY

The amount of current per electrode area needed to convert CO_2 to CO and other hydrocarbons.

4. LIFETIME

How long the electrochemical reactor runs without a loss in energy efficiency or current density.

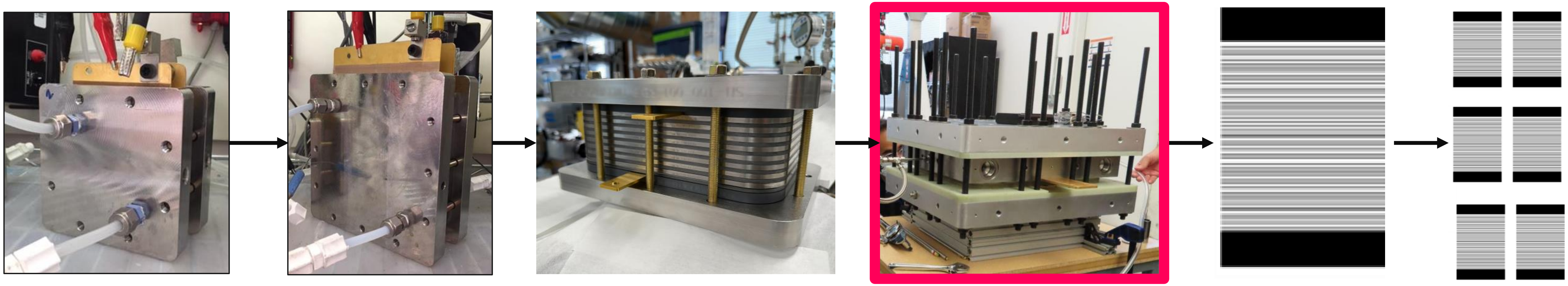
5. CO_2 UTILIZATION

How much of the input CO_2 to the reactor is converted to product in a single pass.

Improving technical performance metrics that dictate system OpEx and CapEx

Relevance: The BETO grant represents the turning point toward mass production of PEM CO_2 electrolyzer stacks

BETO

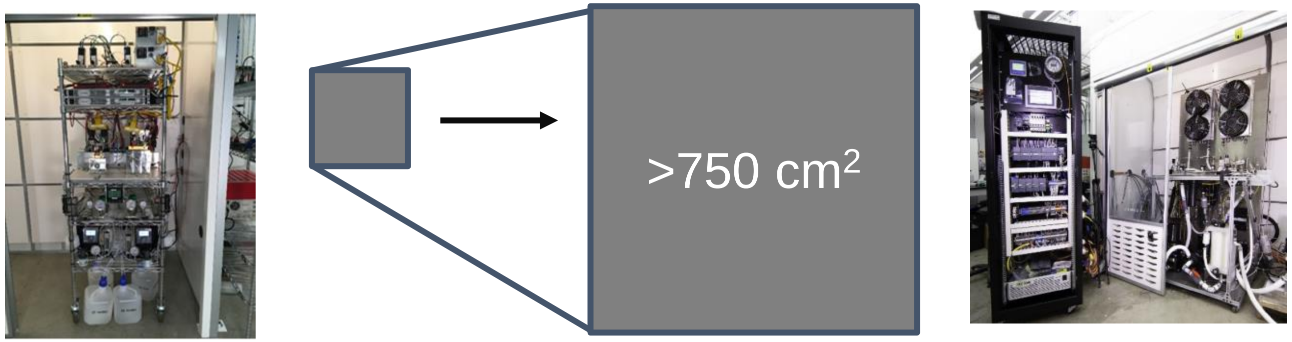


1-cell | 1-cell | 10- to 30-cell | 1-cell | Many cells | Multi-stack

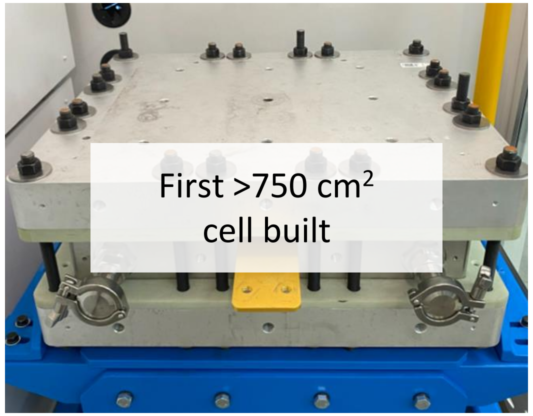
25 cm^2 | 100 cm^2 | >750 cm^2

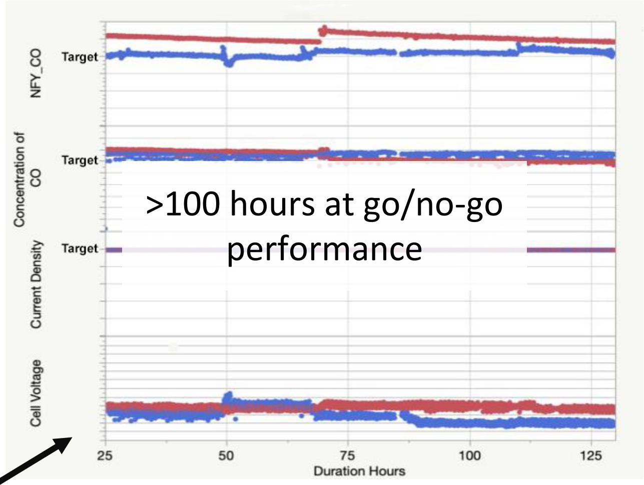
BETO

Scaling size to industrially-relevant >750 cm^2 format which will serve as the platform for our future large-scale systems

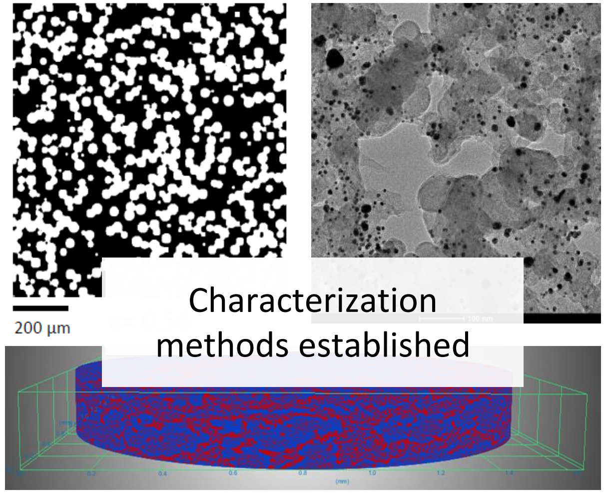


Budget Phases and Go/No-Go Milestones:





BP1 BP2 BP3



Go/No-Go Milestone:

- >750 cm^2
- >100 hours
- 100% of target current density and Faradaic efficiency
- +/- 5% variation across 4 samples

End of Project Goal:

- >750 cm^2
- >1000 hours
- 100% of target current density, Faradaic efficiency, and CO_2 utilization

National Laboratory and Academic Collaboration:
Project participants and expertise

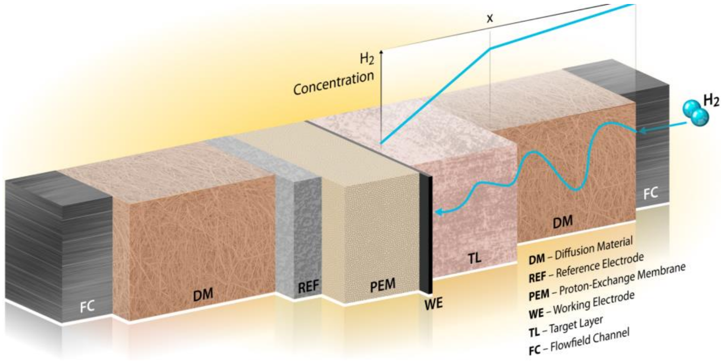
KC Neyerlin
Operando diagnostics

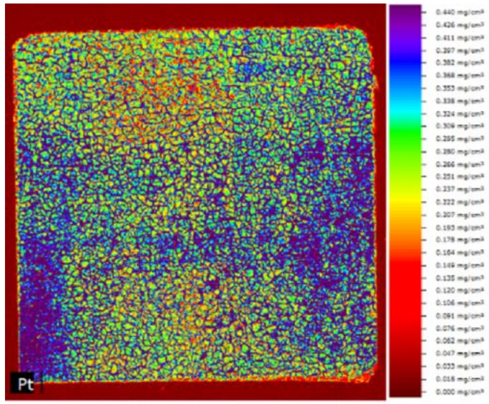
Ling Tao
LCA and process modeling

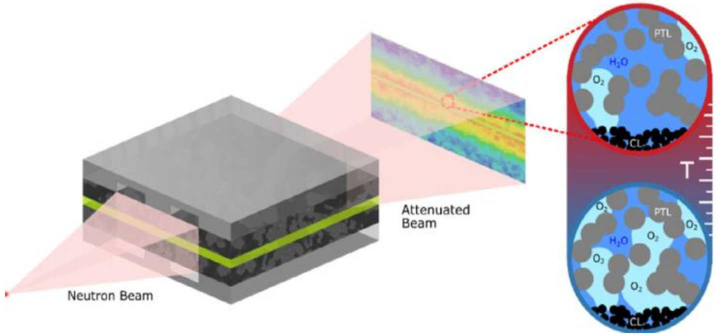
Xiong Peng
X-ray characterization

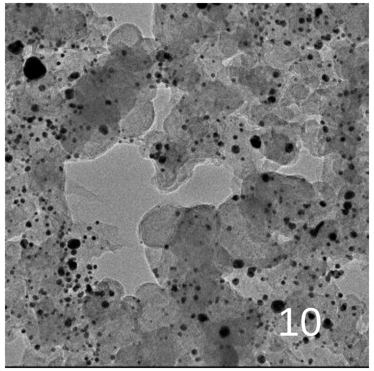
Aimy Bazylak
Anode porous transport layer modeling

Jasna Jankovic
TEM and EDS









Project Management; Risks and Mitigation

- Bimonthly internal meetings
- Monthly/bimonthly external meetings

Dedicated project monitor:

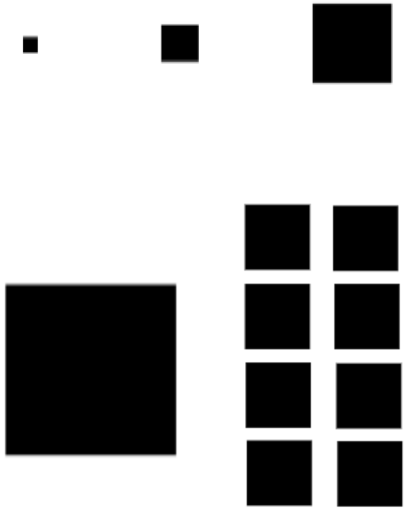
Dr. Kathryn Corp
Technical Program Manager

Risk	Mitigation
Instrument/time availability	Twelve engineers visited our collaborators to expedite method development and optimize worker time
Supply chain constraints	To address long lead times for certain equipment, Twelve is socializing with vendors and collecting bids from multiple vendors
Interruptions during long-term electrolyzer testing	Twelve has installed uninterruptible power supplies on its electrolyzer test stations and also implemented automated shut off procedures for abnormal temperatures, flow rates, and voltages

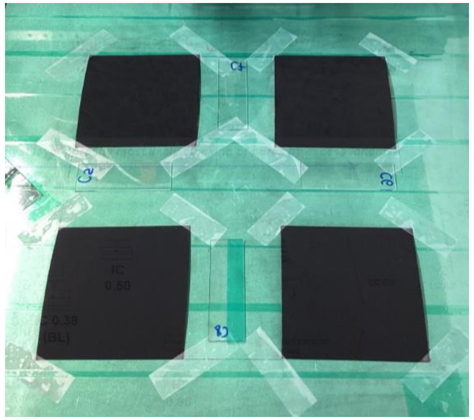
Progress and Outcomes

BETO Project Progress:
Scaling to industrially relevant MEA sizes

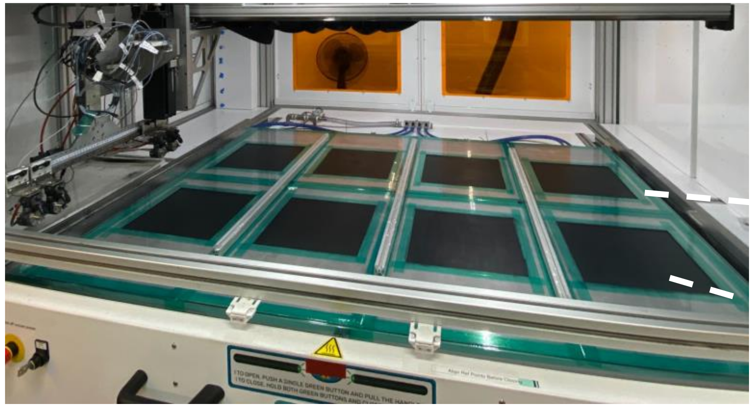
1. Scale MEA active area to >750 cm² (2022-2023)

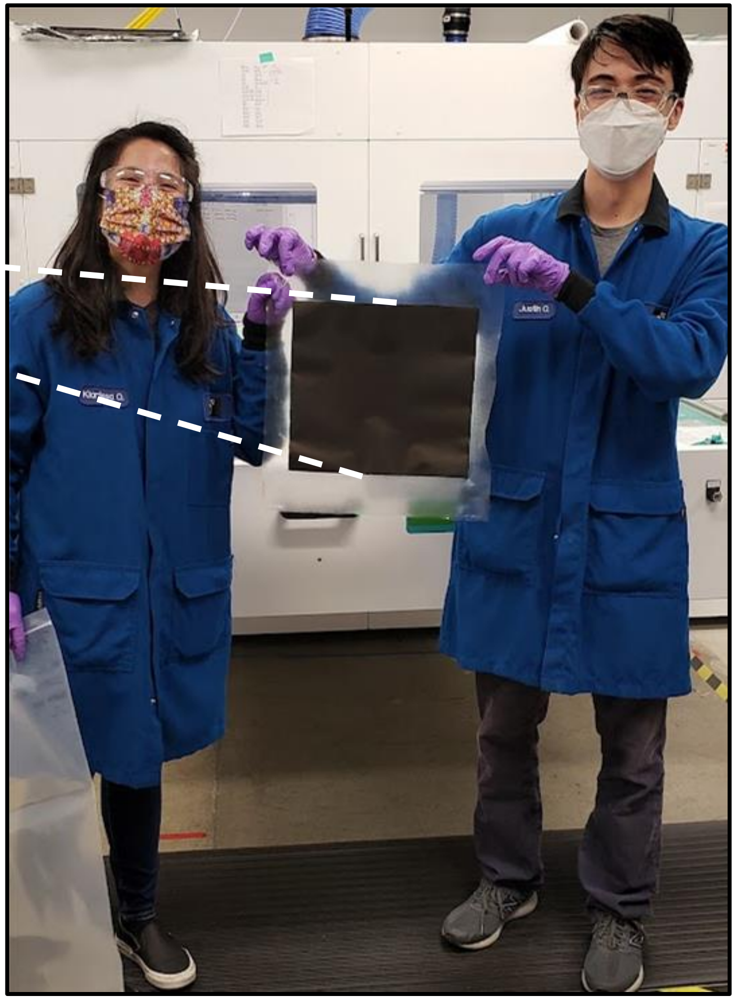


4 x 100 cm² MEAs



8 x 750 cm² MEAs



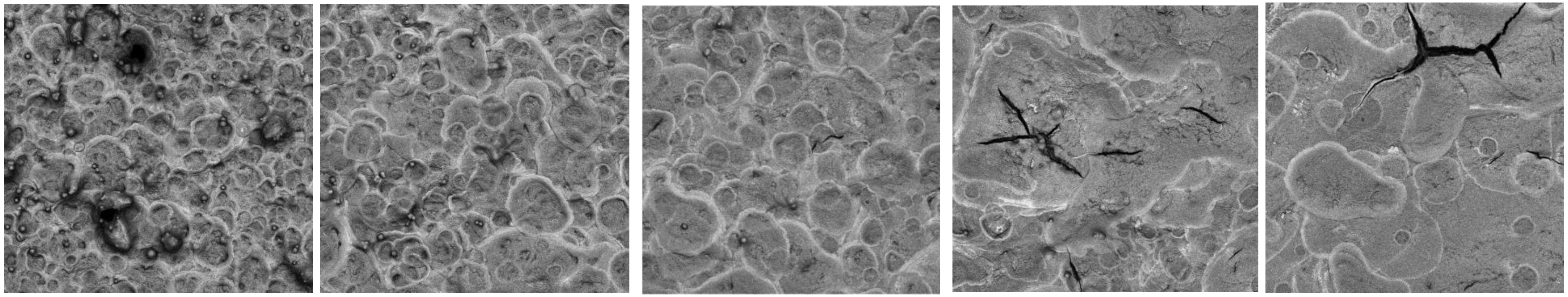


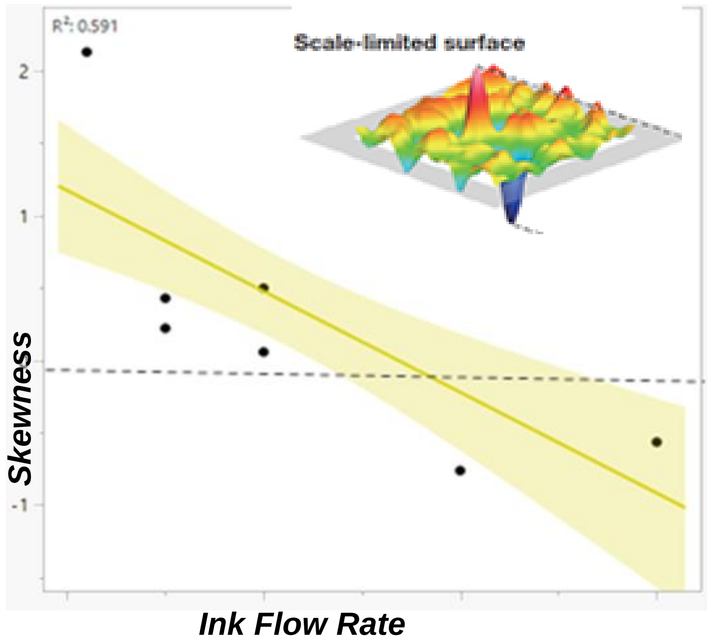
MEA active area scaleup

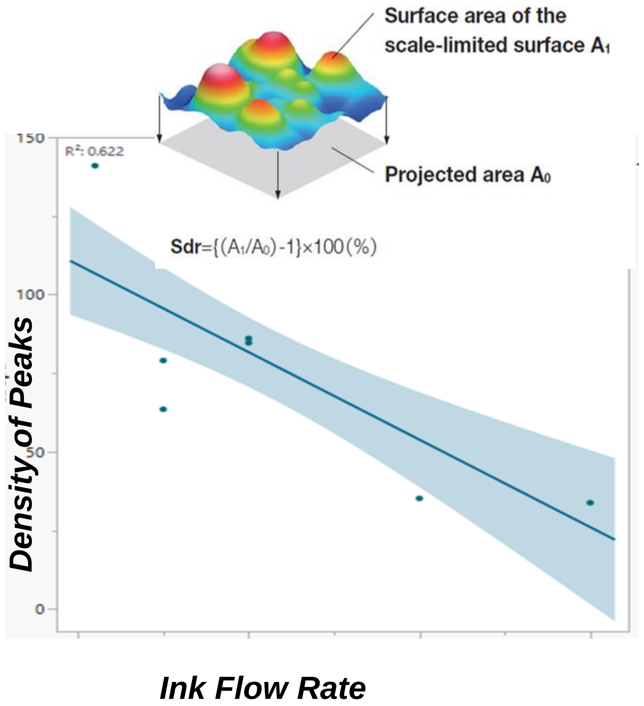
Fabrication system scaleup

Establishing Structure-Property Correlations:
Catalyst layer roughness and porosity

Optimizing morphology by tuning fabrication parameters



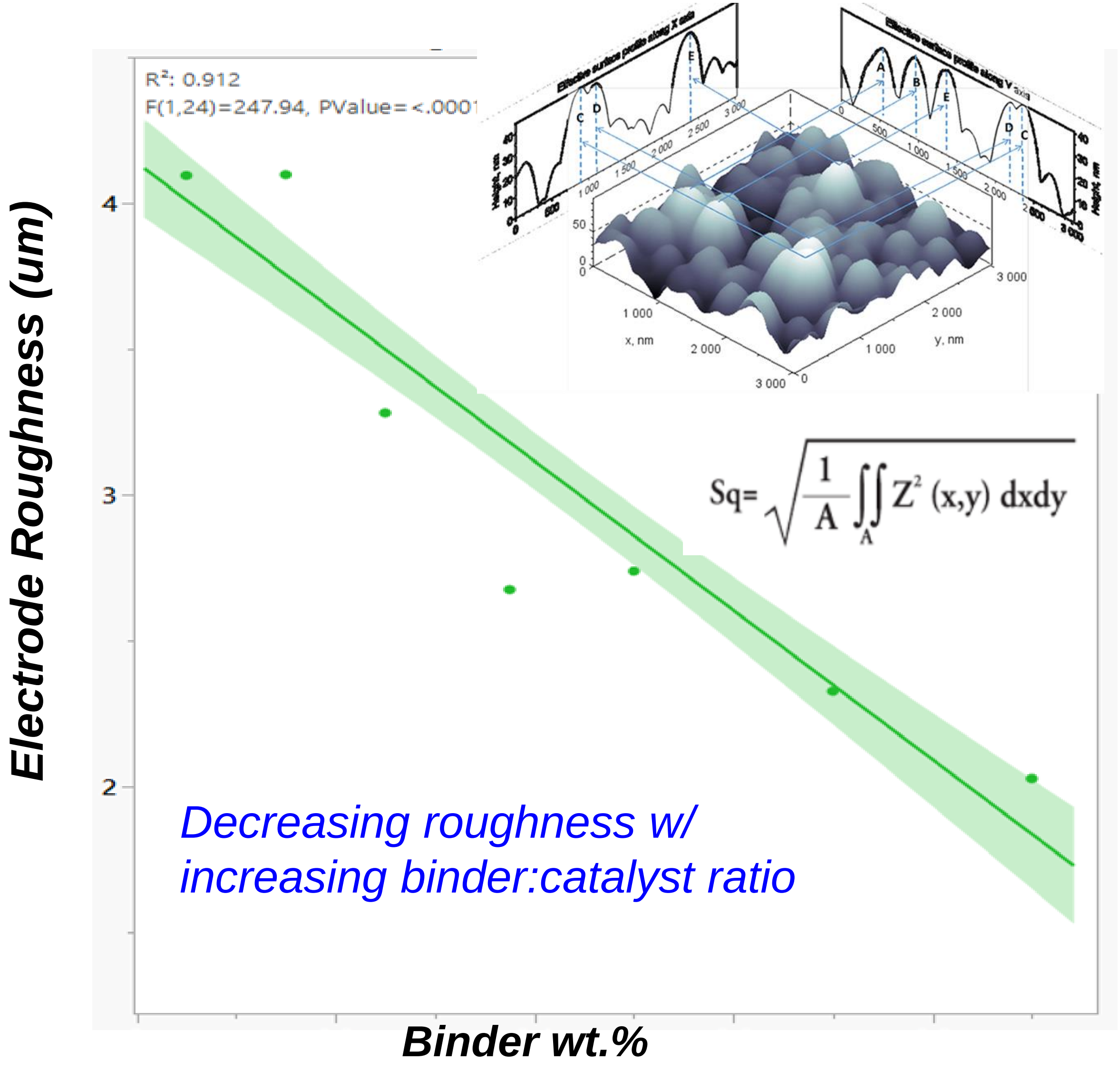


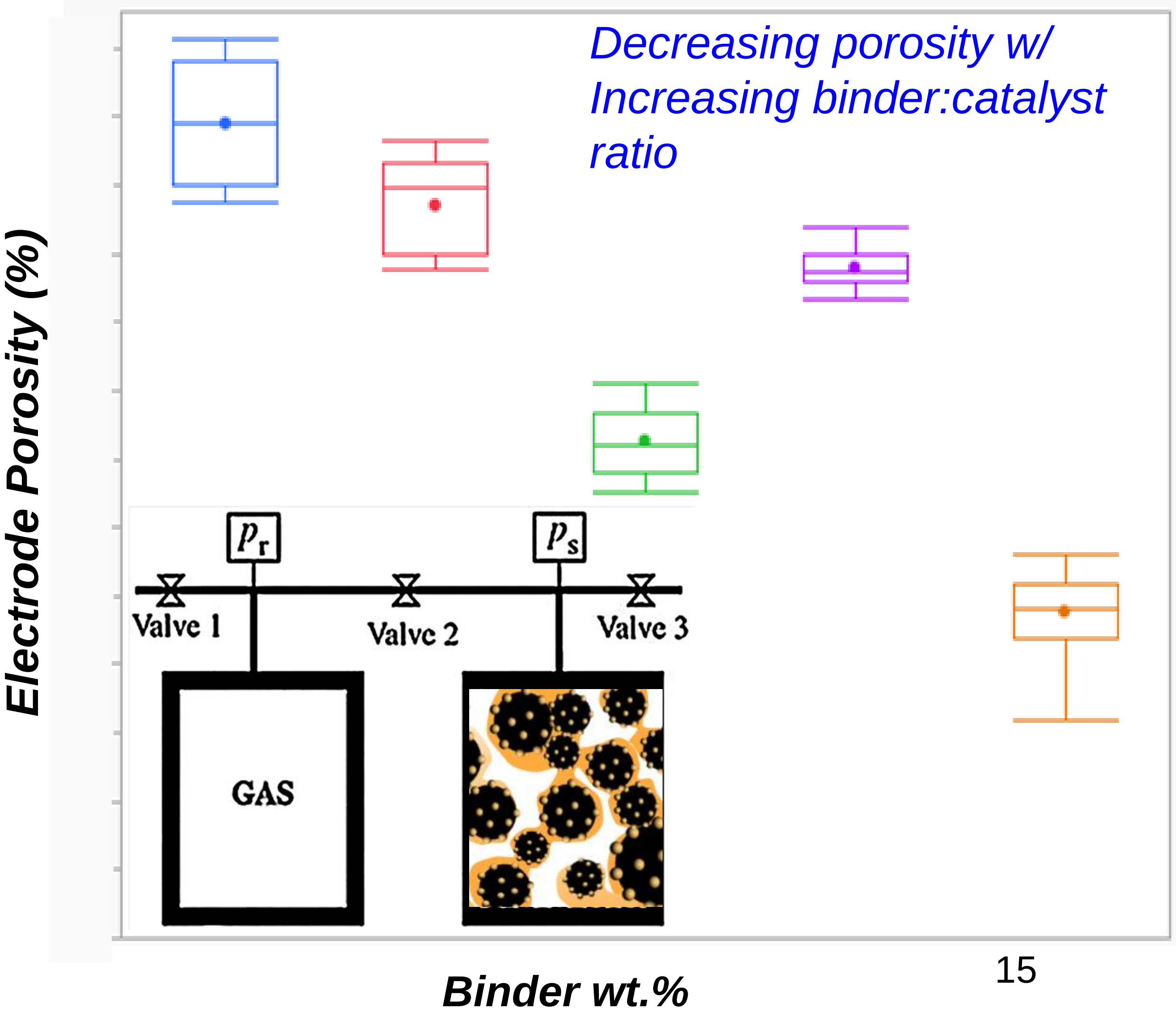


Fabrication parameters:

- Temperature
- Nozzle type
- Nozzle frequency
- Flow rate
- Distance of nozzle to substrate
- Speed
- Solvents
- Solids wt.%

Tuning MEA Fabrication Parameters:
Optimizing catalyst layer morphology





BETO Project Progress:
Developing scalable stack hardware

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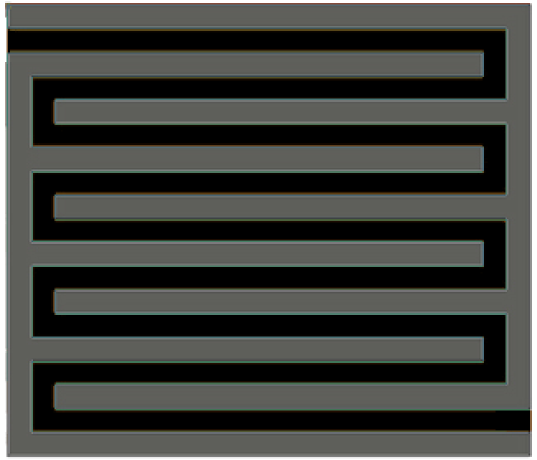
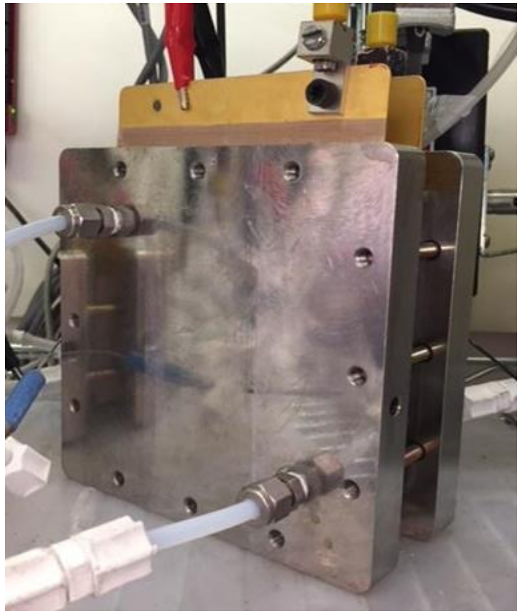
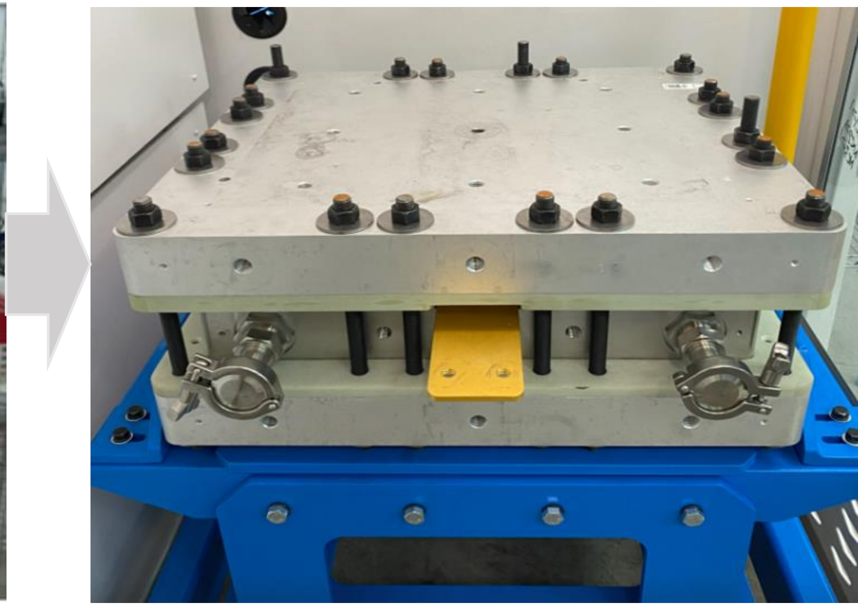
2. Design and build single-cell stacks (2023)

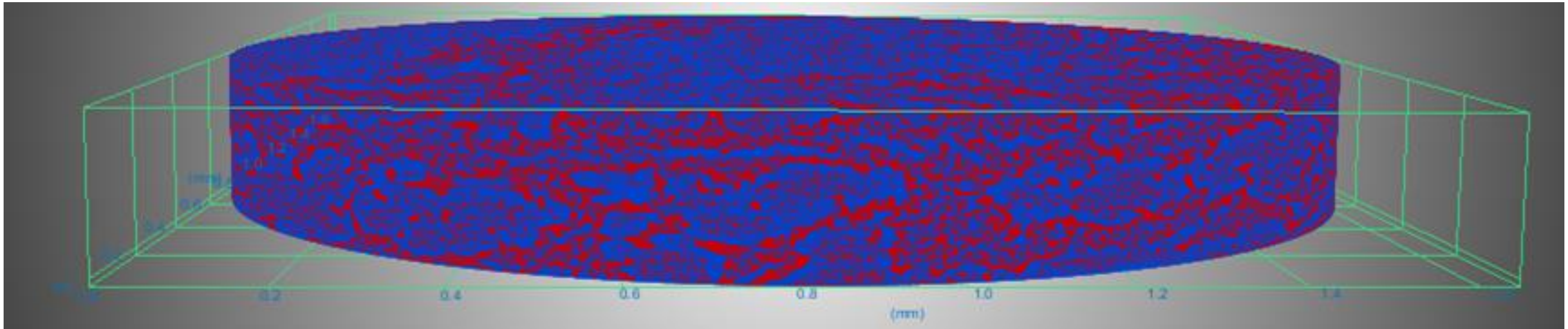


- Cell hardware is attached to a test stand to control the flow of CO_2 and water through the cell, deliver electrical current and measure voltage, and measure product CO
- We will be using this same >750 cm^2 flow field design, cell hardware, and stack procedures for developing our multi-cell stacks

X-ray Computed Tomography (XCT):
Analyzing porosity of gas diffusion layers (GDLs)

BERKELEY LAB

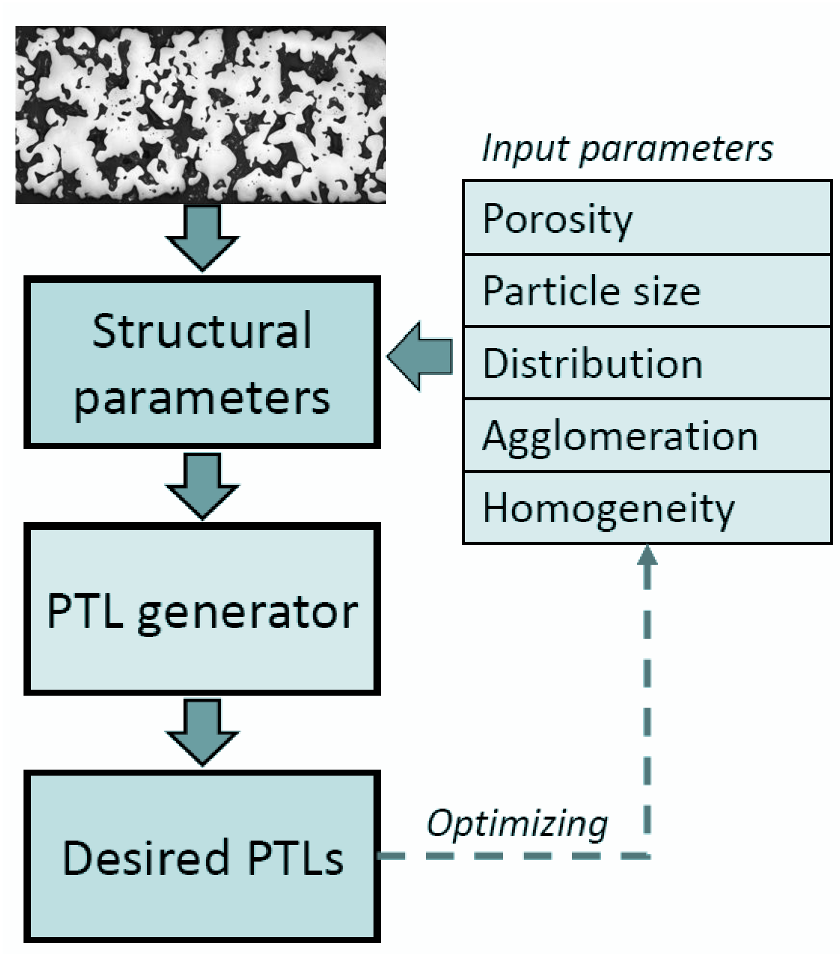
- Method validation: calculation from air and solid yields similar results (± 1%)
- Results: porosity ranges from 50-70% depending on vendor
- In progress: analysis of catalyst layer XCT images



$$Porosity = \frac{air\ vol}{total\ vol}\ or\ 1 - \frac{solid\ vol}{total\ vol}$$

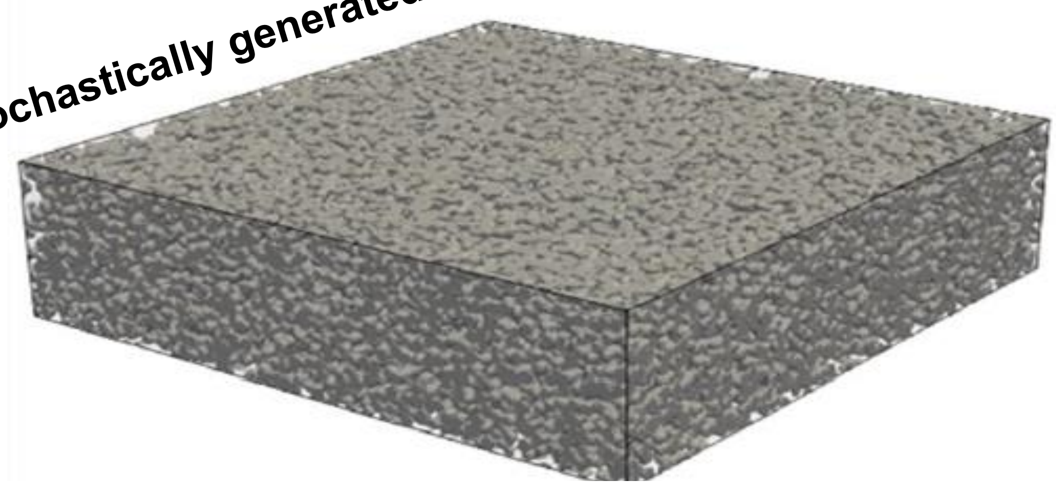
Pore Network Modeling and Operando Imaging:
Predicting multiphase flow behavior

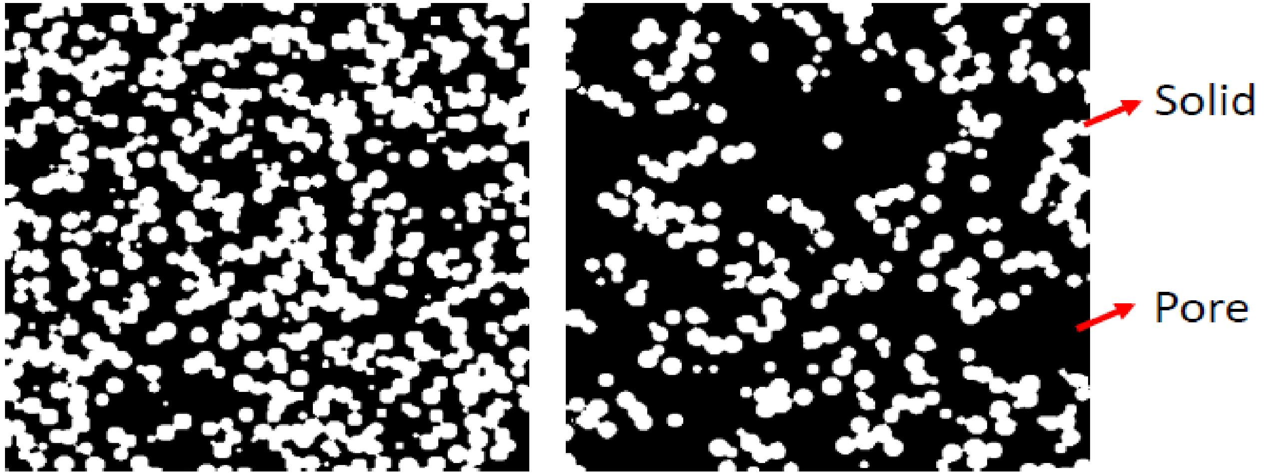
Reference image



Algorithm

Stochastically generated PTL

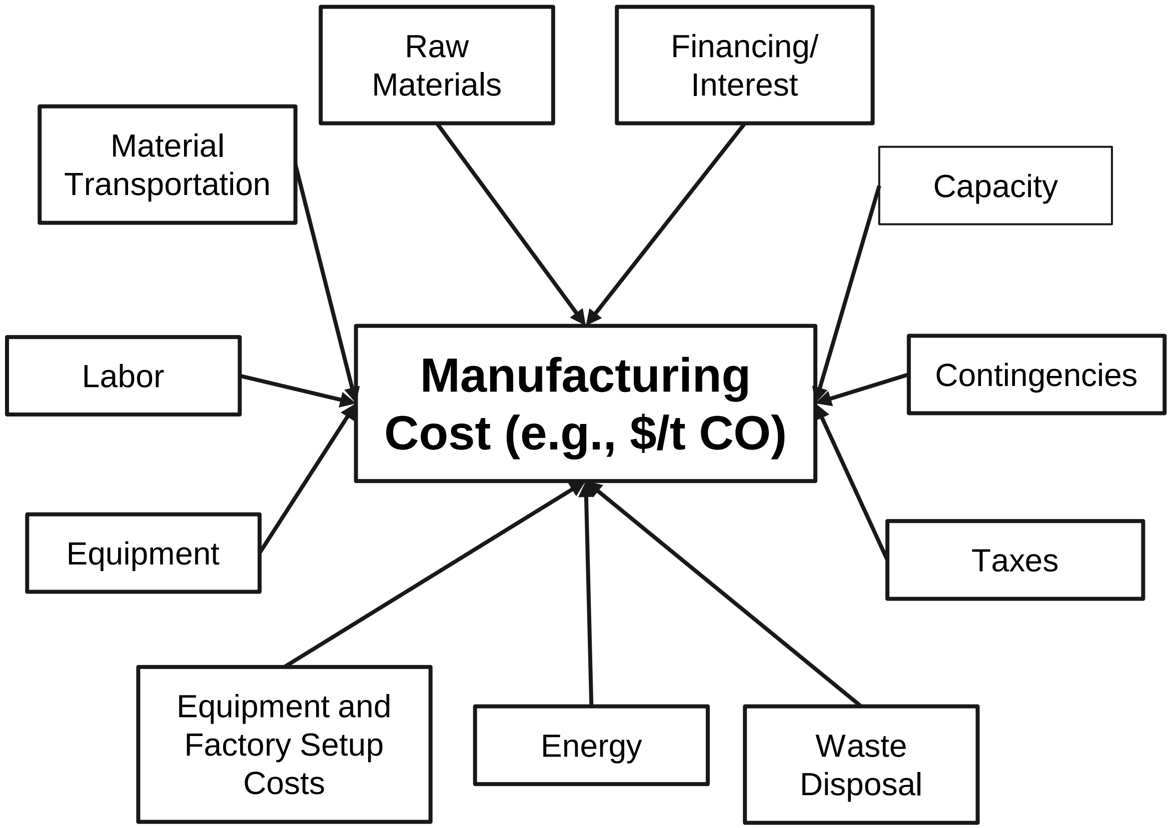




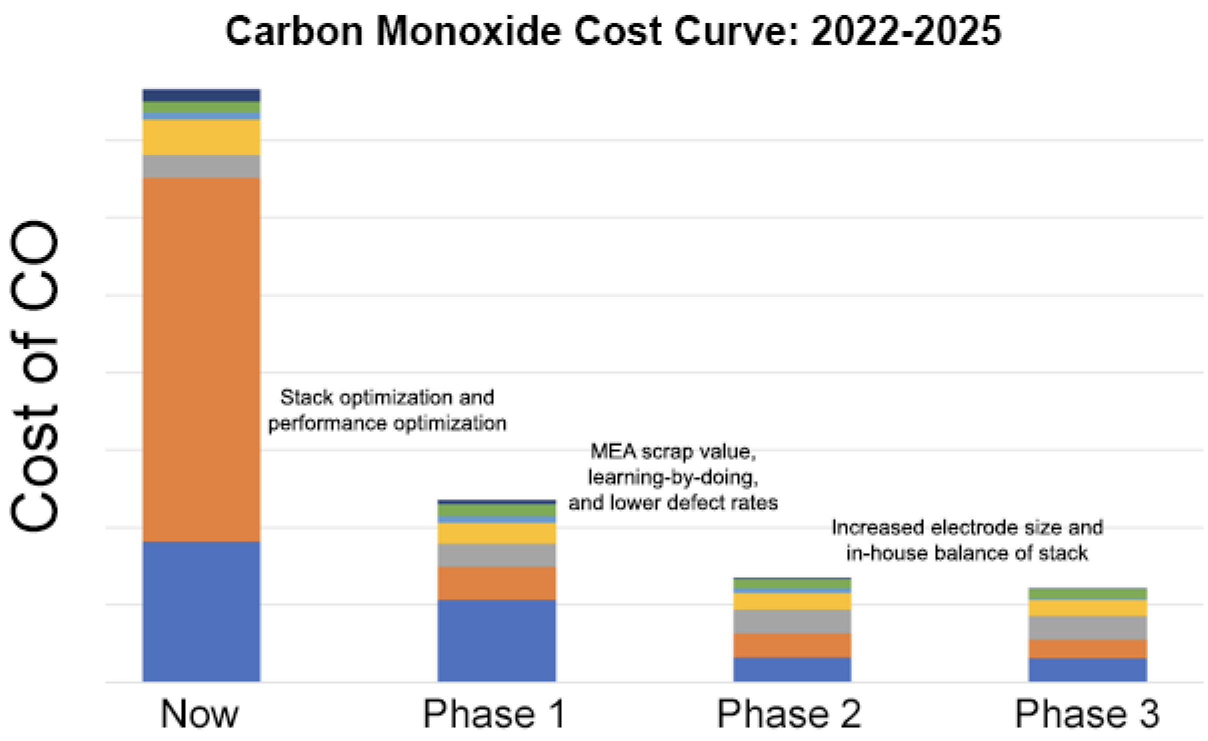
ε= 0.56 ε= 0.76

Parametric control - porosity (ε)

Technoeconomic Analysis:
Comparing developmental pathways to identify cost drivers



Carbon monoxide cost curve



- TEA analysis to compare developmental pathways and identifying key cost drivers
- Current results point to stack optimization, stack performance, and lifetime as R&D priorities

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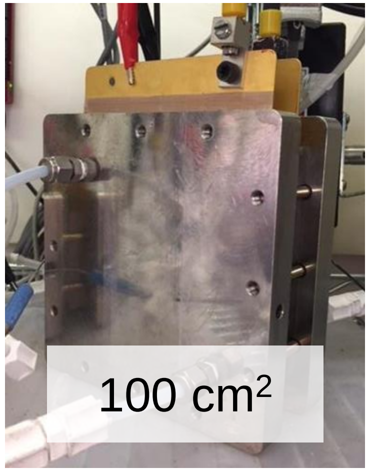
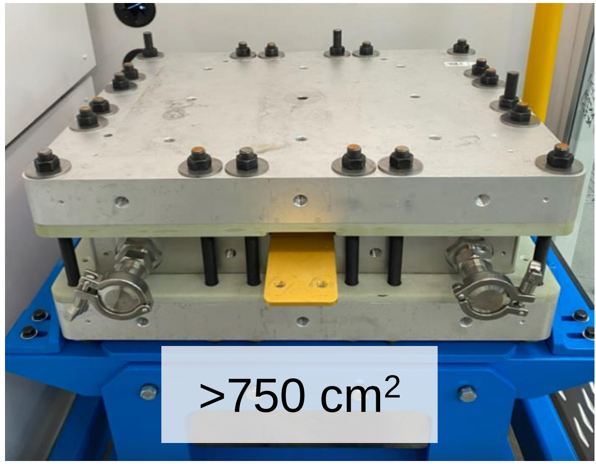
BETO Project Goal:
Demonstrating performance at scale

3. Demonstrate single-cell performance at >750 cm^2 scale (2024)

Current progress: successfully translated 100 cm^2 single cell performance to >750 cm^2 scale (red, blue)



100 cm^2



>750 cm^2

Impact

- Impact on field/industry
- Offtake agreements
- Commercialization potential

Partnerships and Offtake Agreements:
Transforming CO_2 into **CO2Made®** products for flagship customers

U.S. AIR FORCE

P&G

Mercedes-Benz

PANGAIA

world's first CO2Made® ingredients for Tide

world's first CO2Made® auto parts

world's first CO2Made® sunglass lenses

shopify e-jet® by twelve Alaska AIRLINES Microsoft LanzaTech

Offtake Agreements

e·jet by twelve

Microsoft and Alaska Airlines are working with this startup to make clean jet fuel from carbon emissions

CNBC

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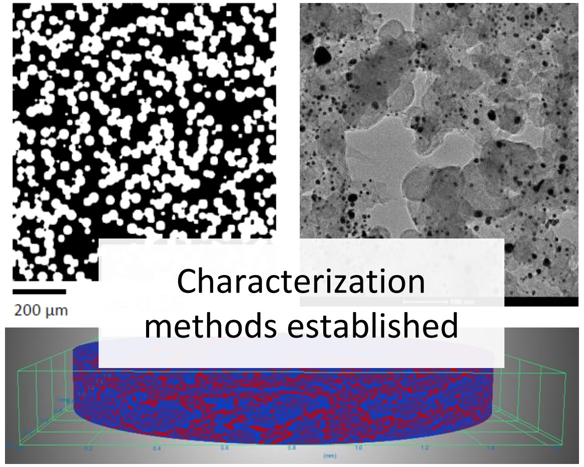
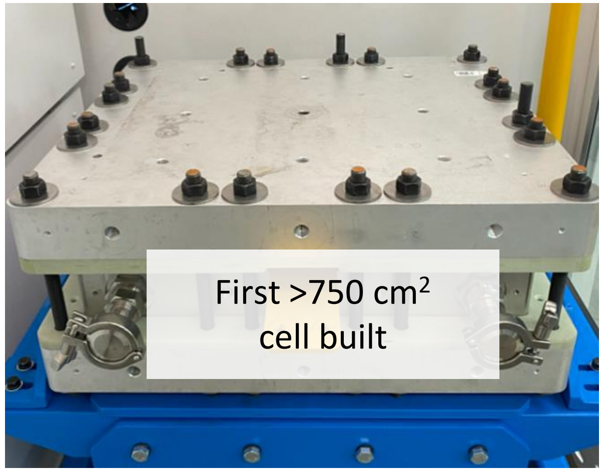
Summary – PEM CO_2 Electrolyzer Scaleup to Enable MW-scale Electrochemical Modules

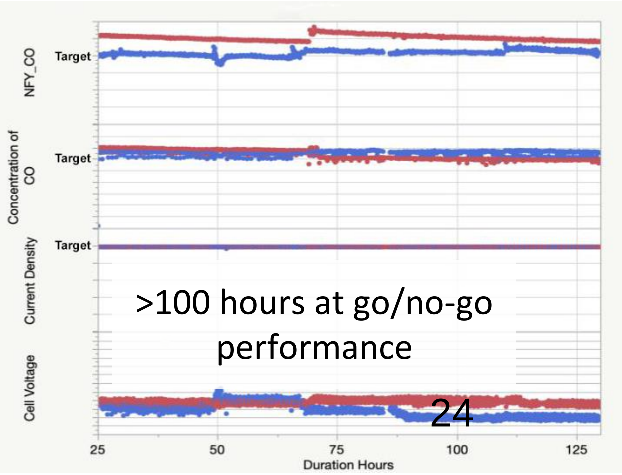
- **Scaled up to industrially-relevant MEA active area**
- **Designed scalable stack hardware; building deeper understanding of our system**
- **Built and tested single-cell stacks**
- Ongoing work:
  - Iterate on cell design and MEA fabrication to optimize electrolyzer performance and lifetime
  - Utilize advanced characterization to identify performance drivers


First >750 cm² MEAs fabricated



Characterization methods established


First >750 cm² cell built



>100 hours at go/no-go performance

Acknowledgements

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BIOENERGY TECHNOLOGIES OFFICE

Ian Rowe, Ryan Lawrence

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UNIVERSITY OF TORONTO

Aimy Bazylak

BERKELEY LAB

Xiong Peng

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Jasna Jankovic

Sadia Kabir

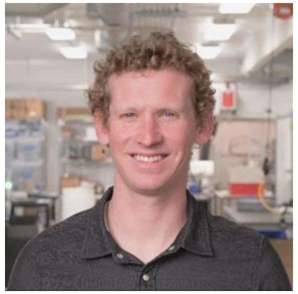
Sichao Ma

Katie Corp

Simon Stone

Tim Bekkedahl

Jason Cooper



Danny Hellebusch

Theodore Gao

Kendra Kuhl

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Questions?

Supporting Slides

- Quad Chart
- DEI
- Highlights from initial verification
- Awards
- Commercialization activities

Quad Chart

Timeline

- *Start: 10/01/2020*
- *End: 06/30/2024*

	FY22 Costed	Total Award
DOE Funding	$243,777 *(10/01/2021 – 9/30/2022)*	$746,516 *(negotiated total federal share)*
Project Cost Share *	$111,823	$326,950

TRL at Project Start: 4

TRL at Project End: 5

Project Goal

The goal of this project is to develop, fabricate, and demonstrate high-performing, large-area, single-cell CO_2 electrolyzers, and establish new experimental and computational methods to accelerate future development.

End of Project Milestone

Demonstrate >750 cm^2 MEAs with >1000 hours of lifetime at industrially-relevant operating conditions, using biogenic CO_2 as a feedstock.

Funding Mechanism

DE-FOA-0002203

Topic area 7, Scalable CO_2 Electrocatalysis 2020

Project Partners

- Academic: UToronto, UConn
- National Lab: LBL, NREL

*Only fill out if applicable.

Diversity, Equity, and Inclusion at Twelve

Aim: reduce barriers for talented people to contribute to the mission

- **64% womxn** and **45% minority** leadership team
- Focused on fostering a culture of belonging
- **Collaboration** and **transparency** are core values

Our Company

- Company-wide, **diversity-focused education** programs (implicit bias training, allyship training, etc)
- **Targeted hiring** outreach to underrepresented demographics

Our Practices

- **Increase underrepresented candidate talent pool** for first interviews by 25% during 2023
- Provide **inclusive leadership training** to 100% of managers by Q4 2023

Our Goals

Awards

1. Fast Company – 3rd on "Most Innovative Companies 2022" https://www.fastcompany.com./90721844/twelve-transforming-carbon-pollution-jet-fuel-plastics

2. TIME – Best Inventions of 2022 https://time.com/collection/best-inventions-2022/6226975/twelve-co2-transformation-device/

3. The New York Times – 2022 Good Tech Award https://www.nytimes.com/2022/12/29/technology/good-tech-awards-2022.html

*Work not solely funded by BETO award

Highlights from Initial Verification

Suggestion	Result
Standardization of membrane fabrication and cell construction procedures	Both membrane fabrication and stack assembly procedures have been standardized, including things like materials and formulations, membrane clamping, stack inspection, subassembly, build, and pre-operational testing.
Performing TEA using a framework from published references	TEA work is ongoing with input from NREL's PEM Manufacturing cost report and other published reports.
More structured project management plan	Dedicated project monitor: Dr. Kathryn Corp, Technical Program Manager.
Verification of consistent MEA morphology and properties across different spray chambers	The performance of MEAs produced in different spray chambers were found to be very similar, with Faradaic yields within ±1% of the average, and voltages within ±2% of the average.

Grants Resulting from BETO Project

Grant Name	RAMP 2020: Realizing Accelerated Manufacturing and Production for Clean Energy Technologies	Scaling Up Single Cell MEA
Funding Organization	California Energy Commision	Southern California Gas Company (SoCalGas)
Award Date	March 3, 2021	December 15, 2020
Award Amount	$3,000,000	$500,000
Relationship to BETO Project	BETO is cost share for this grant	Cost share for BETO

First signed E-Jet Attribute Offtake Agreement

Shopify's goal: 100% carbon neutral Black Friday/Cyber Monday. This purchase is the first step toward that goal and is Shopify's first carbon transformation purchase.

Highlights:

- $2.5M customer contract
- Purchase is tied to the carbon impact from our technology

Creates precedent and contractual framework for additional, larger customer offtakes

*Work not solely funded by BETO award