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

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Area of Interest 1 – Synthesis of Value-Added Organic Products

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

Applicant Name: University of Delaware

Application Address: 210 Hullihen Hall, Newark, DE, 19716 (USA)

Principal Investigator: Feng Jiao
Additional Team Member: Bri-Mathias Hodge, UC Boulder

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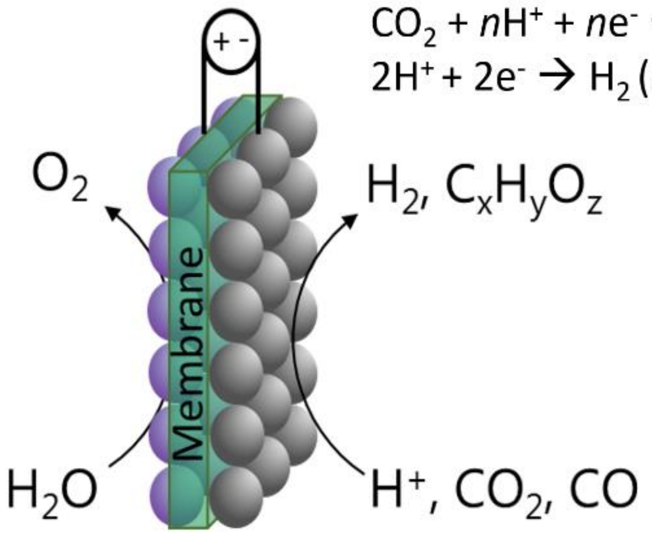
Federal Share: $1,000,000
Cost Share: $250,000
Total Estimated Project Cost: $1,250,000

Introduction to CO_2 Electrolyzer



Key components:
two electrodes (cathode & anode)
one polymer membrane

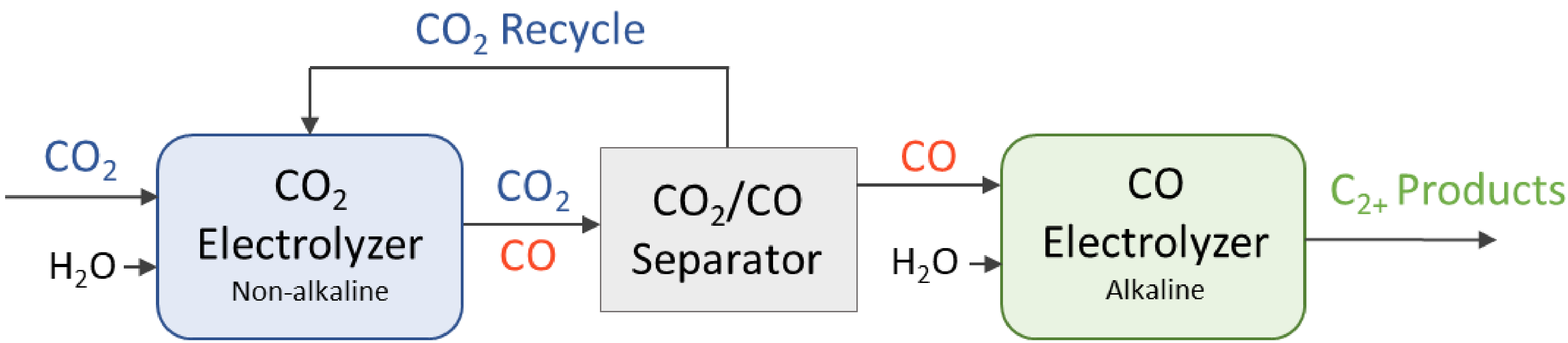
CO_2 electroreduction occurs on the cathode side, whereas the water oxidation reaction occurs on the anode side.

Reaction	E (V) vs. SHE
$CO_2 + 2H^+ + 2e^- \rightarrow HCOOH$	-0.61
$CO_2 + 2H^+ + 2e^- \rightarrow CO + H_2O$	-0.53
$CO_2 + 4H^+ + 4e^- \rightarrow C + 2H_2O$	-0.20
$CO_2 + 4H^+ + 4e^- \rightarrow HCHO + H_2O$	-0.48
$CO_2 + 6H^+ + 6e^- \rightarrow CH_3OH + H_2O$	-0.38
$CO_2 + 8H^+ + 8e^- \rightarrow CH_4 + 2H_2O$	-0.24

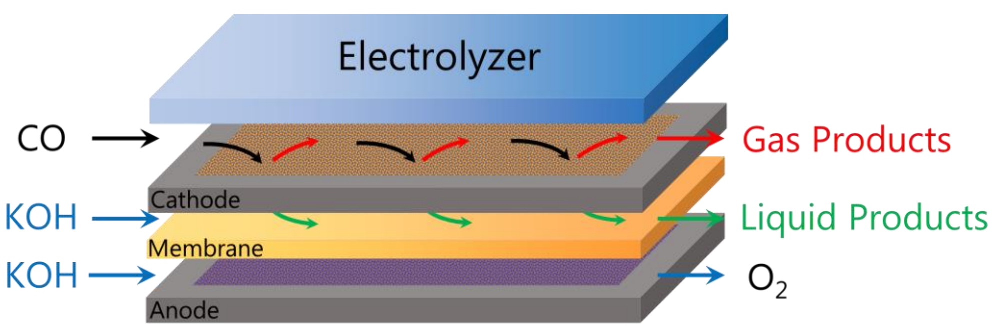
Technical Challenges:
- **Product Selectivity**
- **Energetic Efficiency**
- **Durability**

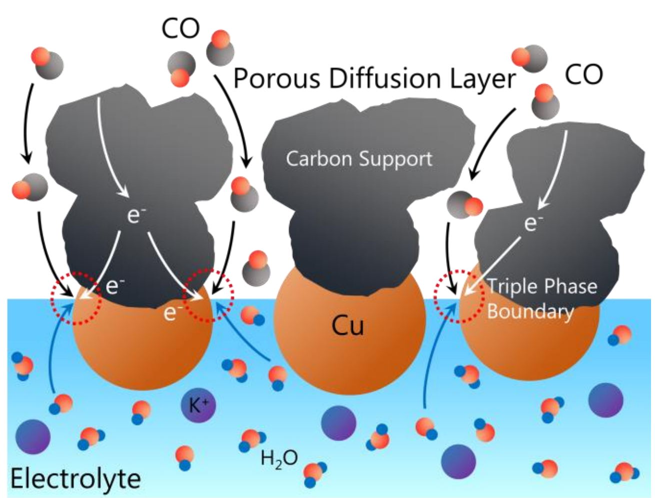
1) Hori, in Modern Aspects of Electrochemistry. (Springer, New York, 2008), vol. 42, pp. 89-189.
2) Jiao *et al*. Nano Energy, 2016.

Tandem electrolysis through CO intermediate



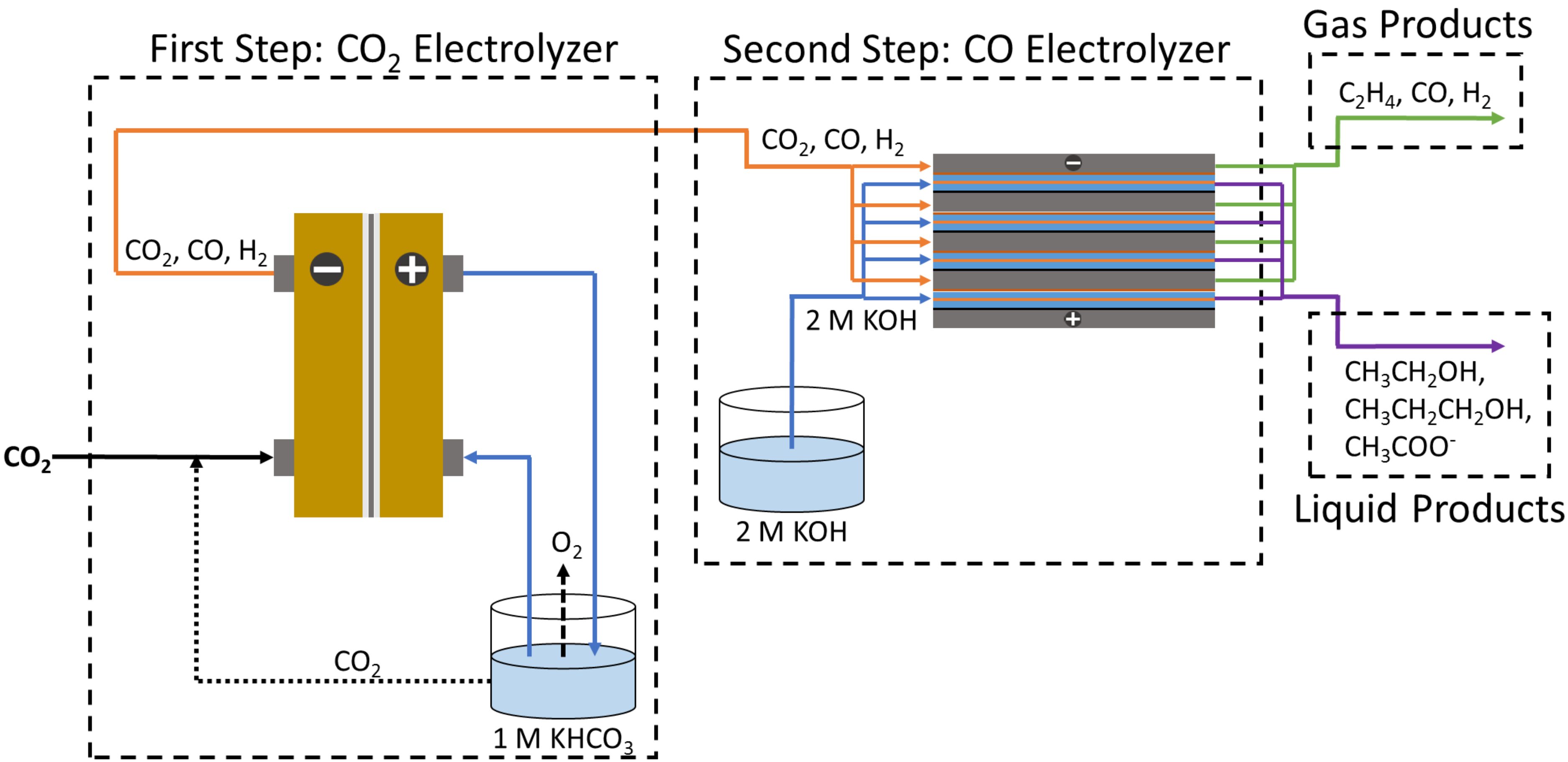
→ Decoupling of the electrolysis steps allows sustainable C_{2+} production



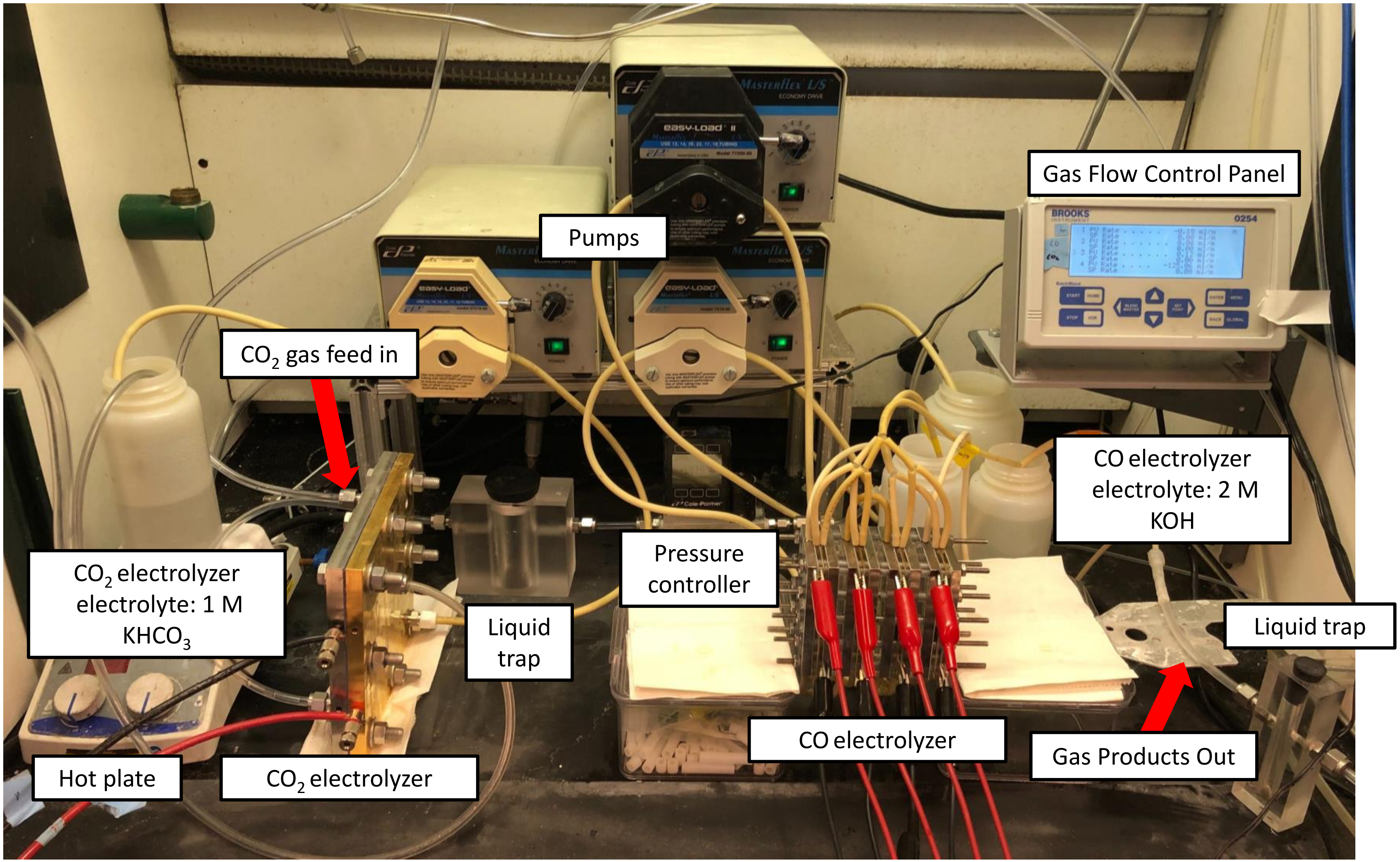


M. Jouny, W. Luc, & F. Jiao, *Nature Catalysis* 1, 748-755 (**2018**).

Schematic of Two-Step CO_2 Electrolysis Process

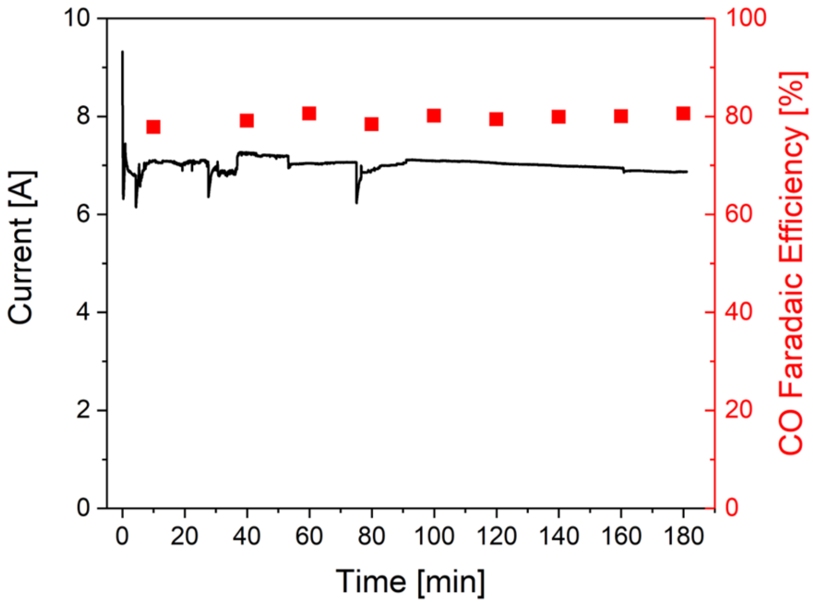


Two-Step Electrochemical Conversion of CO_2 to Alcohols

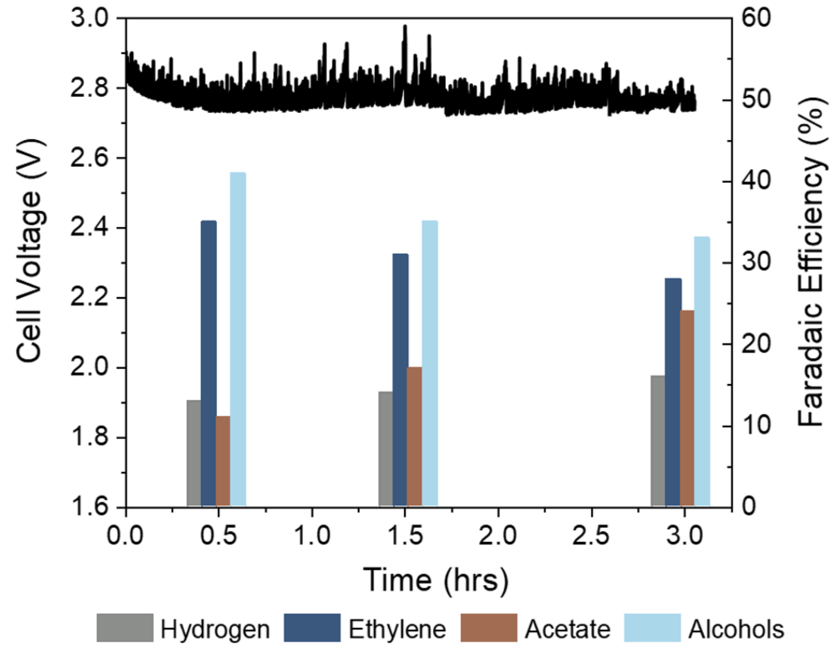


Electrolyzer subsystem performance

CO_2 electrolyzer sub system



CO electrolyzer sub system



- A stable performance for the two-step process was achieved.
- ~80% CO FE for the first step and ~40% alcohol FE for the second step

University of Delaware

Project Objectives and Approach

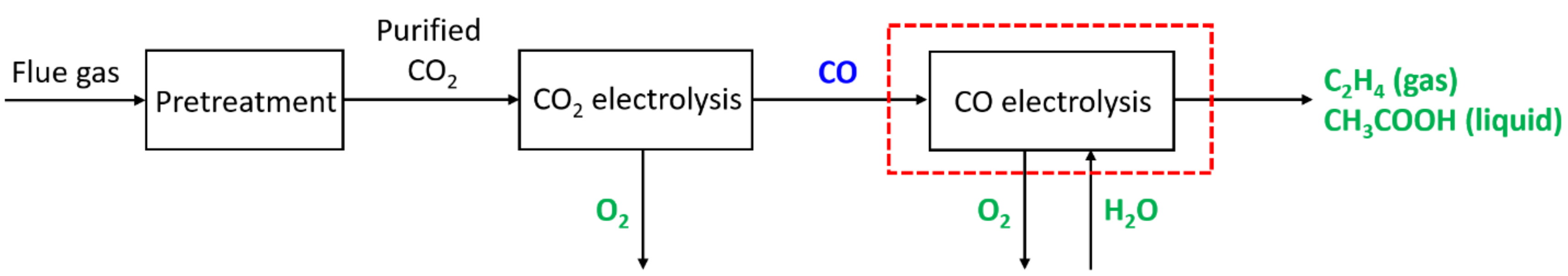
The objectives of this project include:

(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

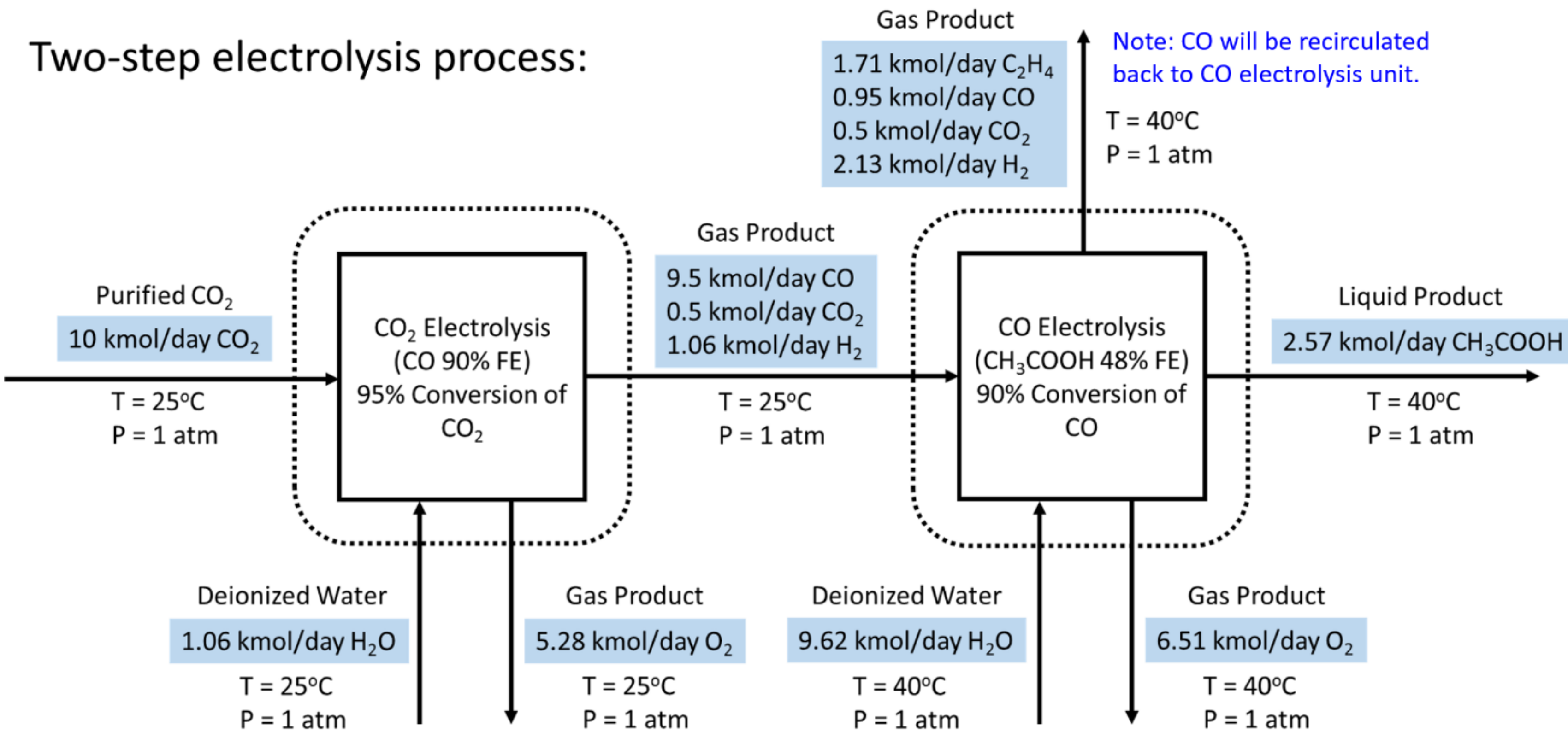
(2) constructing and assessing CO electrolysis multi-cell stack reactor prototype with a **90% carbon selectivity** and **a total power of 0.9 kW**

(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:



Two-step electrolysis process:

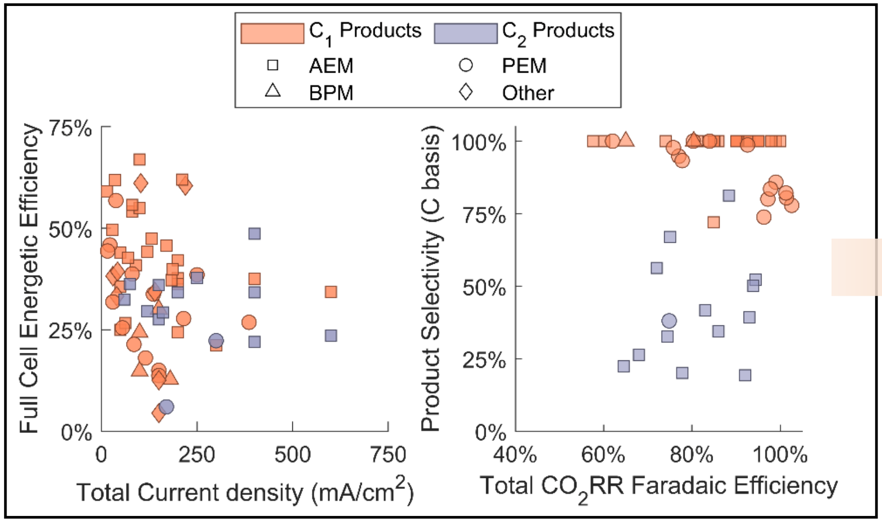


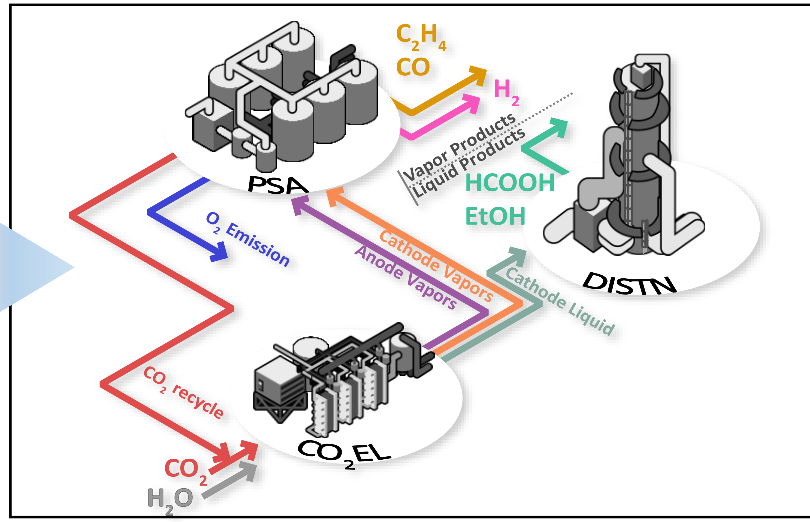
A full mass balance analysis of the two-step CO_2 electrolysis system for acetate and ethylene co-production. Operating conditions for each electrolysis unit are also indicated.

	Units	Measured/Current Performance	Projected/Target Performance
Synthesis Pathway Steps			
Step 1 (based on CO_2)	mol^{-1}	$2CO_2 \rightarrow 2CO + O_2$	
Step 2-1	mol^{-1}	$2CO + \mathbf{2H_2O} \rightarrow C_2H_4 + 2O_2$	
Step 2-2	mol^{-1}	$2CO + \mathbf{H_2O} \rightarrow CH_3COOH + O_2$	
Source of external intermediate 1		**Pure water**	
Reaction Thermodynamics			
Reaction		**Electrochemical reaction**	
ΔH^o_{rxn}	KJ/mol	**Acetate: 873.2** **Ethylene: 1323.1**	
ΔG^o_{rxn}	KJ/mol	**Acetate: 786.6** **Ethylene: 1331.5**	
Conditions		(range)	**(range)**
CO_2 Source		Pure CO_2	**Simulated CO_2 source with common flue gas contaminants**
Catalyst		Cu (cathode) IrO_x (anode)	**Cu (cathode)** **Ni-FeO_x or Co-Pi (anode)**
Pressure	bar	1-2	**1-5**
CO_2 Partial Pressure	bar	1	**>0.9**
Temperature	°C	~25	**30-70**
Performance		(range)	**(minimum)**
Nominal Residence Time	sec	48-184	**32**
Selectivity to Desired Product[a]	%	30-45	**50 (Acetate)** **80 (Acetate + ethylene)**
Product Composition		(range)	**(optimal)**
Desired Product (Acetate)	mol%	15-25	**40**
Desirable co-Product (Ethylene)	mol%	10-15	**20**
Unwanted By-Products:	mol%		
Ethanol	mol%	2-4	**<1**
1-Propanol	mol%	1-2	**<1**
Carbon Monoxide	mol%	15-27	**<10**
Hydrogen	mol%	>40	**<30%**
Grand Total	**mol%**	**--**	**100%**

Synthesis of Value-Added Organic Products *Technology Performance Data*

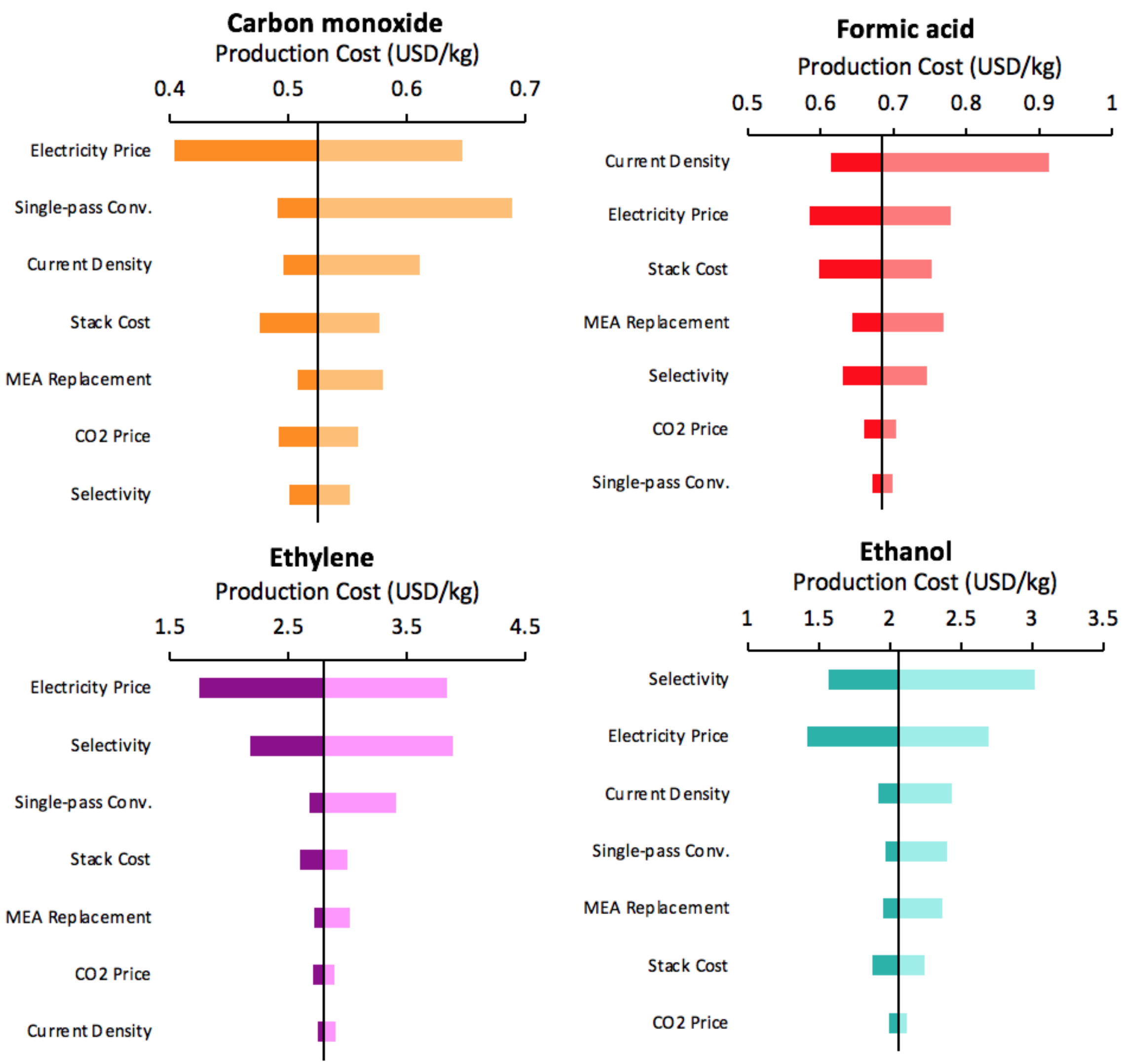
Techno-economic Analysis of CO_2 Electrolysis





- Survey the current state-of-the-art technology in the field for the past 5 years.
- Incorporate the current leading-edge performances into TEA.
- Evaluate the economic feasibility of electrochemical CO_2 conversion to products.
- Provide a roadmap for future research direction.

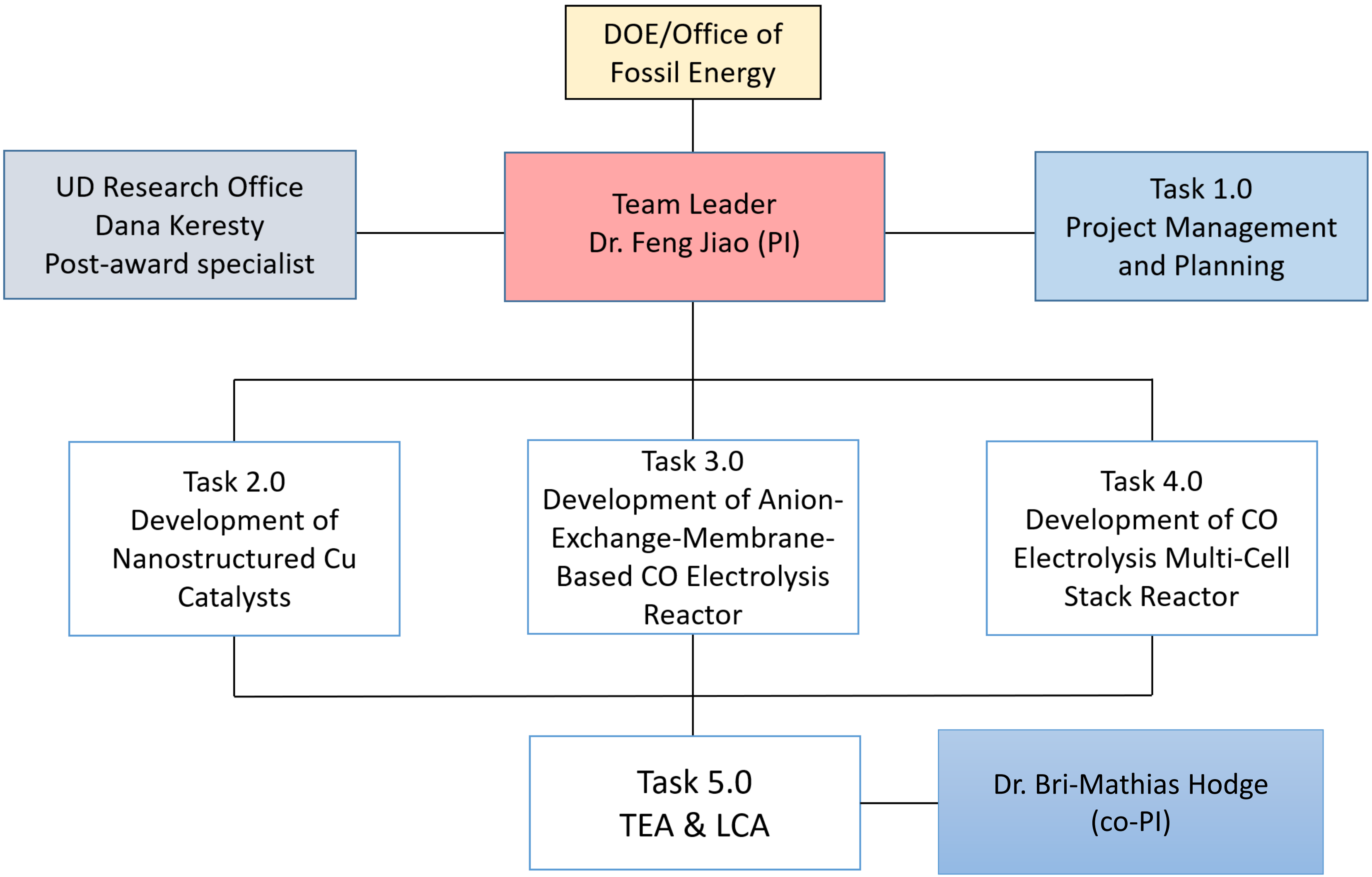
Roadmap to Market-competitive Production



- Overall, **electricity cost** is one of the key parameters in cost reduction for all products.
- With a current technology, C_1 product production is economically viable, while C_2 product production still demands tech enhancement.

Shin, H.#, Hansen, K. U.# & Jiao, F.* Techno-economic assessment of low-temperature carbon dioxide electrolysis. *Nature Sustainability* (in press). doi: 10.1038/s41893-021-00739-x

Project Management



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								●

Key Decision Points

Task/ Subtask	Milestone Title & Description	Planned Completion Date	Verification method
Task 2.0	Milestone A – Complete the Development of Nanostructured Cu Catalysts	02/28/2021	Documented performance data
Task 3.0	Milestone B – Complete the Development of Anion-Exchange-Membrane-Based CO Electrolysis Reactor	08/31/2021*	Photograph of the prototype and documented performance data
Task 4.0	Milestone C – Complete the Development of CO Electrolysis Multi-Cell Stack Reactor	08/31/2022	Photograph of the prototype and documented performance data
Task 5.0	Milestone D – Complete the Techno-Economic Analysis and Life-Cycle Assessment	08/31/2022	Documented analysis results

* A 3-month no-cost time extension was requested.

Acknowledgements

NATIONAL ENERGY TECHNOLOGY LABORATORY

Project manager:
Andrea T. McNemar

Thank you