Electrochemical Reduction of Flue Gas CO_2 to Commercially Viable C2 – C4 Products

Project: DE-FE0031916

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U.S. Department of Energy

National Energy Technology Laboratory

Carbon Management Project Review Meeting

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Project Overview

Funding

- DOE: $1,000,000
- Cost Share: $252,536 (UofL - $188,536, UND - $64,000)

Overall Project Performance Dates

- One budget period
- Start: October 1, 2020
- End: September 30, 2022, No-cost extension to March 31, 2023

Project Participants

- Recipient – University of Louisville
  - PI – Joshua Spurgeon – Theme Leader for Solar Fuels, Conn Center for Renewable Energy Research
  - Co-PI – Craig Grapperhaus, Professor, Chemistry Department
- Subrecipient – University of North Dakota
  - Co-PI – Nolan Theaker, Research Engineer, Institute for Energy Studies
- Partner – Minnkota Power Cooperative

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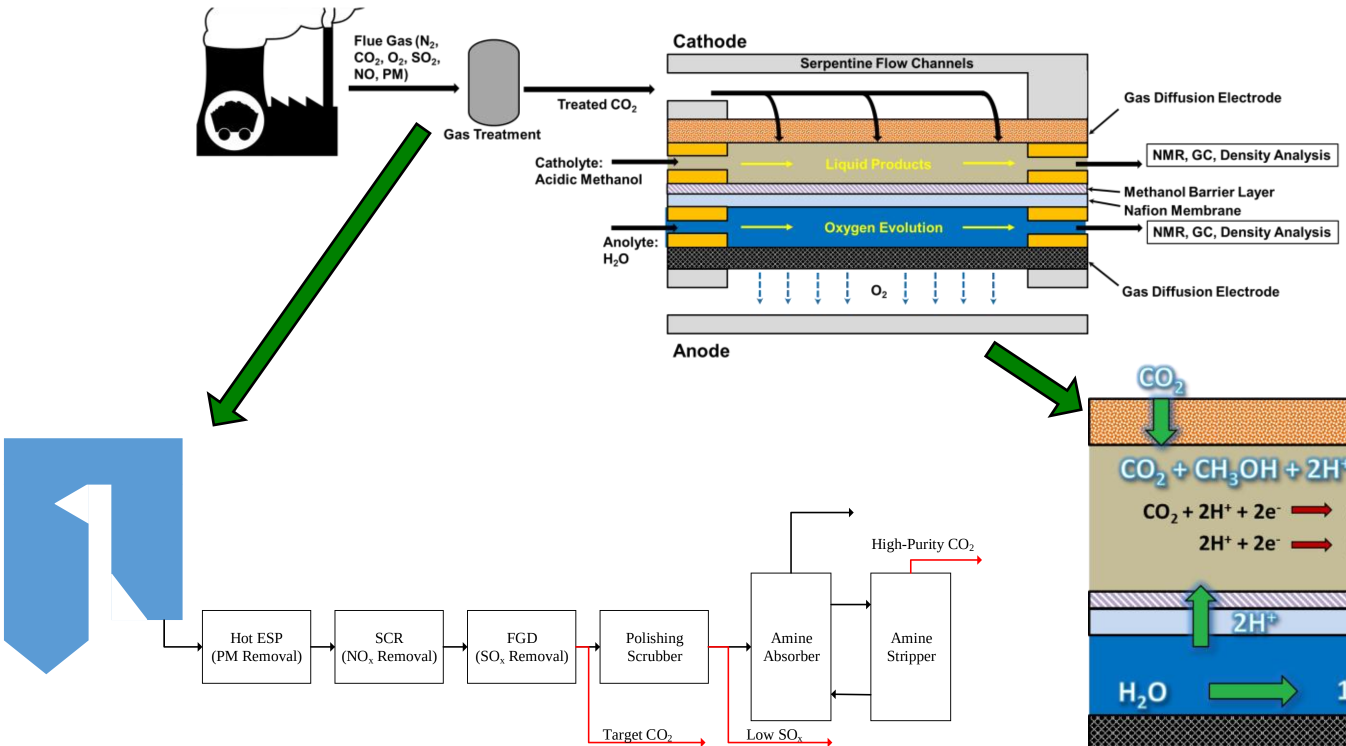
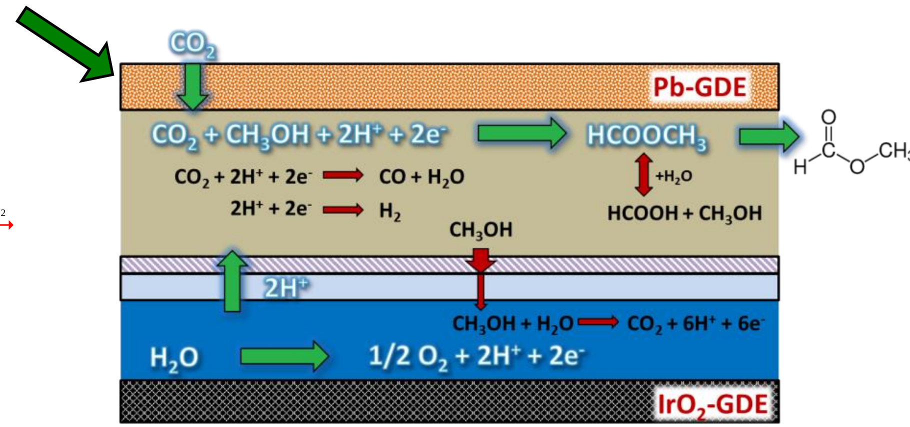
Technology Background



T = 25 °C
P = 1 atm
V_{app} = 2.5 – 4.0 V



Technology Overview:

- Use of power plant flue gas derivatives for CO_2 reduction
- Electrolysis flow cell reactor for stable high current, high faradaic efficiency
- Nonaqueous catholyte to enable high selectivity production of novel products not found in aqueous CO_2 reduction
- Dual electrolyte approach with aqueous anolyte to have sustainable water oxidation

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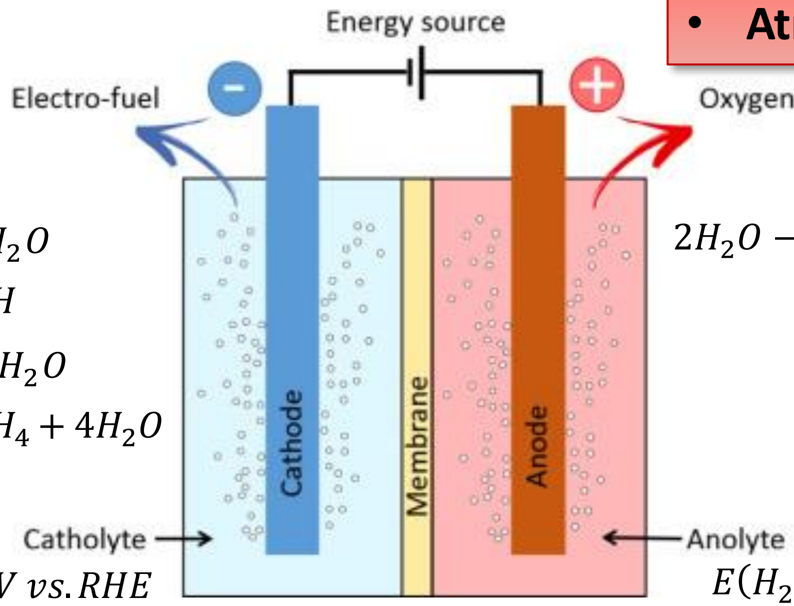
Electrochemical CO_2 Reduction

Typical aqueous electrolysis
- **Room temperature**
- **Atmospheric pressure**

$$2H^+ + 2e^- \rightarrow H_2$$
$$CO_2 + 2H^+ + 2e^- \rightarrow CO + H_2O$$
$$CO_2 + 2H^+ + 2e^- \rightarrow HCOOH$$
$$CO_2 + 8H^+ + 8e^- \rightarrow CH_4 + H_2O$$
$$2CO_2 + 12H^+ + 12e^- \rightarrow C_2H_4 + 4H_2O$$



$$2H_2O \rightarrow 4H^+ + 4e^- + O_2$$

$$E(cath) = -0.25 \; - +0.20\, V\; vs. RHE$$

$$E(H_2O \setminus O_2) = 1.23\, V\; vs. RHE$$

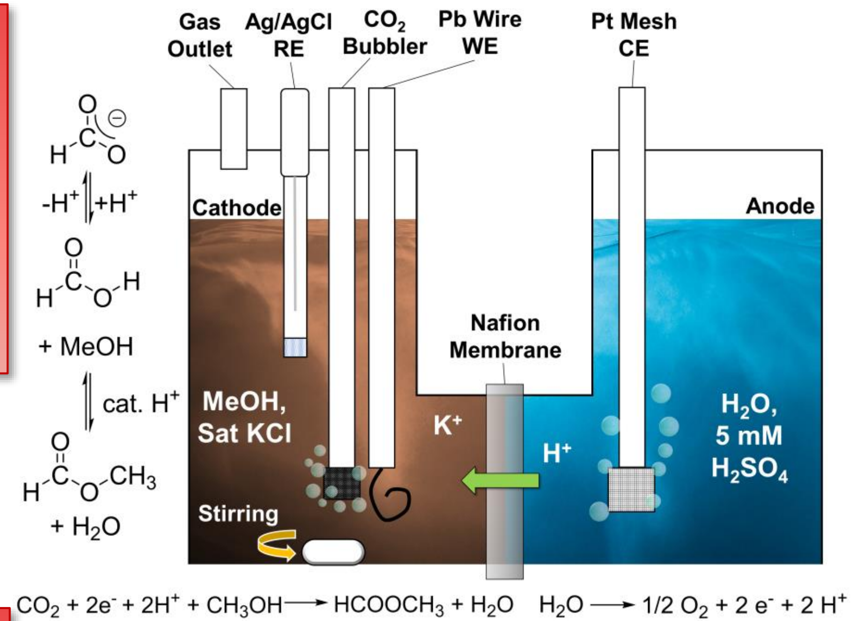
$$\Delta E = 1.03 \; - 1.48\, V$$

- **Selectivity limited by catalyst, competition with hydrogen evolution, CO_2 mass transfer**
- **CO_2 reduction partial current limited by CO_2 solubility/mass flux, applied bias and overpotential, catalyst area**

Technology Background

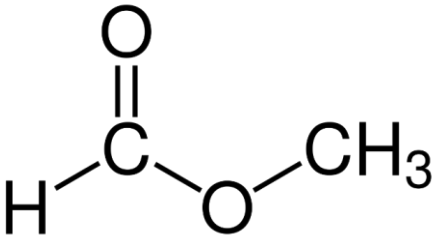
Methanol electrolyte enables

- Higher CO_2 solubility (0.17 M compared to 0.033 M in water)
- Chemical addition of CO_2 with solvent as an intermediate for non-standard CO_2 reduction products



Methyl formate

- <u>Initial</u> target C2 product
- Not an aqueous electrochemical CO2RR product
- Must come from waste CO_2, rigorously exclude anodic methanol oxidation
- Combined CO2RR to HCOOH and in-situ esterification reaction with methanol
- Similar C3 – C4 product routes in ethanol and propanol to be pursued later



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Technical Advantages

- Flow cell for high current, high selectivity operation
- Nonaqueous catholyte for high solubility and intermediate reactant addition
- Aqueous anolyte for sustainable water oxidation rather than methanol oxidation which does not incorporate CO_2

Economic Advantages

- Electroreduction – room temperature, atmospheric pressure, use for intermittent or curtailed electricity
- Waste CO_2 turned into value added product - 45Q tax credit - $35/ton CO_2 utilized
- Byproduct H_2 is still valuable
- Direct utilization of flue gas – no CAPEX for CO_2 capture plant
- Methanol ~ $400/ton, methyl formate ~ $1600-1800/ton

Technical Challenges

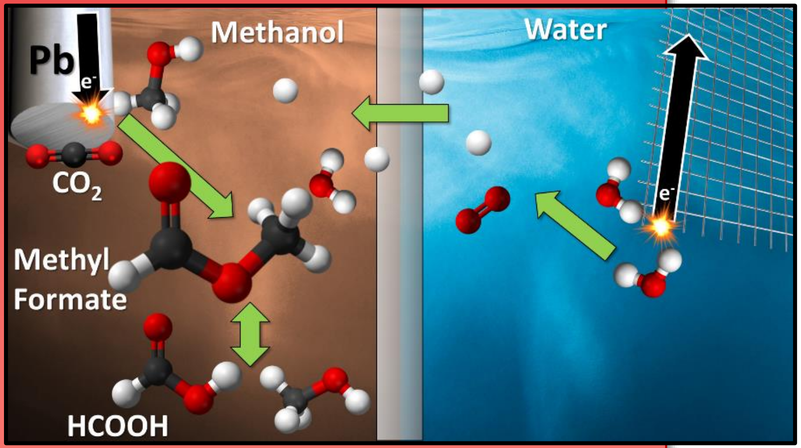
- Flue Gas - Mitigate contaminants degrading stability (SO_x, NO_x), dilute O_2 decreasing faradaic efficiency (FE), lower CO_2 concentration
- Chemistry – Maintain low pH for high FE to methyl formate, low methanol crossover
- Engineering – Achieve high CO_2 flux to cathode in methanol solvent

Economic Challenges

- Achieving high current density and FE for acceptable capital costs
- Minimizing methanol anodic oxidation as an operating expense
- Market size for chemicals vs. industrial CO_2 output – need for diversified products with favorable TEA

Overall Project Objectives

- **Objective 1 – Establish mechanistic pathway and characterize vs potential and pH**

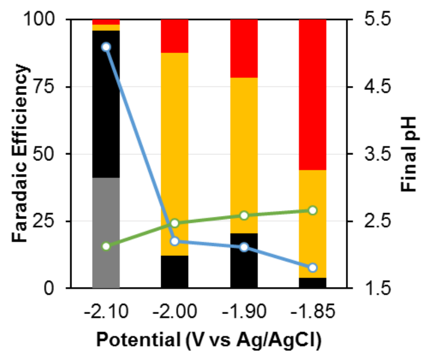


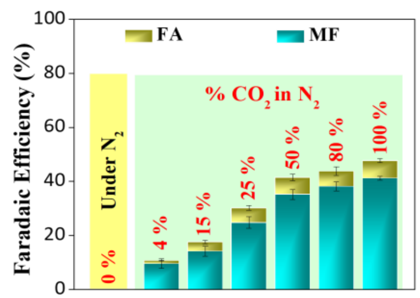
- **Objective 2 - Build an electrolysis flow cell reactor for high current density performance**
- **Objective 3 – Demonstrate direct conversion of flue gas at high faradaic efficiency and current density**
- **Objective 4 - Integrate flue gas feed with the optimized flow cell reactor to achieve performance and stability targets for commercial viability**
- **Objective 5 - Perform technoeconomic analysis (TEA) and life cycle analysis (LCA)**

Work Plan

- Task 1 (Q1) – Project Management and Planning
- Task 2 (Q1-7) – Improvement of Faradaic Efficiency to C2-4 Products
- Task 3 (Q1-7) – Develop Electrolysis Reactor for High-current CO_2 Reduction
- Task 4 (Q3-7) – CO_2 Electrolysis System from Power Plant Flue Gas Derivatives
- Task 5 (Q5-8) – Full System Integration with Commercially Relevant Performance
- Task 6 (Q7-8) – Technoeconomic Analysis and Life Cycle Analysis

Quarter	1	2	3	4	5	6	7	8
Key Milestone	Fabricate Flow Cell Electrolyzer	Complete pH and Applied Potential Study	Demonstrate C2+ FE > 40%	Complete Flue Gas Contaminants Study	Methanol Crossover < 5% FE CH_3OH Oxidation	Current Density > 600 mA cm^{-2}	Flue Gas Performance > 100 h with > 40% FE C2+	Operation on Utility Site Flue Gas > 1 Week





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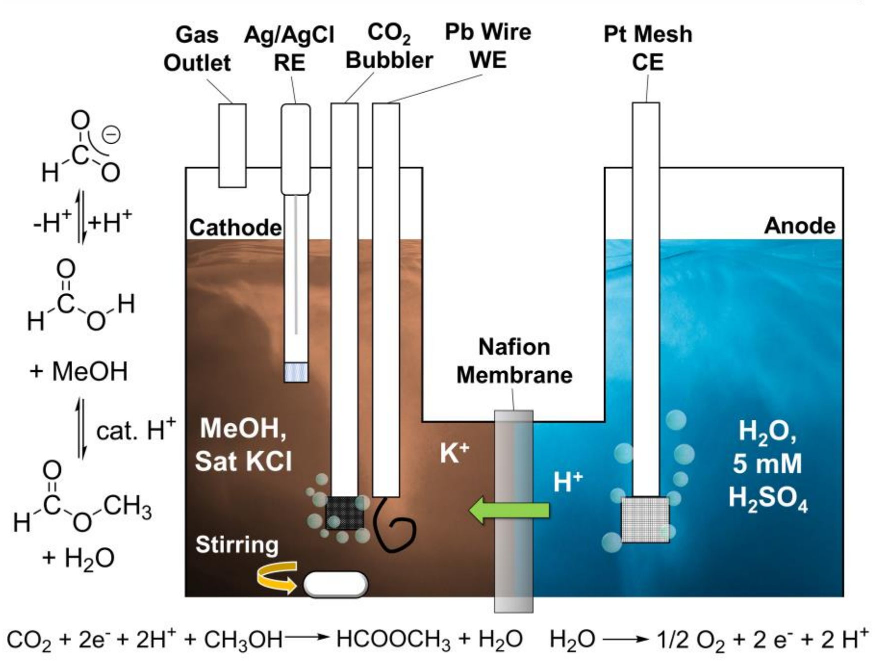
Task 2 – Improvement of Faradaic Efficiency to C2-4 Products

- Again, the initial focus was on methyl formate as the desired product
- Directed electrochemistry studies in an H-cell to inform the flow reactor testing

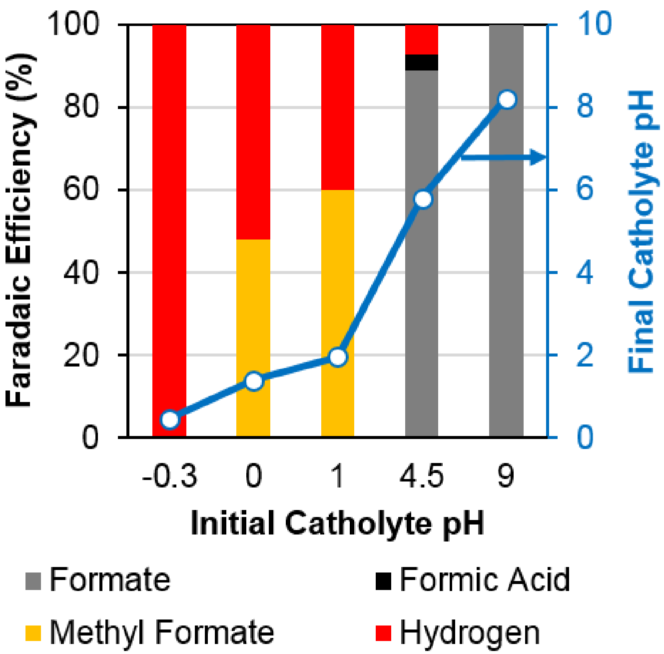
Direct H-cell studies with a Pb wire cathode



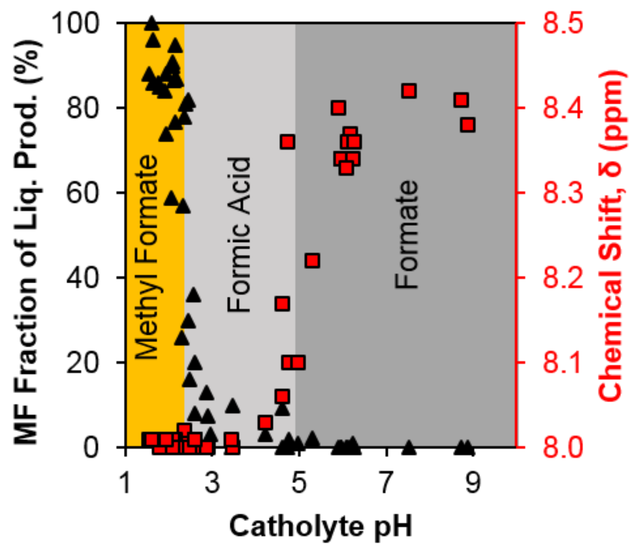
Task 2 – Improvement of Faradaic Efficiency to C2-4 Products

- **Determination of System Parameter Effects – Effect of pH**

☑ Milestone 2.e – Complete Acid Concentration/pH Study



Faradaic efficiency vs. catholyte pH for Pb in methanol catholyte with water anolyte.



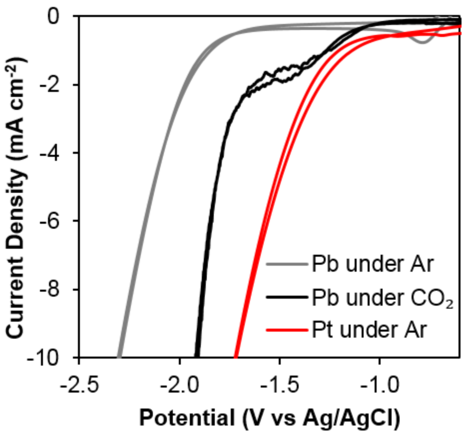
Conversion of the CO_2RR liquid product to methyl formate vs. pH.

- **pH < 2.5 to favor methyl formate**
- **pH < 1 starts to promote H_2 evolution and hurt methyl formate FE**

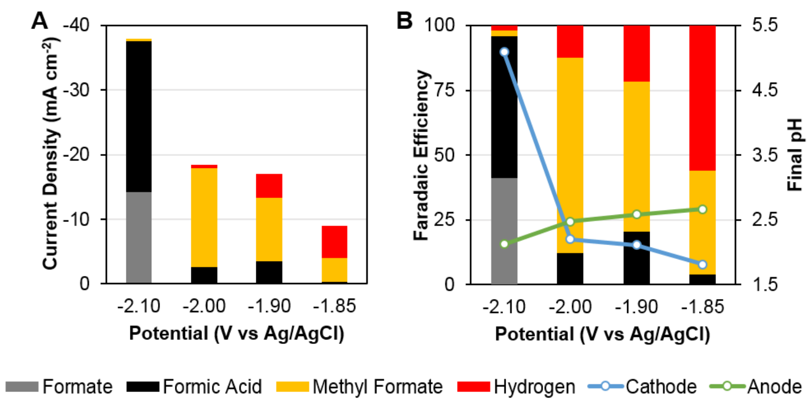
Task 2 – Improvement of Faradaic Efficiency to C2-4 Products

- **Determination of System Parameter Effects – Effect of Applied Potential**

☑ Milestone 2.c – Complete Applied Potential Study



Sat. KCl, pH 1.5 CH_3OH catholyte and 3 mM HCl in water anolyte separated by Nafion.

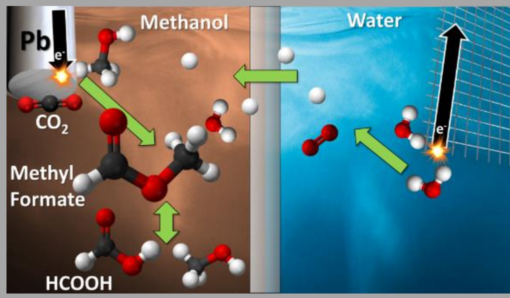


Partial current densities and FE vs. applied potential measured after potentiostatic operation for 30 min.

- **H_2 evolution strongly suppressed on Pb relative to Pt**
- **Up to *75% FE methyl formate* at -2.0 V vs. Ag/AgCl**

Publication:

Hofsommer, D.T., Liang, Y., Uttarwar, S.S., Pishgar, S., Gupta, M., Gulati, S., Grapperhaus, C.A., and Spurgeon, J.M., "The pH and Potential Dependence of Pb-catalyzed Electrochemical CO_2 Reduction to Methyl Formate in a Dual Methanol/Water Electrolyte", *ChemSusChem*, **2022**, *15 (5)*, e202102289. doi.org/10.1002/cssc.202102289



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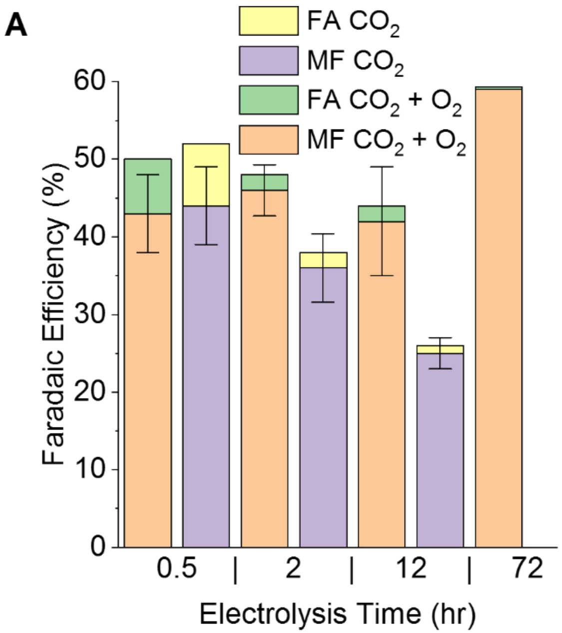
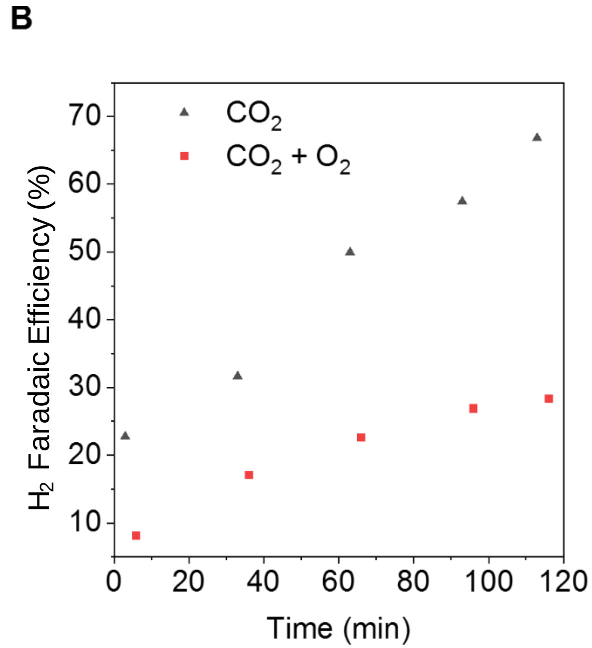
Task 2 – Improvement of Faradaic Efficiency to C2-4 Products

- **Optimization of Catalyst and Electrolysis Conditions**

☑ Milestone 2.f – Demonstrate High C2-4 Product Faradaic Efficiency



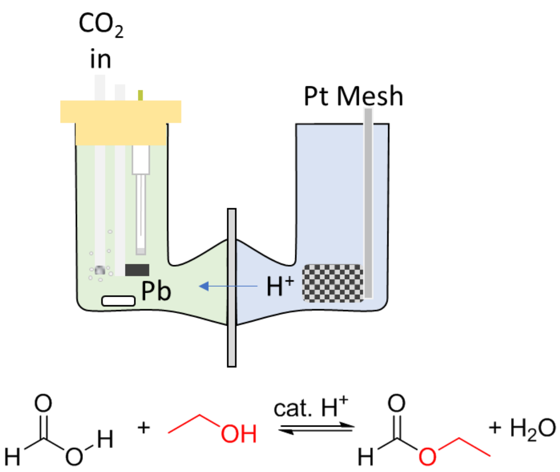


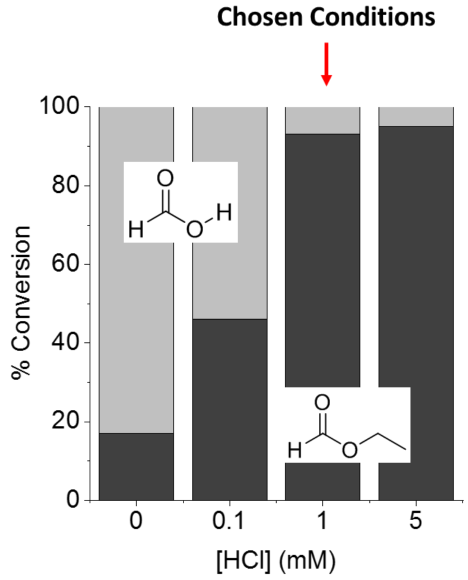
- **The inclusion of 4% O_2 in the gas feed was found to enable durable faradaic efficiency for methyl formate by inhibiting increasing H_2 evolution.**
- **Methyl formate FE greater than 40% has been maintained > 72 hours.**

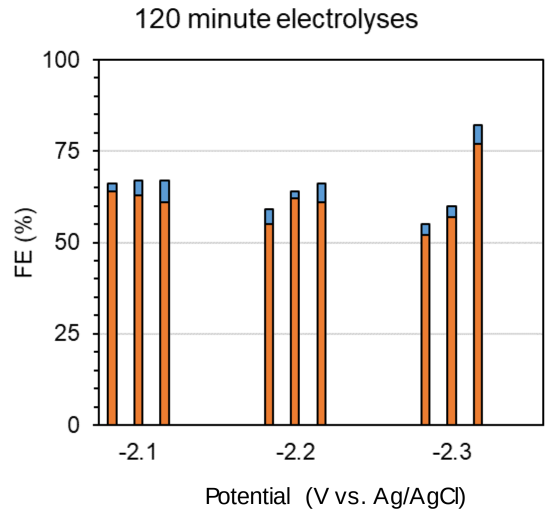
Task 2 – Improvement of Faradaic Efficiency to C2-4 Products

- Alternate Solvent Study

CO_2 reduction in ethanol to produce C3 species ethyl formate





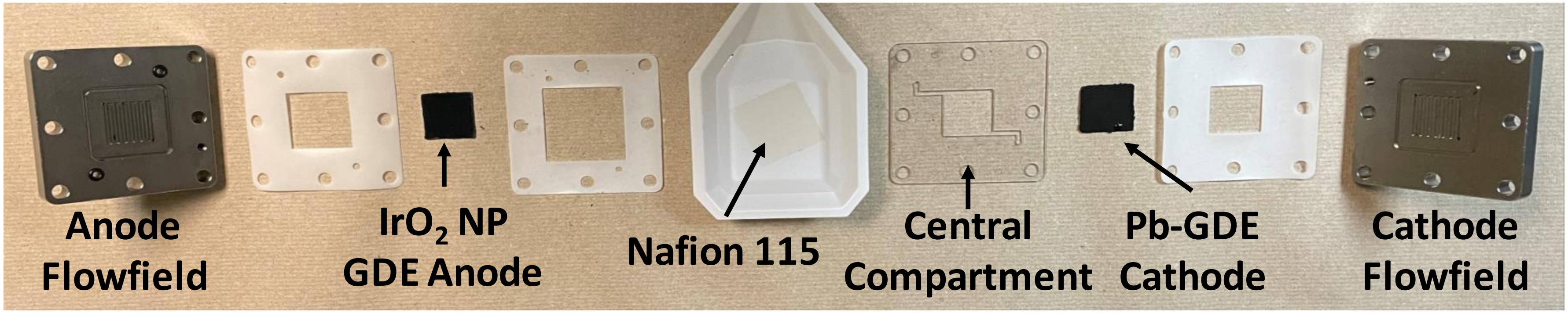


- Early testing, H-cell studies only
- CO2RR + esterification with ethanol works for three-carbon product
- Ethyl formate at *up to 75% faradaic efficiency achieved*

Task 3 – Develop Electrolysis Reactor for High-current CO_2 Reduction

- **Electrolyzer Chassis Design**

☑ Milestone 3.a – Fabricate Flow Cell Electrolyzer for High Current



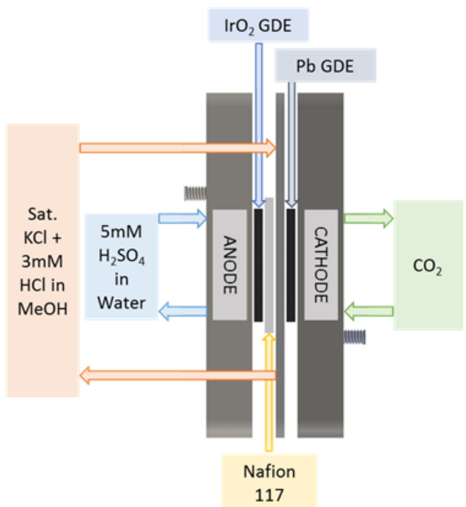
Flow cell exploded view.

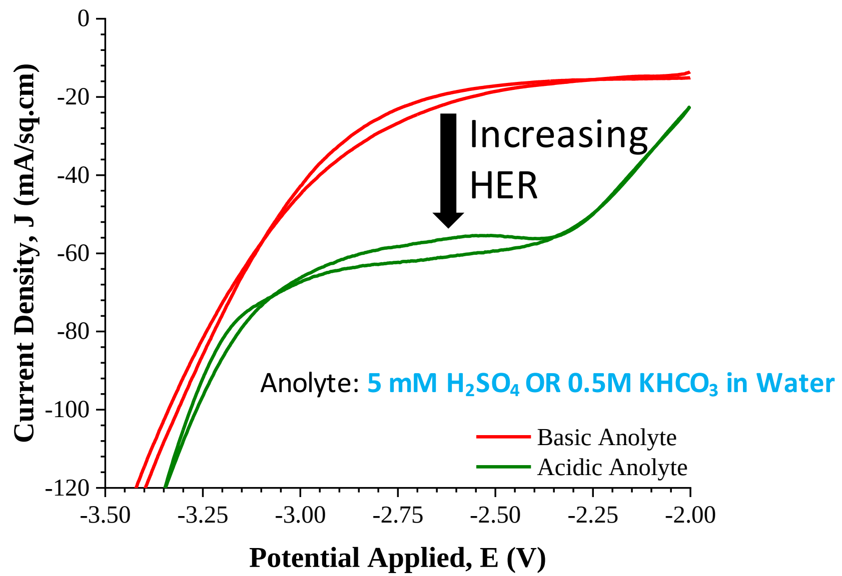
Flow cell system setup.

- **Acid-stable components for low pH operation**
- **Porous carbon Toray paper gas diffusion electrodes (GDE) for high catalyst loading and high mass flux of reactants**
- **Three-compartment arrangement with methanol through central compartment and gaseous CO_2 through cathode flowfield**
- **Peristaltic and/or syringe pumps for electrolyte flow**

Task 3 – Develop Electrolysis Reactor for High-current CO_2 Reduction

- CO_2 Feed to the Cathode – Baseline Flow Cell Performance





- The pH was maintained < 2.5 to promote methyl formate
- A current density plateau occurs with acidic anolyte due to increasing H_2 evolution as H^+ crosses the membrane
- Flow cell methyl formate selectivity has been low so far, with FE < ~20%
- Flooding of the GDE cathode is a problem due to poor wet-proofing of methanol

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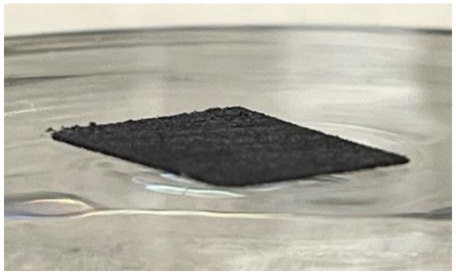
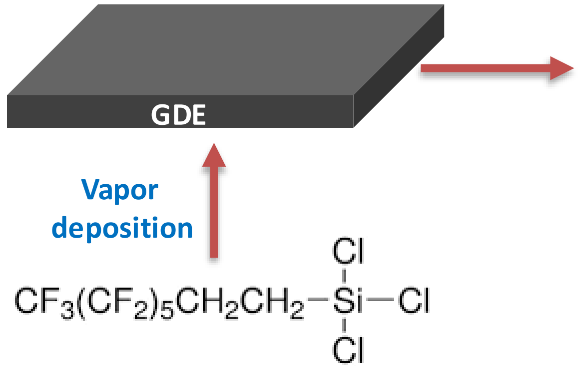
Task 3 – Develop Electrolysis Reactor for High-current CO_2 Reduction

- CO_2 Feed to the Cathode – Alternate Wet-proofing Layer



Methanol drop on PTFE-coated GDE



1H,1H,2H,2H-perfluorooctyltrichlorosilane (PFOTS)

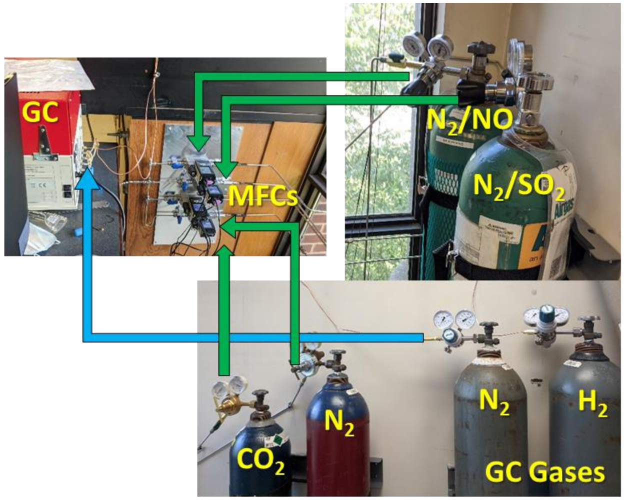
Methanol drops on PFOTS-coated GDE

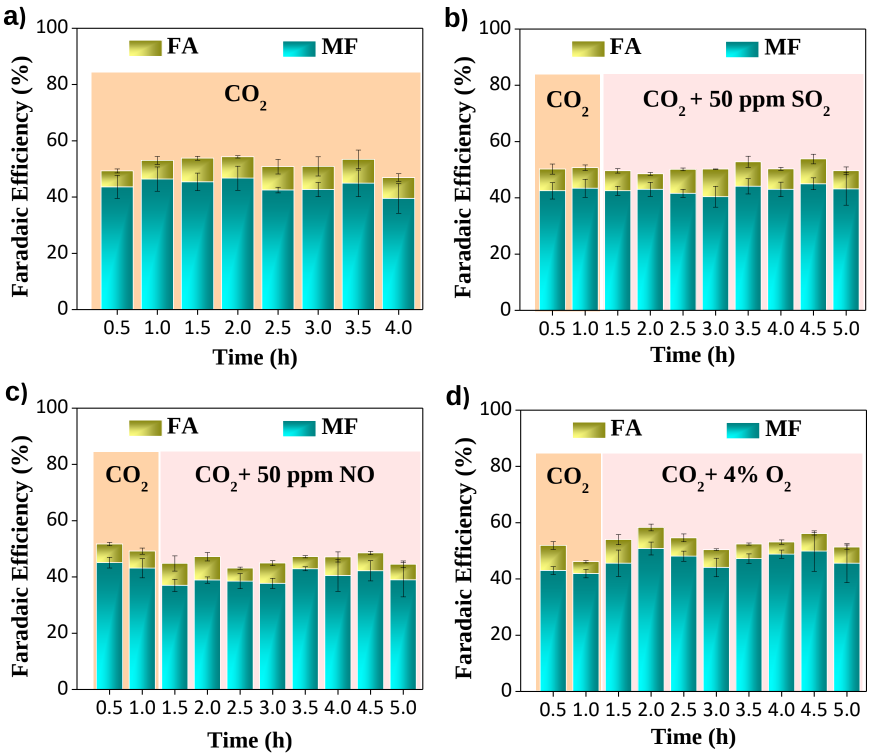
- **Using an alcohol-repellent coating to try to make effective gas diffusion electrodes for operation in methanol**
- **The modified GDE holds back methanol.**
- **Functional alcohol-repellent cathodes are under development and testing.**

After 1 hour

Task 4 – CO_2 Electrolysis System from Power Plant Flue Gas Derivatives

- Impurity and CO_2 Concentration Effects – Flue Gas Contaminants Study



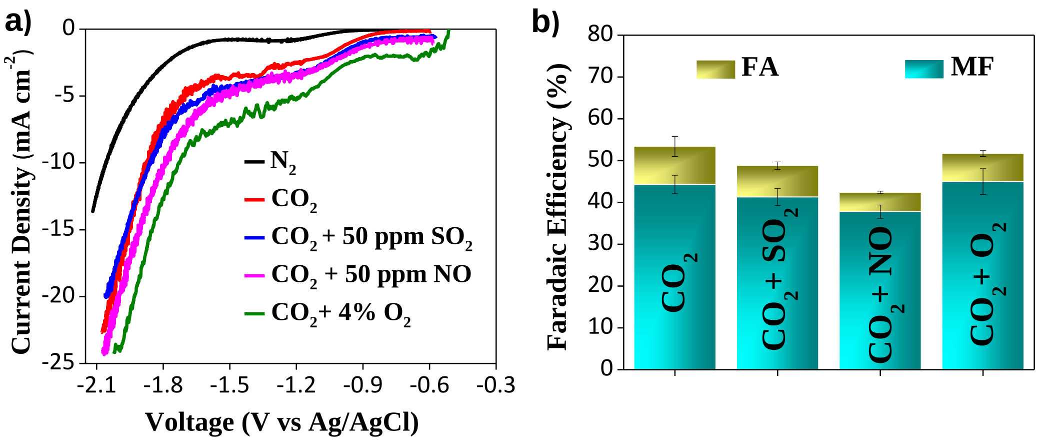


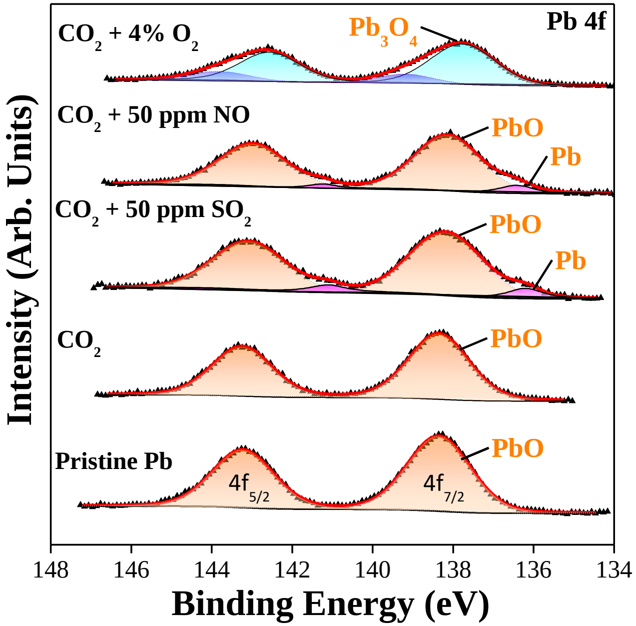
- Methyl formate selectivity/faradaic efficiency was stable at 40 – 45%
- Performance was tolerant to individual contaminants (SO_2, NO, O_2) at flue gas concentrations

Task 4 – CO_2 Electrolysis System from Power Plant Flue Gas Derivatives

- Impurity and CO_2 Concentration Effects – Flue Gas Contaminants Study

☑ Milestone 4.a – Complete Flue Gas Contaminants Study





- Slight MF FE drop with SO_2 and NO due to preferential reduction of the contaminant
- Parasitic oxygen reduction FE with 4% O_2 was low – low O_2 solubility in methanol
- Surface with O_2 was different (Pb_3O_4) – maintaining an in-situ surface oxide suggested to kinetically inhibit HER and promote CO2RR

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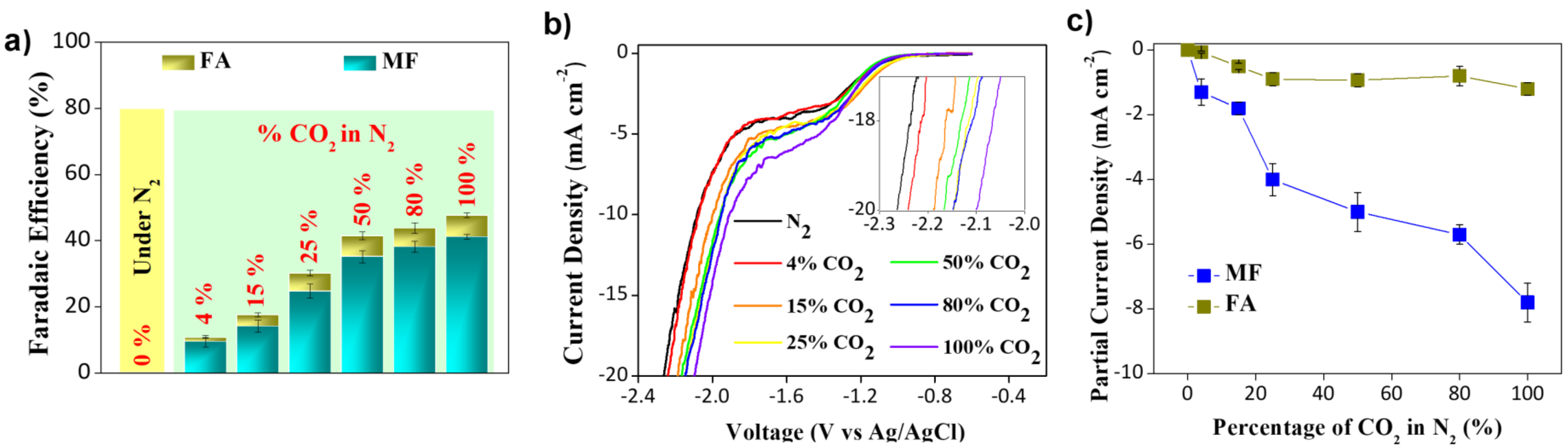
Task 4 – CO_2 Electrolysis System from Power Plant Flue Gas Derivatives

- Impurity and CO_2 Concentration Effects – CO_2 Concentration Study

☑ Milestone 4.b – Complete CO_2 Concentration Study



- The partial current density for methyl formate decreases with the concentration of CO_2 due to declining reactant mass flux
- At greater than 50% CO_2, there is only a modest decrease in the MF FE compared to pure CO_2

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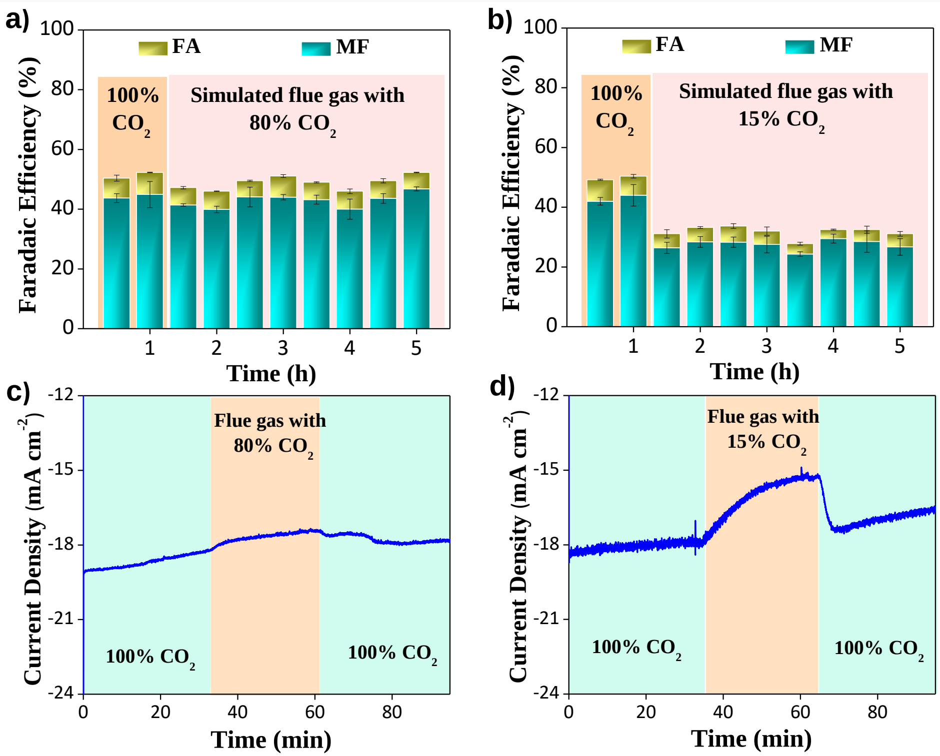
Task 4 – CO_2 Electrolysis System from Power Plant Flue Gas Derivatives

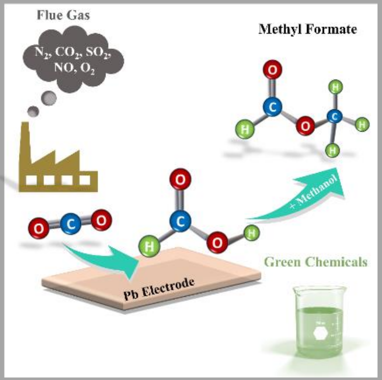
- Impurity and CO_2 Concentration Effects – Simulated Flue Gas

Simulated flue gas with 4% O_2, 50 ppm SO_2, 50 ppm NO in CO_2/N_2



Publication:

Gautam, M., Hofsommer, D.T., Uttarwar, S.S., Theaker, N., Paxton, W.F., Grapperhaus, C.A., and Spurgeon, J.M., "The Effect of Flue Gas Contaminants on Electrochemical Reduction of CO_2 to Methyl Formate in a Dual Methanol/Water Electrolysis System", *Chem Catalysis*, Accepted, **2022**.



- **Performance is tolerant to simulated flue gas with CO_2 down to 80% v/v concentration.**
- **The presence of O_2 led to better performance than comparable dilute CO_2 without contaminants.**
- **Actual flue gas level 15% CO_2 led to significant performance degradation.**

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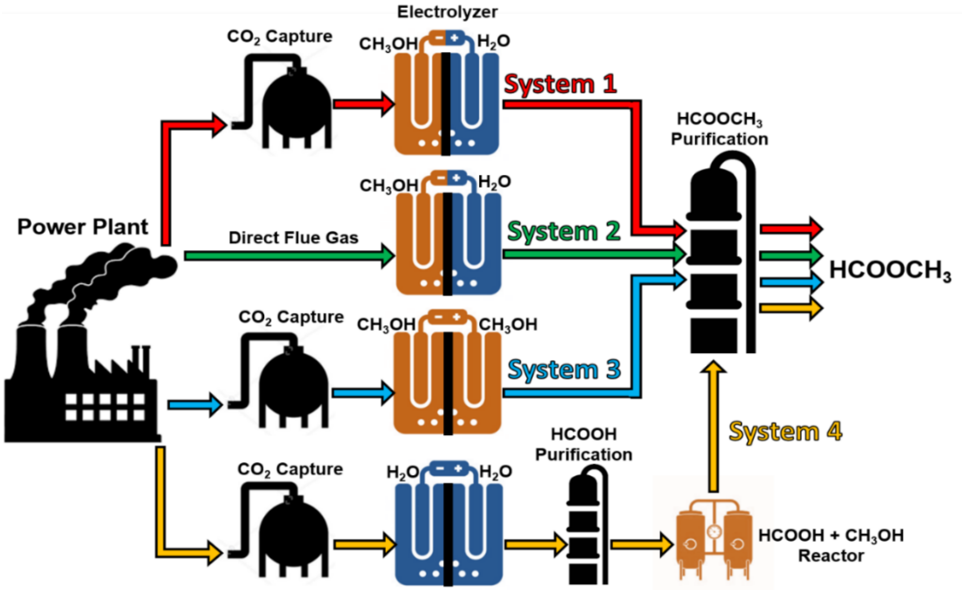
Task 6 – Technoeconomic Analysis and Life Cycle Analysis

- TEA of Flue Gas Conversion to C2 Product

- Systems to be modeled for comparison:
  1) CO2RR in dual CH_3OH/H_2O electrolyzer from captured pure CO_2
  2) CO2RR in dual CH_3OH/H_2O electrolyzer from flue gas CO_2
  3) CO2RR in CH_3OH only electrolyzer from captured pure CO_2
  4) CO2RR in H_2O electrolyzer to HCOOH, then downstream converted to methyl formate



- Basis: 1×10^5 kg MF/day – starting point for mass balance
- Same operating voltage and current density assumed for all systems
- Aspen software used to model distillation columns for separation of liquids

Task 6 – Technoeconomic Analysis and Life Cycle Analysis

- TEA of Flue Gas Conversion to C2 Product

Product	Market price ($ kg^{-1})	Molecular weight (g mol^{-1})	Electrons per molecule	Price per electron ($ mol^{-1} electron) x 10^3
Carbon monoxide	0.60	28.01	2	8.4
Formic acid	0.70	46.03	2	16.1
Methanol	0.40	32.04	6	2.1
Methane	0.18	16.04	8	0.4
Ethylene	1.30	28.05	12	3.0
Ethanol	1.00	46.07	12	3.8
Propanol	1.43	60.10	18	4.8
Methyl formate	1.60	60.05	2	48.0

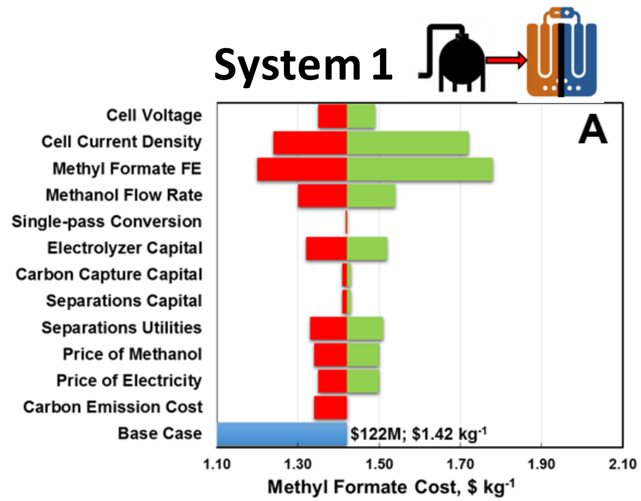
$$CO_2 + 2H^+ + 2e^- + CH_3OH \rightarrow HCOOCH_3 + H_2O$$

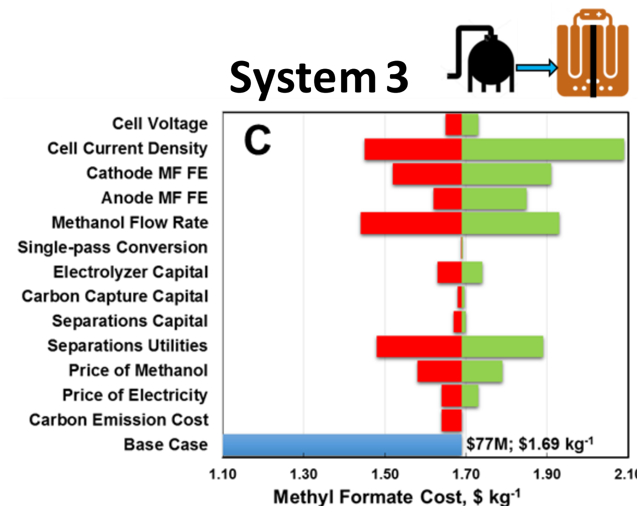
Economics of CO_2 reduction to methyl formate look encouraging because:

- **High market price per kg**
- **High molecular weight**
- **Only 2 electrons per molecule of MF (or 8 if CH_3OH must be synthesized from CO_2 as well)**
- **Low cost of methanol reactant**

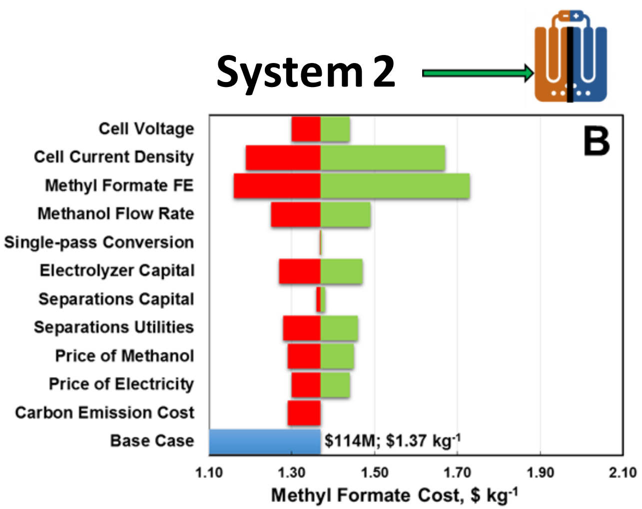
Task 6 – Technoeconomic Analysis and Life Cycle Analysis

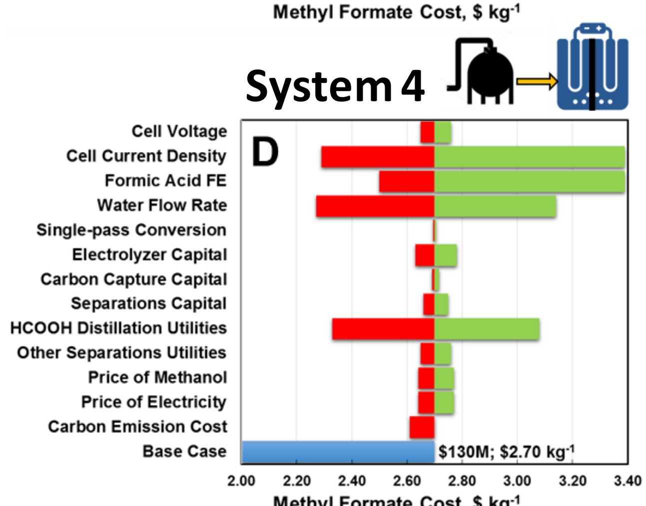
- **Sensitivity Analysis**





System 3: Uses and distills twice as much CH_3OH – catholyte AND anolyte





System 4: Very energy-intensive to distill HCOOH from H_2O

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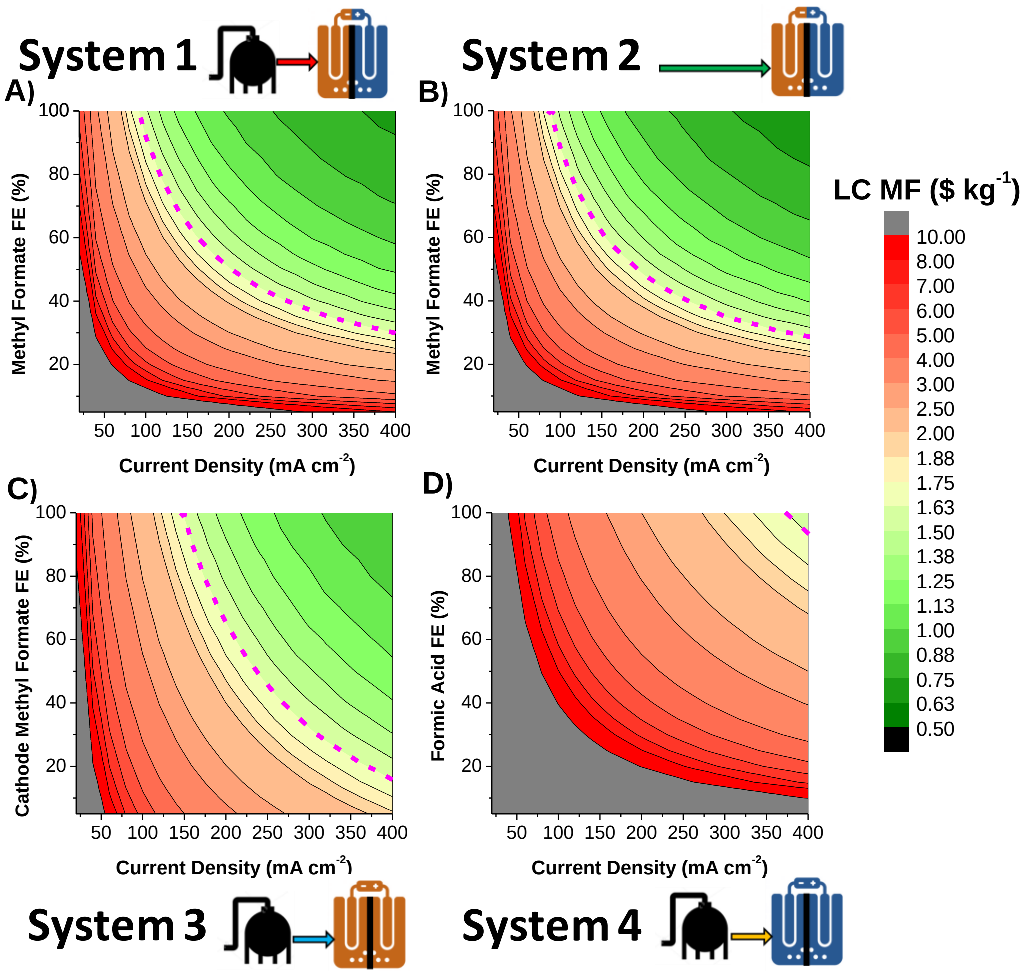
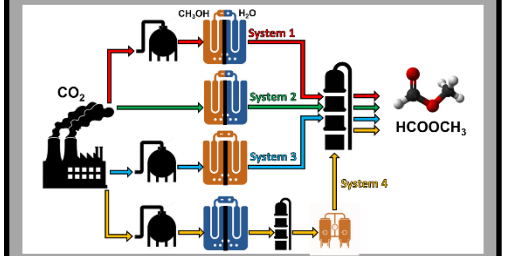
Task 6 – Technoeconomic Analysis and Life Cycle Analysis

- Cost contour plots



Publication:

Spurgeon, J.M., Theaker, N., Phipps, C.A., Uttarwar, S.S., and Grapperhaus, C.A., "A Comparative Technoeconomic Analysis of Pathways for the Electrochemical Reduction of CO_2 with Methanol to Produce Methyl Formate", Submitted, **2022.**



Current Status

- Task 2 has established stable high selectivity MF synthesis, and is now extending this to the C3 ethyl formate in ethanol solvent
- Task 3 flow cell electrolyzer design and testing has made progress but a cathode design for high CO_2 flux in methanol needs to be optimized
- Task 4 flue gas electrolysis showed tolerance to contaminants but sensitivity to decreased CO_2 concentration, and the results need to be extended to the flow cell and real flue gas
- Task 5 integration of the advances needs an effective flow cell gas diffusion electrode to proceed
- Task 6 technoeconomic analysis is complete, and life-cycle analysis work has begun

Quarter	1	2	3	4	5	6	7	8
Key Milestone	Fabricate Flow Cell Electrolyzer	Complete pH and Applied Potential Study	Demonstrate C2+ FE > 40%	Complete Flue Gas Contaminants Study	Methanol Crossover < 5% FE CH_3OH Oxidation	Current Density > 600 mA cm^{-2}	Flue Gas Performance > 100 h with > 40% FE C2+	Operation on Utility Site Flue Gas > 1 Week

Plans for Future Testing/Development/Commercialization

Plans for the future

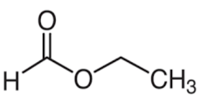
- On-site flue gas testing of flow cell electrolyzer at a power plant
- Continue development of high performance nonaqueous catholyte CO_2 electrolyzers for additional novel products

Three-carbon products

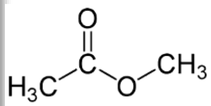
- Ethyl formate, $C_3H_6O_2$ – like methyl formate route, CO_2 reduction to formic acid and esterification in ethanol
- Methyl acetate, $C_3H_6O_2$ – CO_2 reduction to acetate and esterification in methanol

Four-carbon products

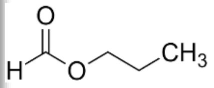
- Propyl formate, $C_4H_8O_2$ – CO_2 reduction to formic acid and esterification in propanol



Ethyl formate



Methyl acetate



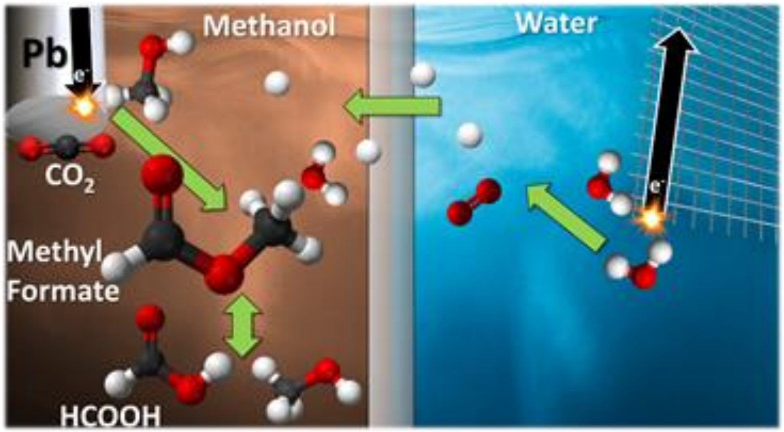
Propyl formate

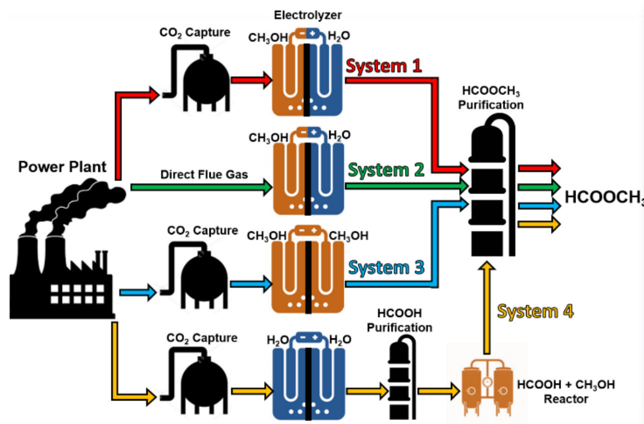
Commercialization plan

- Provisional/non-provisional patent applications of generated IP
- Pursue SBIR funding for device scale-up
- Look for collaborative opportunities with large electrolyzer manufacturers
- Customer discovery through utilities, cement producers, chemical manufacturers, oil companies
- Potentially license technology to CO_2 electrolysis companies like Dioxide Materials or Opus 12

Summary Slide

Waste CO_2 can be electrochemically upgraded in nonaqueous solvent to species not produced in aqueous systems, like methyl formate. Conversion can be accomplished with high selectivity and current and high tolerance to flue gas impurities, but effective gas diffusion electrodes in alcohols are need for a high performance flow cell.





- **Up to 75% FE $HCOOCH_3$ achieved**
- **System needs catholyte 1 < pH < 2.5 for methyl formate**
- **Methyl formate FE > 40% steady for > 72 h with 4% O_2 added**
- **Steady performance tolerant to flue gas contaminants**
- **Technoeconomics looks favorable for the methyl formate electrosynthesis if high current density is achieved**

UNIVERSITY OF LOUISVILLE. CONN CENTER

UND Institute for Energy Studies, University of North Dakota

NETL National Energy Technology Laboratory

- State Point Data Table
- Organization Chart
- Gantt Chart

THANK YOU FOR LISTENING

CO-PIS:

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UND INSTITUTE FOR ENERGY STUDIES UNIVERSITY OF NORTH DAKOTA

NETL NATIONAL ENERGY TECHNOLOGY LABORATORY

State Point Data Table

Synthesis of Value-Added Organic Products

Technology Performance Data

	Units	Measured/Current Performance	Projected/Target Performance
Synthesis Pathway Steps[1]			
Step 1 (based on CO_2) - Cathode	mol^{-1}	$CO_2 + 2H^+ + 2e^- + \mathbf{CH_3OH} \rightarrow HCOOCH_3 + H_2O$	
Step 2 - Anode	mol^{-1}	$2H_2O \rightarrow O_2 + 4H^+ + 4e^-$	
Step – Full Reaction	mol^{-1}	$CO_2 + \mathbf{CH_3OH} \rightarrow HCOOCH_3 + 1/2O_2$	
Source of external intermediate 1		Methanol (CH_3OH) – from natural gas	
Reaction Thermodynamics[2,3]			
Reaction[4]		Electrochemical	
ΔH^o_{Rxn}	KJ/mol	+266.0	
ΔG^o_{Rxn}	KJ/mol	+322.4	
Conditions		(range)	(range)
CO_2 Source[5]		Pure CO_2, simulated flue gas	Coal-fired flue gas
Catalyst[6]		Pb foil	Pb nanoparticles
Pressure	bar	1.013	1.013
CO_2 Partial Pressure	bar	1.013 to 0.15	0.15
Temperature	oC	25	25
Performance		(range)	(minimum)
Nominal Residence Time[7]	sec	15-30	15
Selectivity to Desired Product[8]	%	85-90	95
Product Composition[9]		(range)	(optimal)
Desired Product – Methyl Formate	mol%	40 - 60	60
Desirable Co-Products - Hydrogen	mol%	30 - 60	37
Unwanted By-Products – Formic Acid	mol%	3 - 10	3
Grand Total	**mol%**	**100**	**100%**

UNIVERSITY OF LOUISVILLE. CONN CENTER

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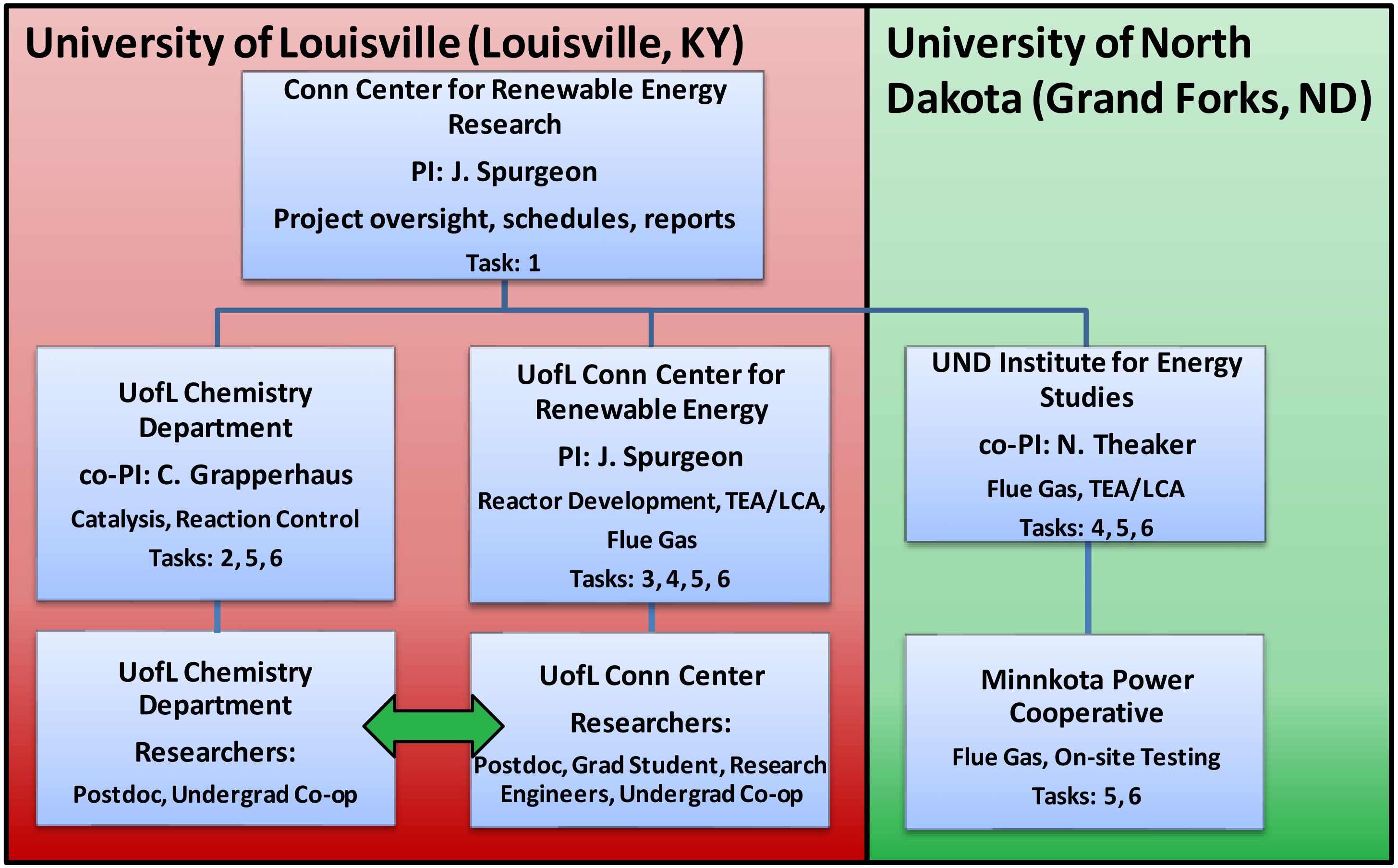
NETL NATIONAL ENERGY TECHNOLOGY LABORATORY

ORGANIZATION CHART



GANTT CHART

Task Name	Year 1				Year 2			
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Task 1.0 - Project Management and Planning	O							
Task 2.0 – Improvement of Faradaic Efficiency to C2-4 Products		O		O		O		
Task 3.0 – Develop Electrolysis Reactor for High-current CO_2 Reduction	O		X		O	X		
Task 4.0 - CO_2 Electrolysis System from Power Plant Flue Gas Derivatives				O	O		X	
Task 5.0 – Full System Integration with Commercially Relevant Performance								X
Task 6.0 – Technoeconomic Analysis and Life Cycle Analysis							O	X

Task Duration

Completed Work

O – Complete Milestone
X – Incomplete Milestone

PROJECT METHODOLOGY

- **Gantt Chart/schedule of activities**

Task Name	Team	Resources Allocated	Year 1				Year 2			
			Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Task 1.0 - Project Management and Plannig	UofL, UND	**$12,956**								
Subtask 1.1 - Project Management Plan	UofL, UND	$5,182								
Subtask 1.2 - Technology Maturation Plan	UofL, UND	$7,773								
Milestone 1.a - Intellectual Property Agreement	UofL, UND		X							
Task 2.0 – Improvement of Faradaic Efficiency to C2-4 Products	UofL-Grapperhaus	**$196,547**								
Subtask 2.1 – Establish Mechanistic Pathway	UofL-Grapperhaus	$58,964								
Milestone 2.a - Complete Isotope Labeling Study	UofL-Grapperhaus			X						
Milestone 2.b – Complete Alternate Solvent Study	UofL-Grapperhaus				X					
Subtask 2.2 – Determination of System Parameter Effects	UofL-Grapperhaus	$58,964								
Milestone 2.c – Complete Applied Potential Study	UofL-Grapperhaus			X						
Milestone 2.d – Complete Catalyst Concentration Study	UofL-Grapperhaus				X					
Milestone 2.e – Complete Acid Concentration/pH Study	UofL-Grapperhaus					X				
Subtask 2.3 – Optimization of Catalyst and Electrolysis Conditions	UofL-Grapperhaus	$78,619								
Milestone 2.f – Demonstrate High C2-4 Product Faradaic Efficiency	UofL-Grapperhaus							X		
Task 3.0 – Develop Electrolysis Reactor for High-current CO2 Reduction	UofL - Spurgeon	**$265,041**								
Subtask 3.1 – Electrolyzer Chassis Design	UofL - Spurgeon	$92,764								
Milestone 3.a – Fabricate Flow Cell Electrolyzer for High Current	UofL - Spurgeon		X							
Subtask 3.2 – CO2 Feed to the Cathode	UofL - Spurgeon	$53,008								
Milestone 3.b – Complete Direct Gaseous CO2 Study	UofL - Spurgeon				X					
Milestone 3.c – Complete Liquid-Fed CO2 Study	UofL - Spurgeon					X				
Subtask 3.3 – Methanol Crossover and Oxidation	UofL - Spurgeon	$53,008								
Milestone 3.d – Demonstrate Target Methanol Crossover Rate	UofL - Spurgeon						X			
Subtask 3.4 – High-current CO2 Electrolysis Characterization	UofL - Spurgeon	$66,260								
Milestone 3.e – Demonstrate CO2 Reduction Target Current Density	UofL - Spurgeon							X		
Milestone 3.f – Demonstrate Stability of Electrolysis	UofL - Spurgeon							X		
Task 4.0 - CO2 Electrolysis System from Power Plant Flue Gas Derivatives	UND - Theaker	**$196,134**								
Subtask 4.1 – Impurity and CO2 Concentration Effects	UND - Theaker	$49,034								
Milestone 4.a – Complete Flue Gas Contaminants Study	UND - Theaker					X				
Milestone 4.b – Complete CO2 Concentration Study	UND - Theaker					X				
Milestone 4.c – Complete Catalyst/Electrolyte Flow Rate Study	UND - Theaker						X			
Subtask 4.2 – Mitigation Strategies for Contaminants	UND - Theaker	$58,840								
Milestone 4.d – Determine Impurity/CO2 Concentration Thresholds	UND - Theaker						X			
Subtask 4.3 – Coal-Derived Flue Gas Electrolysis	UND - Theaker	$88,260								
Milestone 4.e – Extended Test with Coal Derived Gas	UND - Theaker							X		
Task 5.0 – Full System Integration with Commercially Relevant Performance	UofL, UND	**$493,820**								
Subtask 5.1 – Integrate Improved Components to Reactor	UofL, UND	$296,292								
Milestone 5.a – Integrated System at Target Electrolysis Metrics	UofL, UND									X
Subtask 5.2 – Downstream Product Separation	UND - Theaker	$74,073								
Milestone 5.b – Downstream C2-4 Separation at Target Purity	UND - Theaker									X
Subtask 5.3 – Practical Demonstration of Technology Readiness	UofL, UND	$123,455								
Milestone 5.c – System Demonstration at Commercial Utility	UofL, UND									X
Task 6.0 – Technoeconomic Analysis and Life Cycle Analysis	UofL, UND	**$88,038**								
Subtask 6.1 – TEA of Flue Gas Conversion to C2-4 Product	UofL, UND	$44,019								
Milestone 6.a – Complete TEA for Demonstrated Performance	UofL, UND									X
Subtask 6.2 – LCA of Flue Gas Conversion to C2-4 Product	UofL, UND	$44,019								
Milestone 6.b – Complete LCA for Overall Process	UofL, UND									X

PROJECT METHODOLOGY

- **Gantt Chart/schedule of activities**

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Milestone 3.a – Fabricate Flow Cell Electrolyzer for High Current	UofL - Spurgeon		X, complete							
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Subtask 6.2 – LCA of Flue Gas Conversion to C2-4 Product	UofL, UND	$44,019								
Milestone 6.b – Complete LCA for Overall Process	UofL, UND									X

Project Success Criteria

- Complete TEA and LCA for realistic system parameters with sensitivity analysis
- Completion of a reactor operating from flue gas at performance metrics for profitability as determined by the TEA (Target Metrics: 600 mA cm^{-2} at > 40% FE C2-4s for > 100 h)

Perceived Risk	Risk Rating			Mitigation/Response Strategy
	Probability	Impact	Overall	
	(Low, Med, High)			
Cost/Schedule Risks:				
Parameter effect studies take too long to keep up with reactor development	Med	Med	Med	Constant communication between catalyst and reactor teams/redirection of priorities
Technical/Scope Risks:				
Flue gas feed performance and stability issues	Med	Med	Med	Multiple catalyst options (Pb, Sn, Bi), decontamination, CO_2 absorber, CO_2 concentration studies
Insufficiently high current density	Med	Med	Med	Flow cell condition optimization, maximize aqueous systems first
Difficulty achieving or maintaining high FE of C2 - C4 product	Med	Med	High	Product distribution mapping, CO_2 mass transfer optimization, pH stabilization
ES&H Risks:				
Covid-19 inhibiting research	High	Low	Low	Safety protocols, remote meetings, limited lab capacity