A Tandem Electrolysis Process for Multi-carbon Chemical Production from Carbon Dioxide

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Project Objectives and Approach

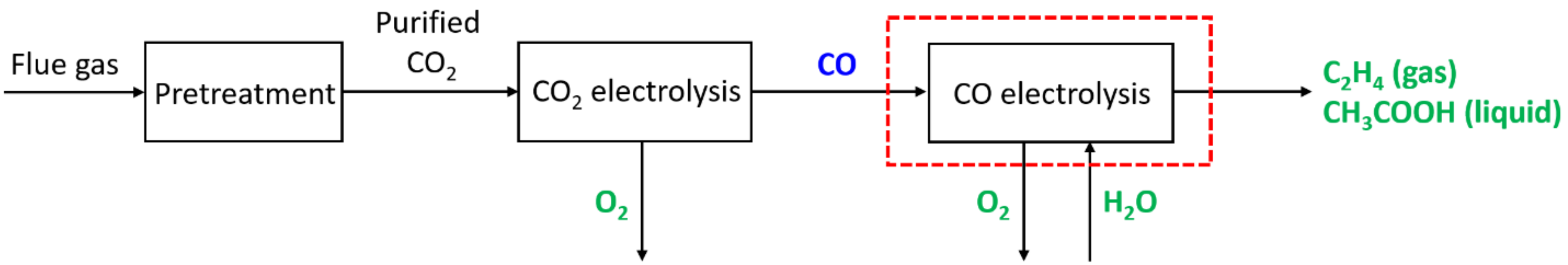
The objectives of this project include:

(1) designing a novel, high-performance carbon monoxide (CO) electrolysis reactor that produces two concentrated product streams, ethylene gas stream on cathode and acetate liquid stream on anode

(2) constructing and assessing CO electrolysis multi-cell stack reactor prototype with a 90% carbon selectivity and a total power of 0.9 kW

(3) performing a full techno-economic analysis (TEA) and a life-cycle assessment (LCA) of the whole two-step carbon dioxide (CO_2) electrolysis technology for CO_2 utilization at a technology readiness level (TRL) 4

Our Approach:

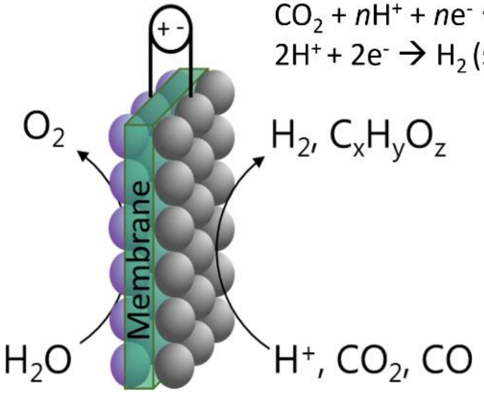


A brief introduction to CO_2 electrolyzer technology

Cathode:

$CO_2 + nH^+ + ne^- \rightarrow C_xH_yO_z$

$2H^+ + 2e^- \rightarrow H_2$ (side reaction)

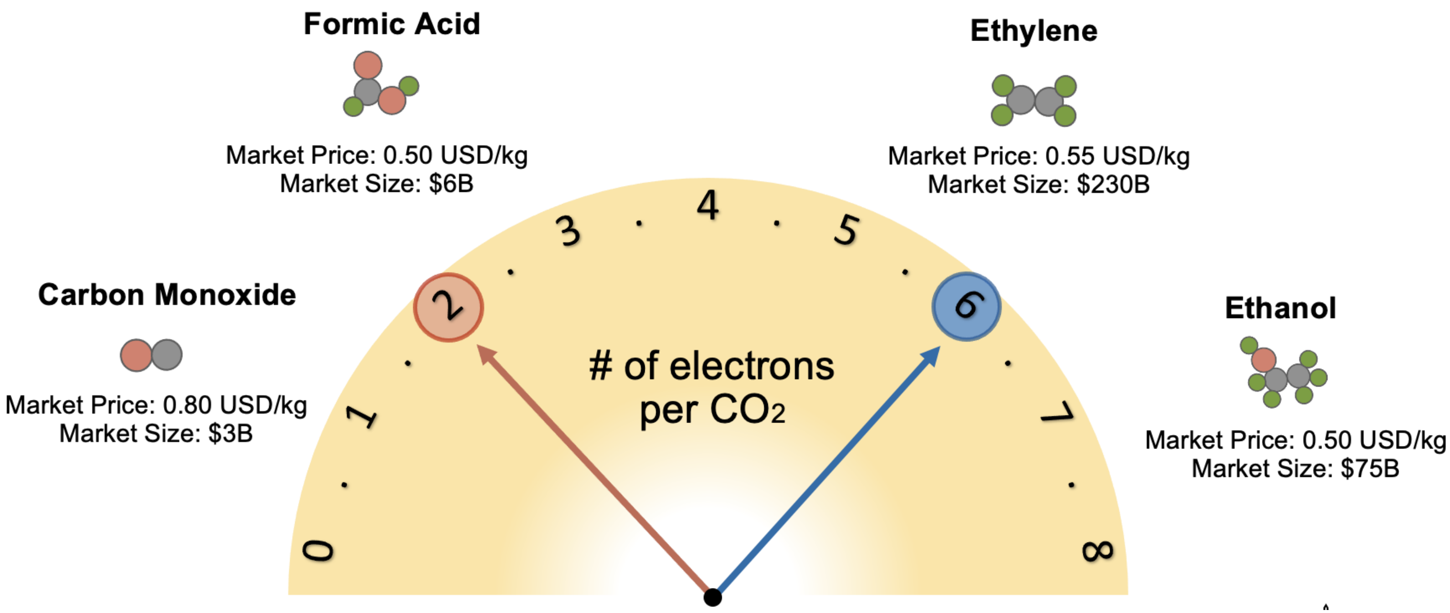


Technical Challenges:

- **Product Selectivity**
- **Energetic Efficiency**
- **Durability**

Technical Terms

- Current Density ($mA\ cm^{-2}$) ≈ Reaction Rate
- Potential (Voltage) ≈ Energetic efficiency
- Faradaic Efficiency (%) ≈ Selectivity



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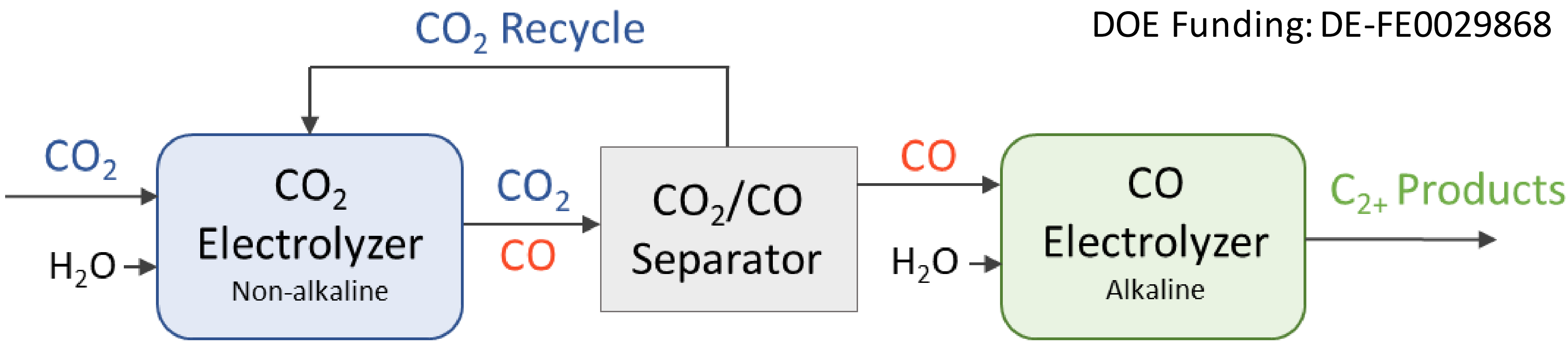
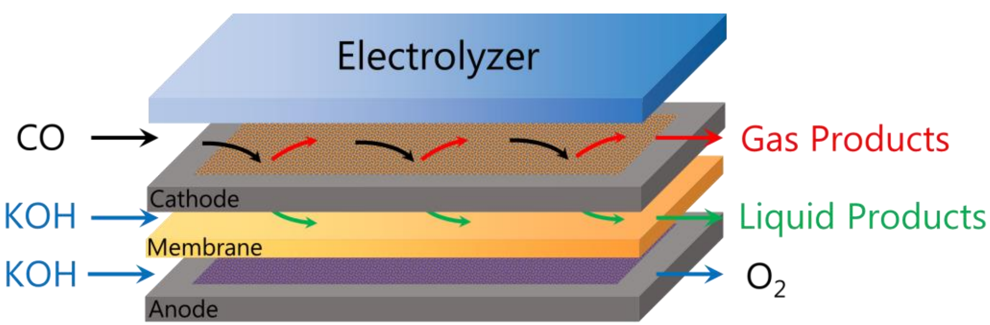
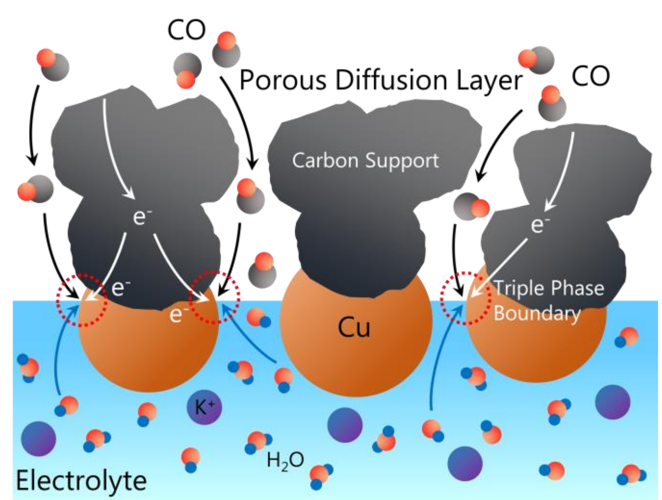
What we have achieved:
Proof-of-concept: Tandem electrolysis through CO intermediate

DOE Funding: DE-FE0029868



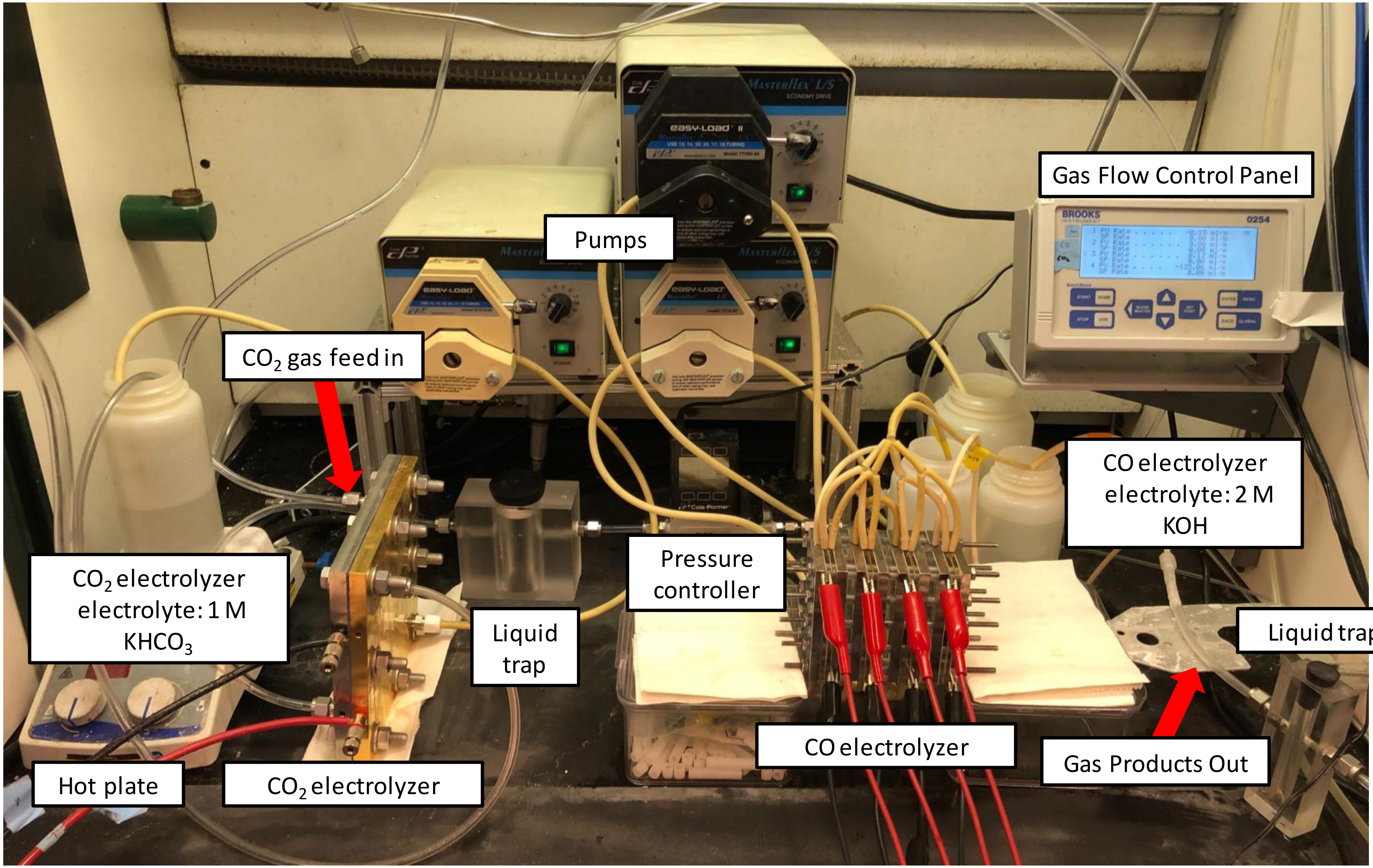
→ Decoupling of the electrolysis steps allows sustainable C_{2+} production



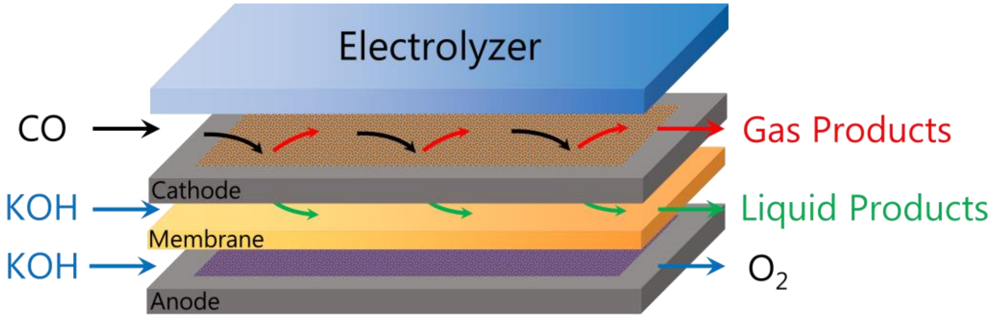


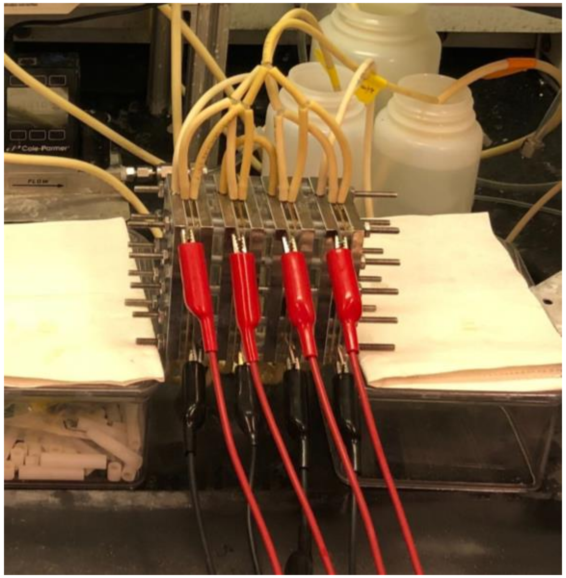
Jouny, Luc, & Jiao, *Nature Catalysis* 1, 748-755 (**2018**).
Jouny, Hutchings, & Jiao, *Nature Catalysis* 2, 1062-1070 (**2019**).

Two-Step tandem CO_2 electrolysis for alcohol production



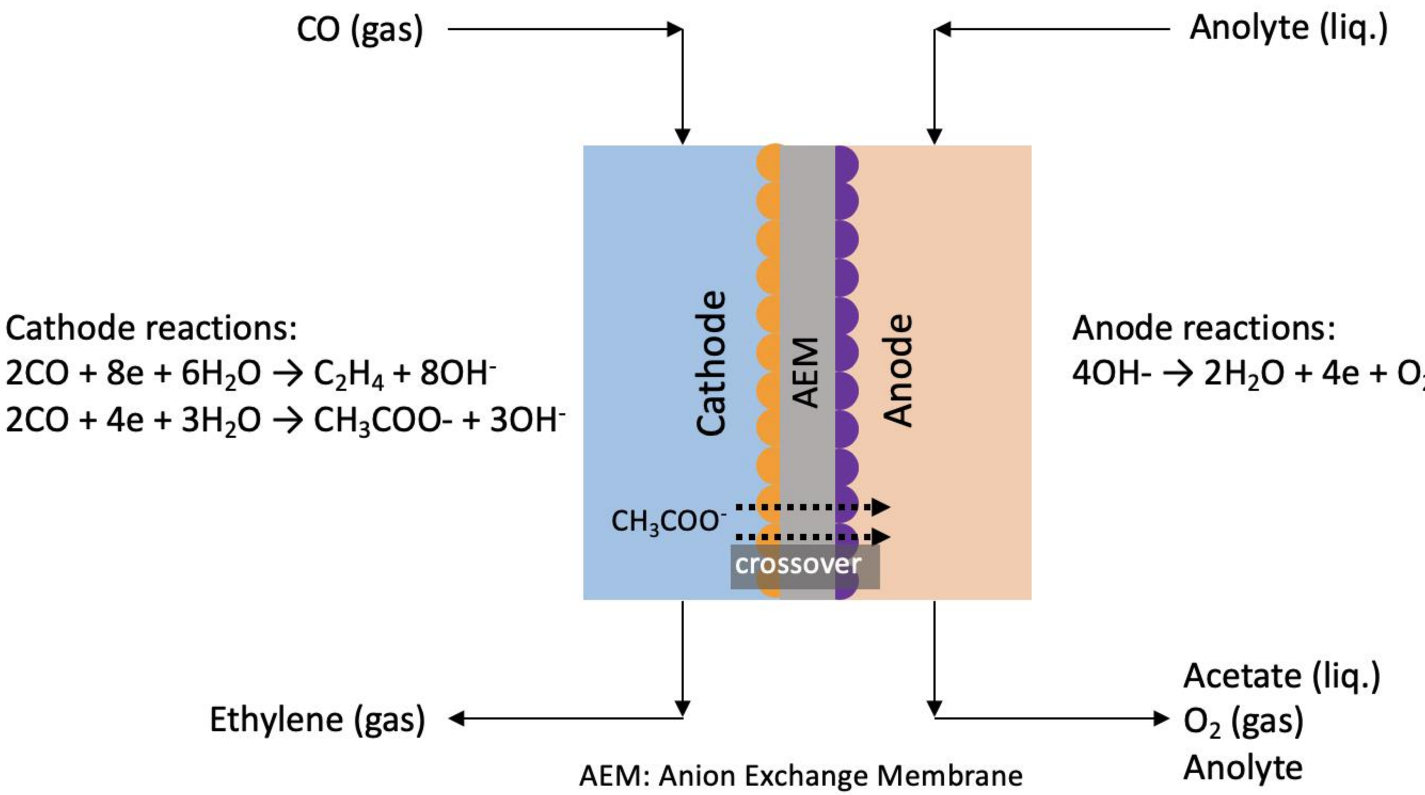
Key technical challenges learned from last project





- Difficulty in **<u>scaling up</u>** due to the microfluidic configuration
  complex flow control and management, uniformity
- Substantial **<u>energy loss</u>** at high current densities
  At high currents, the presence of a liquid electrolyte layer (even with a 1-mm thickness) will cause a significant loss of energetic efficiency.
- Diluted liquid product stream and high **<u>separation cost</u>**
  Because the liquid product(s) will be carried out by the liquid electrolyte (catholyte), a product stream usually has a **<u>low concentration (<10 mM)</u>**, and thus a high separation cost.

New Design for CO Electrolyzer



Key innovations:

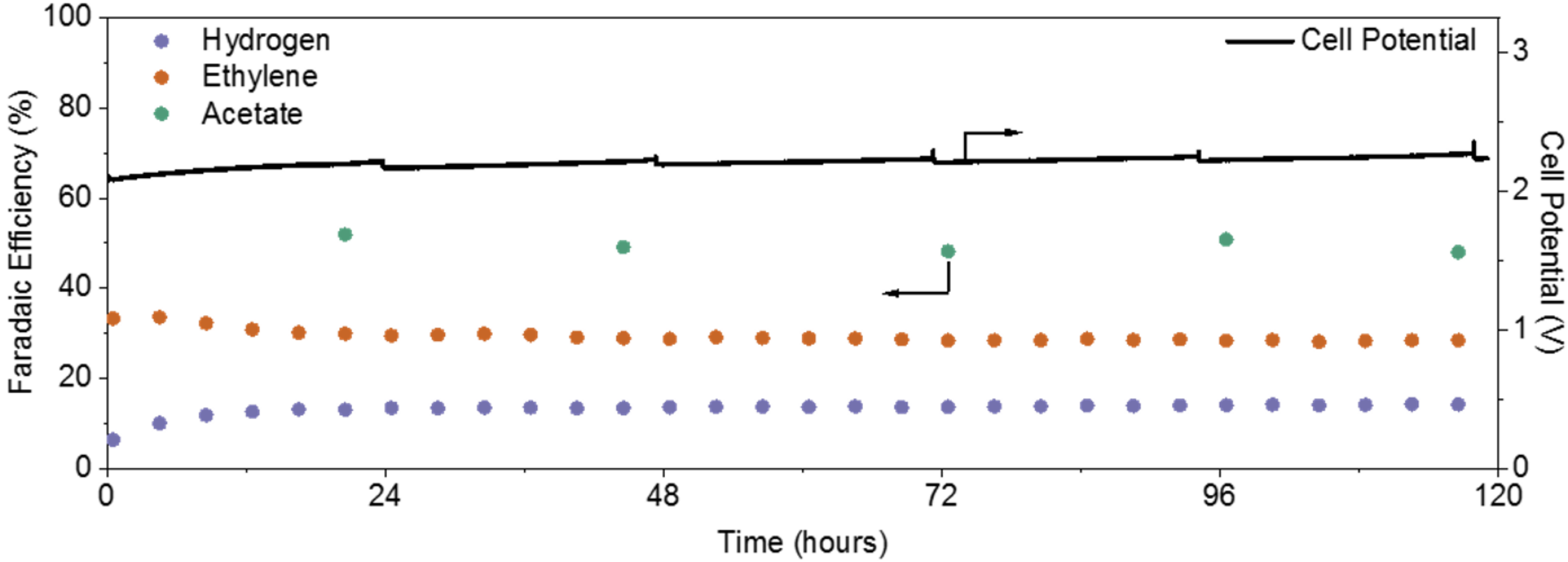
Zero-gap electrolyzer design – scalable and low internal voltage loss (to enhance energetic efficiency)

Liquid product stream at high concentration – reduced separation cost

Cu catalyst – high selectivity towards desired products (ethylene and acetate)

Stack design – multi-cell stack for scaling up to 1kW capacity

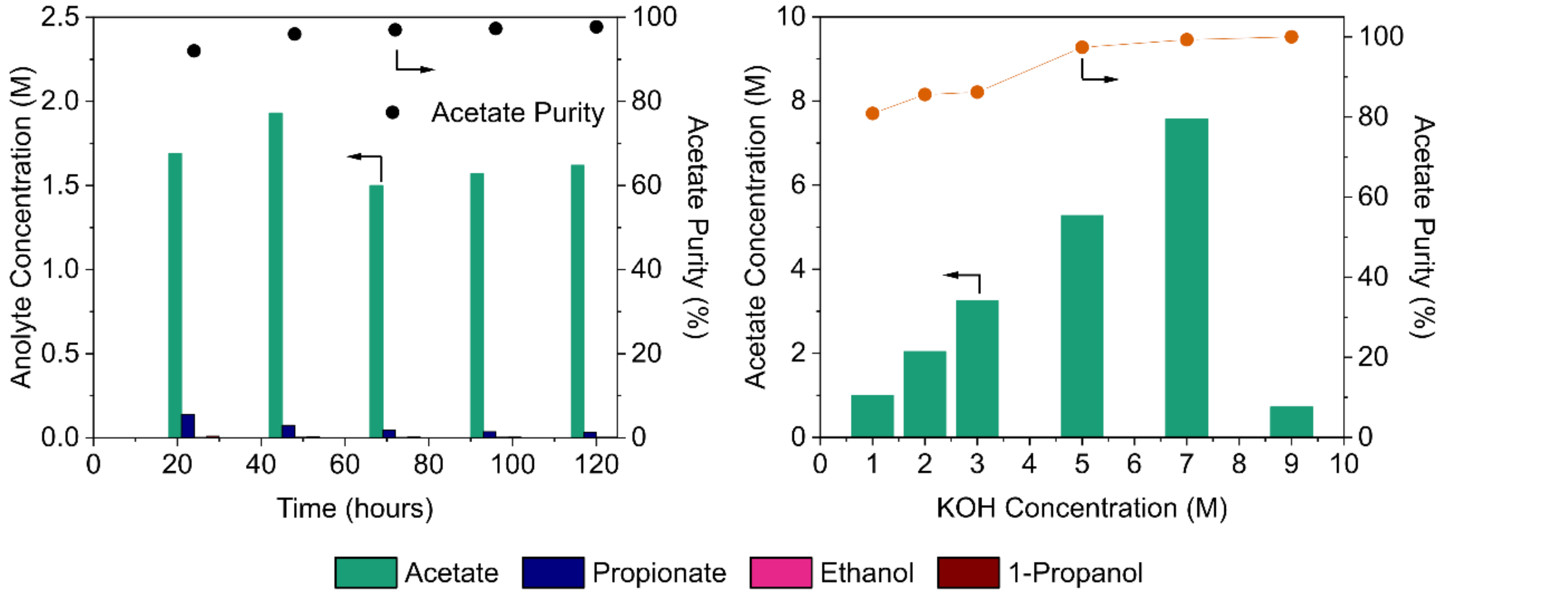
Performance enhancement through reactor engineering

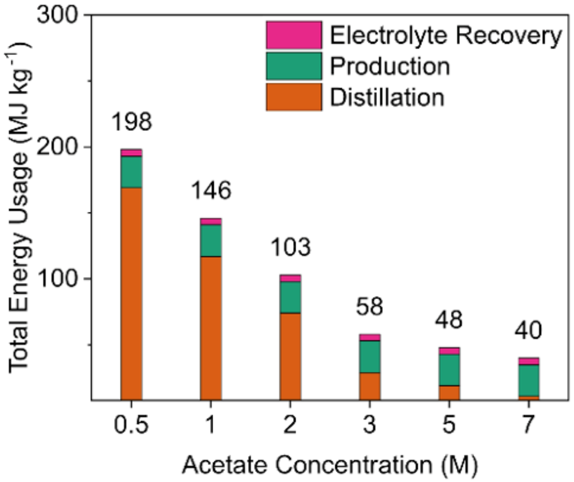


- 130 hours of continuous operation at 300 mA/cm^2 (and counting)
- >85% carbon selectivity towards acetate and ethylene
- Total voltage increase of 2.5 mV hr^{-1}
- Hydrogen Faradaic efficiency increases by <5% and ethylene selectivity is maintained

Jiao et al. (Nature Catalysis, in press)

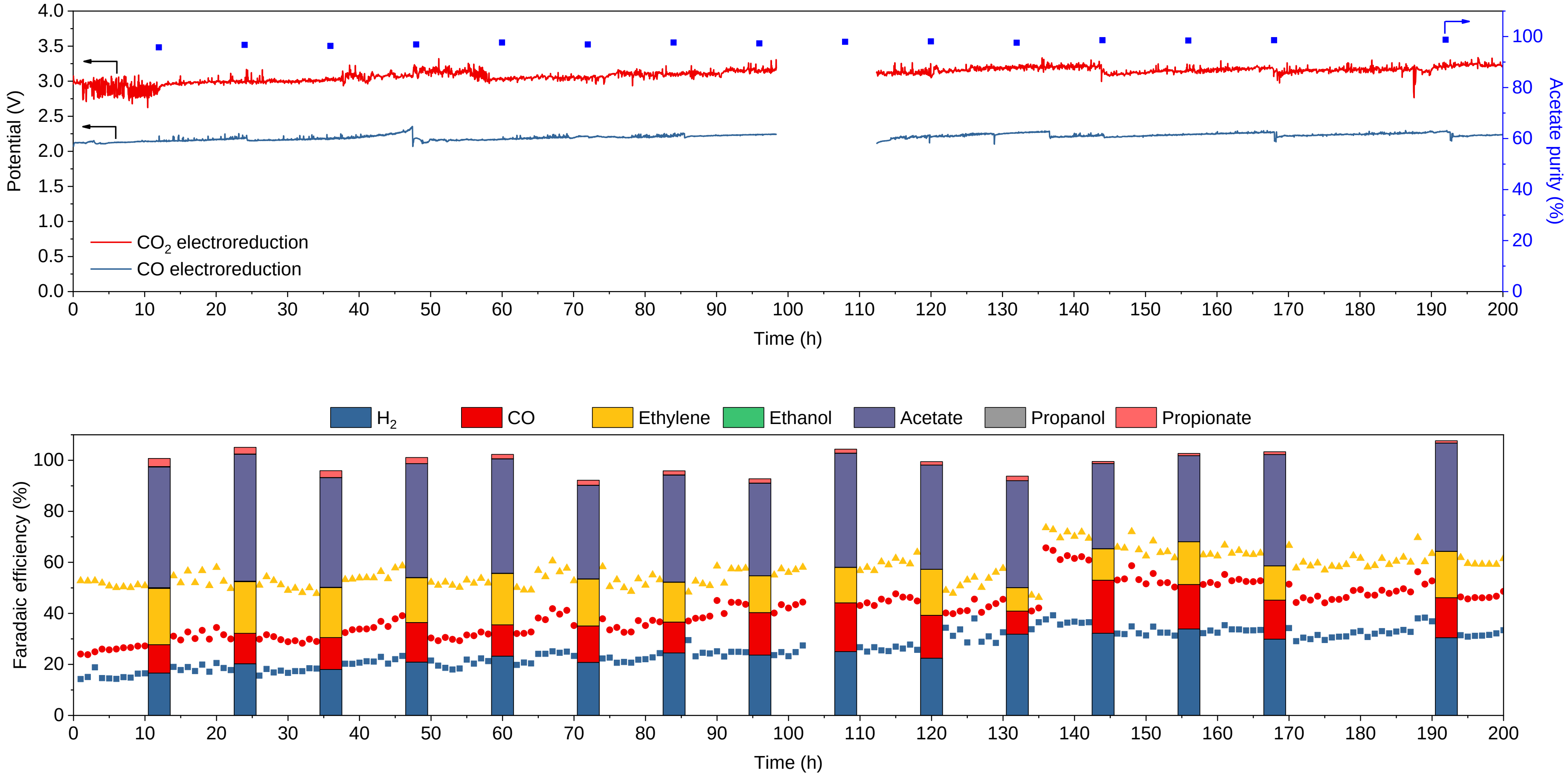
High-performance CO electrolyzer





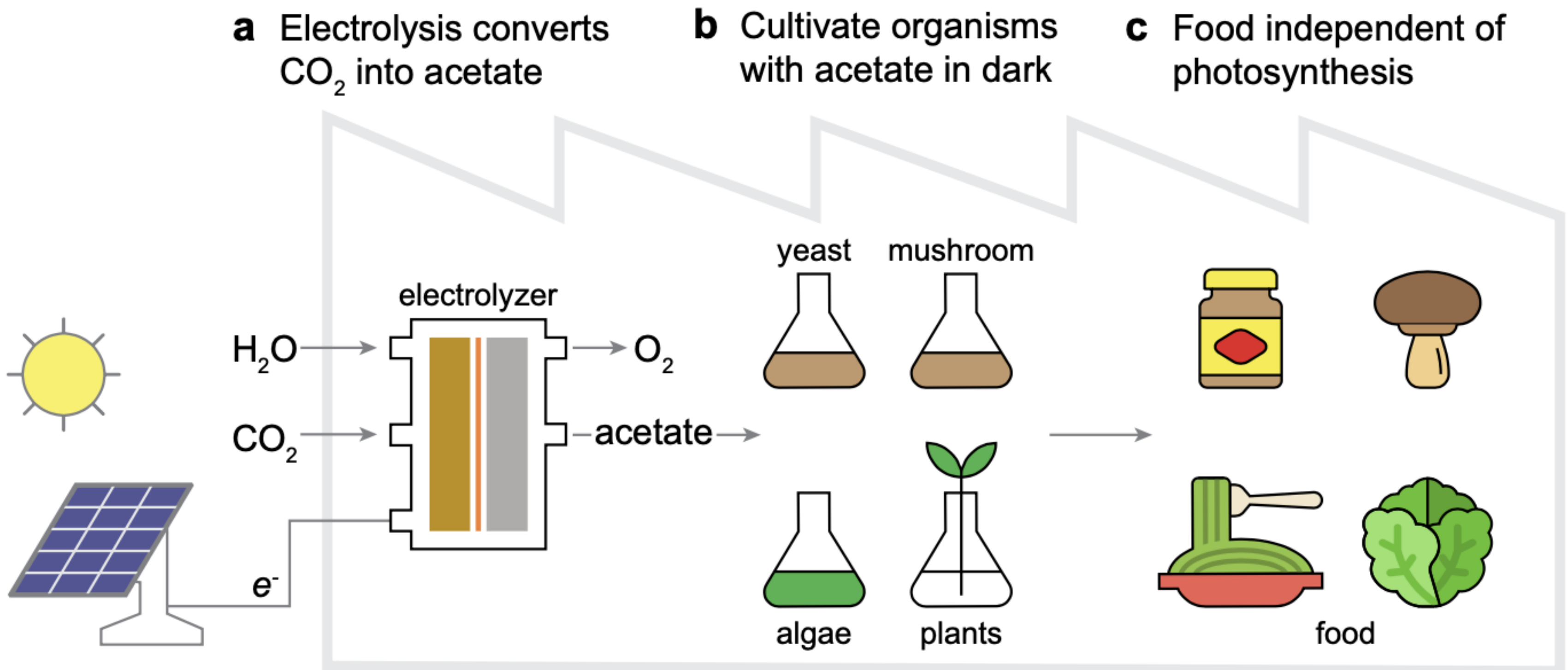
- Acetate concentration of 7M achieved
- High purity of acetate product stream (>95%)
- A much lower energy demand for product separation

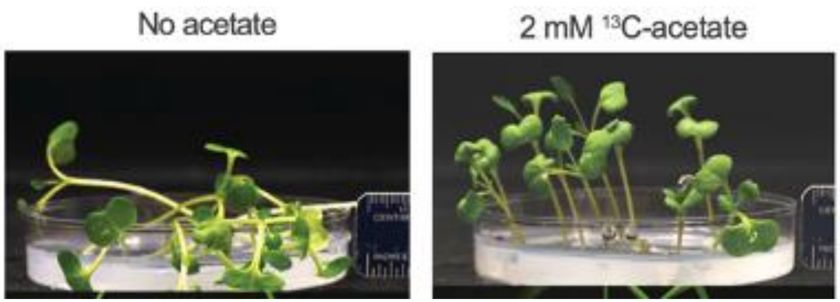
Performance of tandem electrolysis system (200 h)



Acetate and ethylene as the main products; ~99% acetate purity; 200 hrs stability

A hybrid approach for CO_2 utilization

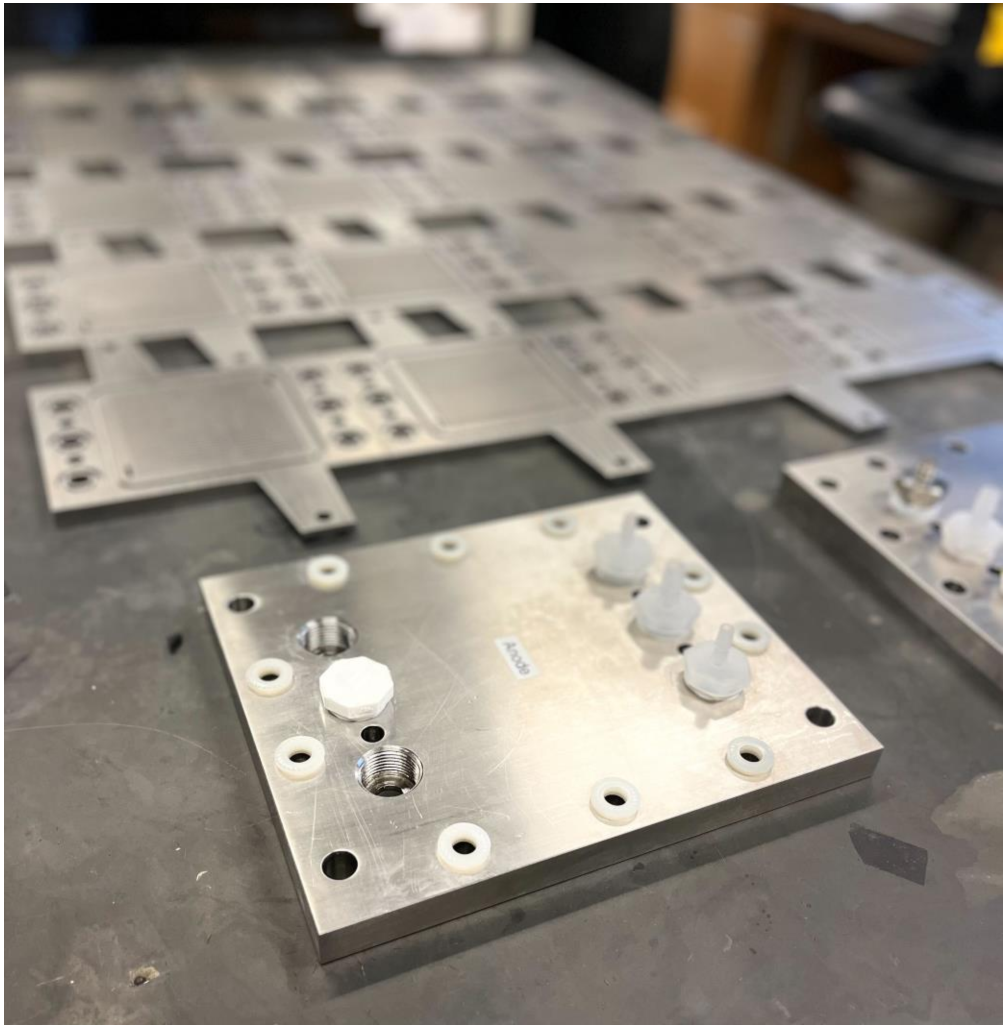




Collaboration with Prof. Robert Jinkerson at UC, Riverside

Jiao, Jinkerson, et. al. Nature Food 3, 461-471 (2022)

Multi-stack CO Electrolyzer (1,000 cm^2)



Stack parts
- 100 cm^2 electrode size
- 10-cell stack

Multi-stack CO Electrolyzer Operation

- 3-cell stack constructed
- Total area of 300 cm^2
- 2.3 V at 300 mA/cm^2 (90 A total)

Project Schedule and Milestones

Task Name	Assigned Resources	Budget Period 1				Budget Period 2			
		Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8
Task 1.0 - Project Management and Planning	Team	■	■	■	■	■	■	■	■
Task 2.0 - Development of Nanostructured Cu Catalysts	Jiao	■	■	■	■				
Subtask 2.1 - Synthesis of Nanostructured Cu with Desired Properties	Jiao	■							
Subtask 2.2 - Catalytic Tests of Nanostructured Cu for CO Electroreduction	Jiao		■						
Subtask 2.3 - Scale-up Synthesis of Nanostructured Cu Catalysts	Jiao			■	■				
Milestone A – Complete the Development of Nanostructured Cu Catalysts	Jiao		◆						
Task 3.0 - Development of Anion-Exchange-Membrane-Based CO Electrolysis Reactor	Jiao	■	■	■	■				
Subtask 3.1 - Investigation of Anion Exchange Membranes	Jiao	■							
Subtask 3.2 - Fabrication of Anion-Exchange-Membrane-Based CO Electrolysis Reactor	Jiao		■	■					
Subtask 3.3 - Evaluation of Anion-Exchange-Membrane-Based CO Electrolysis Reactor	Jiao				■				
Milestone B – Complete the Development of Anion-Exchange-Membrane-Based CO Electrolysis Reactor	Jiao				◆				
Decision Point 1	Team				●				
Task 4.0 - Integration and Evaluation of the Complete Electrolyzer System	Jiao					■	■	■	■
Subtask 4.1 - Scale-up of CO Electrolysis Reactor with an Electrode Area of 100 cm^2	Jiao					■			
Subtask 4.2 - Design and Fabrication of CO Electrolysis Multi-Cell Stack Reactor	Jiao						■		
Subtask 4.3 - Evaluation of CO Electrolysis Multi-Cell Stack Reactor	Jiao							■	
Subtask 4.4 - Durability Test of CO Electrolysis Multi-Cell Stack Reactor	Jiao							■	■
Subtask 4.5 - Flue Gas Compatibility Test of CO Electrolysis Multi-Cell Stack Reactor	Jiao								■
Milestone C – Complete the Development of CO Electrolysis Multi-Cell Stack Reactor	Jiao								◆
Task 5.0 - Techno-Economic Analysis and Life-Cycle Assessment	Hodge			■	■			■	■
Subtask 5.1 - Techno-Economic Analysis	Hodge			■				■	
Subtask 5.2 - Life-Cycle Assessment	Hodge				■				■
Milestone D – Complete the Techno-Economic Analysis and Life-Cycle Assessment	Hodge								◆
Decision Point 2	Team								●

DOE/FECM

Acknowledgement

Thank you