Integrated Capture and Conversion of CO_2 to Methanol (IC^3M) Process Technology (TCF-19-17862)

NETL/ DOE Project Manager: Naomi O’Neil

David J. Heldebrant
Robert A. Dagle
Pacific Northwest National Laboratory

U.S. Department of Energy
National Energy Technology Laboratory
Carbon Utilization Project Review Meeting (Virtual)
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Project Objectives

DOE Funding: $600K / 24 months

SoCalGas Cost Share: $600K / 24 months (funds-in)

Start: 2/2/2020

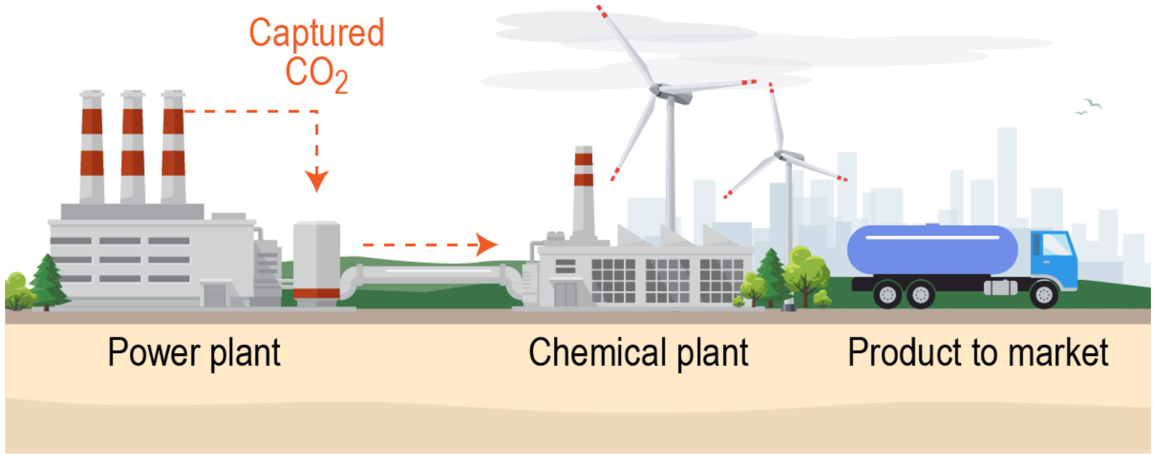
End: 4/30/2022

- Pacific Northwest National Laboratory (PNNL)
- Southern California Gas Company (SoCalGas)

Objective: Develop prototype system that integrates the capture and catalytic hydrogenation of CO_2 into methanol using CO_2 capture solvent

Technology Description

Integrated CO_2 Capture and Conversion to Methanol (IC^3M) Process Technology.



- **Objective:** Design and demonstrate effectiveness for an IC^3M prototype for continuous flow, combined capture/catalytic conversion of CO_2 into MeOH.

- **Motivation:** Potential for reductions to capital and operating costs by at least 20% relative to a benchmark methanol synthesis via gas-phase CO_2 hydrogenation.

Expected Outcomes: Development of a modular system that can be subsequently installed and demonstrated at an industrial CO_2 source (e.g.,. for power generation or anaerobic digestion).

TEA confirmed the potential for market viability against conventional methanol synthesis.

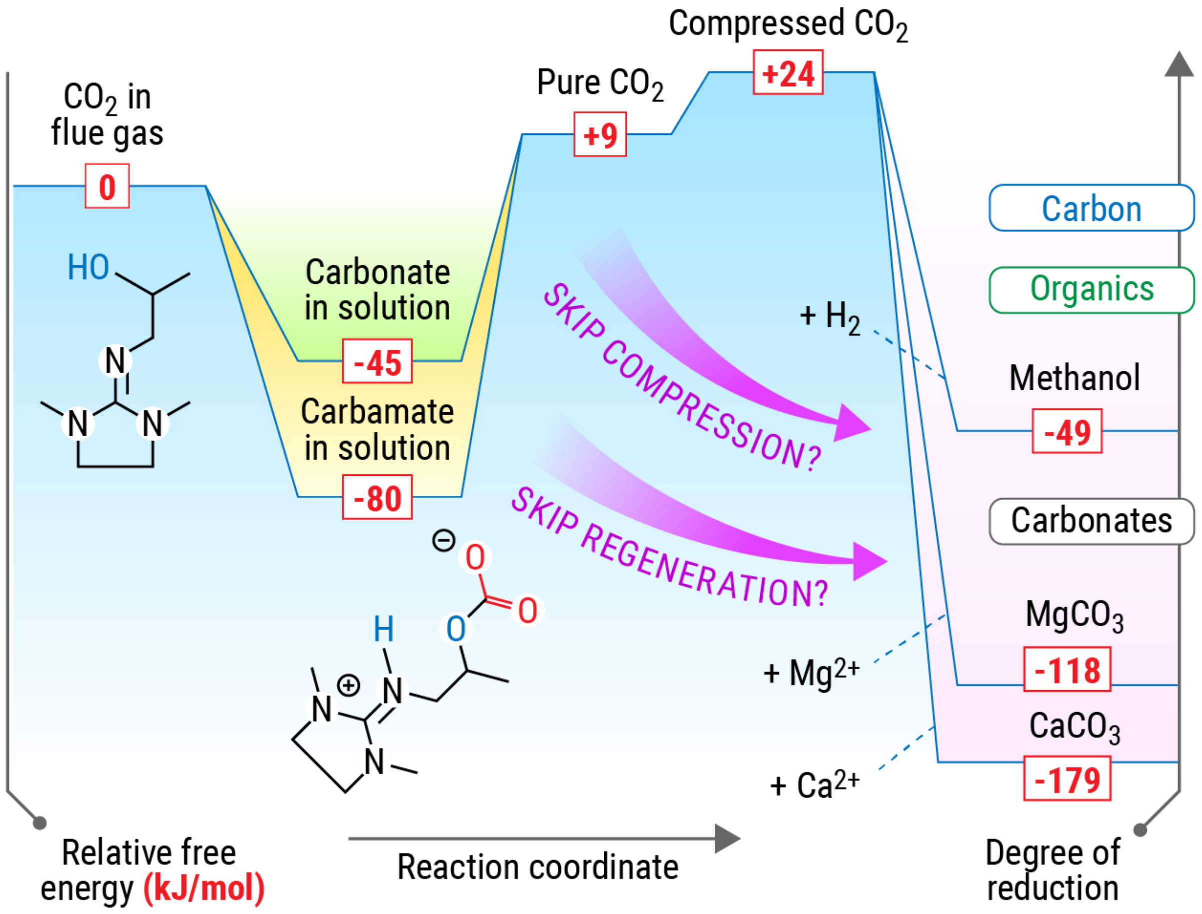
Project Scope – Remaining Milestones

Type	Description	Date
Milestone	**(Task 3) Reactor design and fabrication** – design and fabricate the bench scale reactor that will be utilized for the integrated demonstration.	10/31/21
Milestone	**(Task 4) Final TEA and Technology-to-Market** – leveraging the preliminary TEA in place at PNNL update parameters to assess CAPEX/OPEX projections for at least one scale and application (e.g., flue gas, biogas, waste-water treatment, manure, etc.) using the data obtained in this study.	01/31/22
Milestone	**(Task 5) Demonstration of integrated capture and conversion** – using a fabricated, modular portable bench scale system evaluate performance for a chosen catalyst and capture solvent in place. Evaluate single pass performance for the integrated capture and conversion system. Assess overall catalyst performance (conversion, selectivity) for a period of at least 10 hours' time-on-stream using the best process conditions identified in the catalyst studies.	4/30/22
Deliverable	**Final report**	6/30/22

Success Criteria: Demonstrate integrated capture and conversion, update TEA using experimental data from this project, and demonstrate a scalable reactor system that could be subsequently installed at an industrial CO_2 source (e.g., for power generation or anaerobic digestion).

The Case for Integrating CO_2 Capture With Conversion

Performing catalysis on CO_2 captured in solution avoids the process energies associated with capture, desorption, and compression.



IC³M Platform:

- Capture and conversion in same medium
    - Saves energy
    - Saves costs
    - Ship product not CO_2
- Exploits new reactivities of CO_2 captured in solution
- Versatile, change products by changing reagent co-feed
- Modular

Condensed-Phase Methanol Synthesis Exploits Similar Chemical Reactivity

The same chemicals that capture CO_2 also promote conversion.

1˚ & 2˚ Amines

Pathway (a)

$$CO_2 \overset{\text{Step 1}}{\xrightarrow{2RNH_2}} RNHCOO^-\ RNH_3^+ \overset{\text{Step 2}}{\xrightarrow[-RNH_2]{H_2}} HCOO^-\ RNH_3^+ \overset{\text{Step 3}}{\xrightarrow[-H_2O]{}} RNH\text{-}CHO \overset{\text{Step 4}}{\xrightarrow[-RNH_2]{2H_2}} CH_3OH$$

carbamate *formate* *formamide*

Alcohols & 3˚ Amines or superbases

Pathway (b)

$$CO_2 \overset{\text{Step 1}}{\xrightarrow[R'OH]{NR_3}} ROCOO^-\ HNR_3^+ \overset{\text{Step 2}}{\xrightarrow{H_2}} HCOO^-\ R_3NH^+ \overset{\text{Step 3}}{\xrightarrow[-H_2O]{ROH}} HCOOR \overset{\text{Step 4}}{\xrightarrow[-ROH]{2H_2}} CH_3OH$$

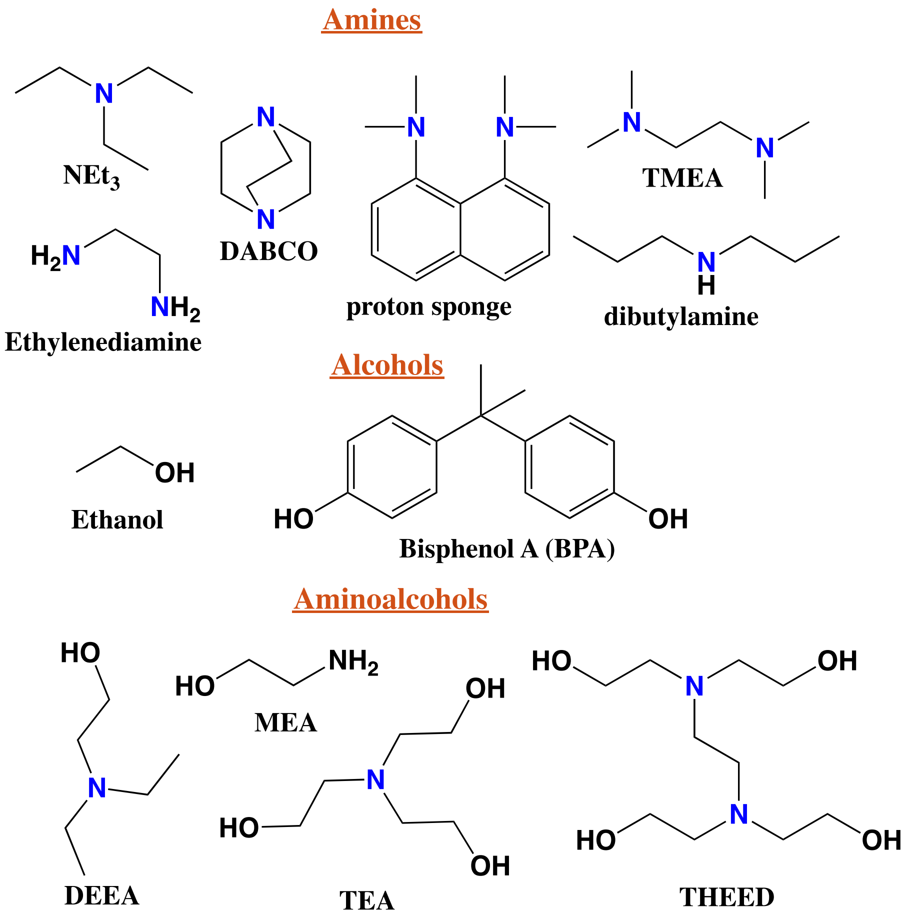
carbonate *formate* *formate ester*

- Addition of amine or alcohol additives to homogeneous catalysis promotes the formation of methanol via formate ester and formamide intermediates.

Catal. Sci. Tech., *2018*, 8, 5098-5103. U.S. Patent 10,961,173.

CO_2 Hydrogenation in the Presence of Amines

The combination of alcohols and 3˚ amines favors methanol formation.

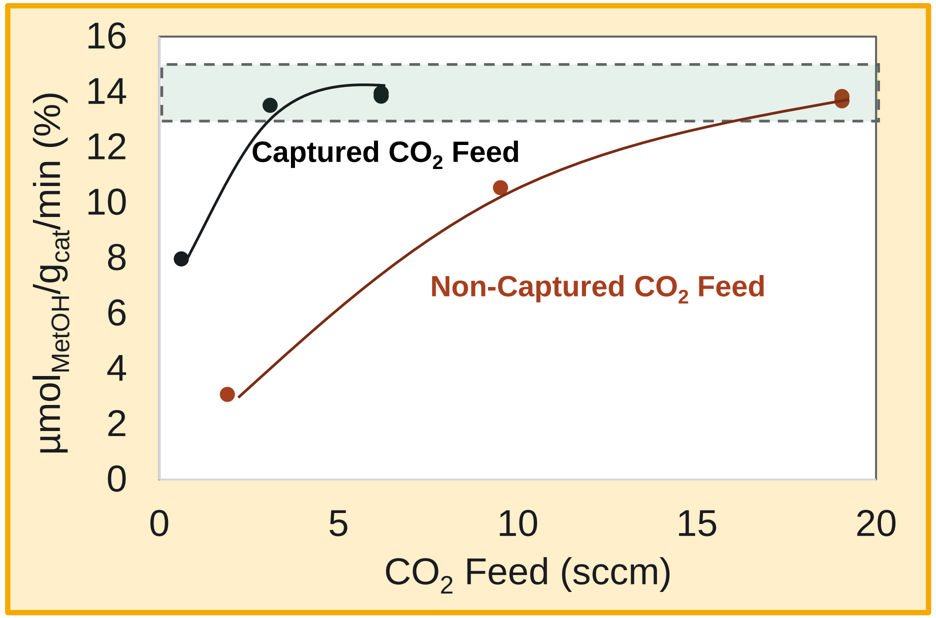


Entry	Promoters	$HCOO^-$(%)[a]	HCOOR (%)[a]	N-CHO (%)	MeOH (%)
1	Ethylenediamine	-	-	7%	-
2	Dibutylamine	-	-	2%	-
3	Ethylenediamine: Ethanol	trace	3%	6%	-
4	THEED	-	-	-	-
5	TEA	-	-	-	-
6	DEEA	trace	trace	-	4%
7	NEt_3:BPA	-	-	-	-
8	Proton sponge:Ethanol	-	-	-	-
9	TMEA:10Ethanol	-	1%	-	18%
10	DEEA-10Ethanol	0.5	trace	-	21%
11	NEt_3:10Ethanol	3%	trace	-	100%
12[a]	NEt_3:10Ethanol	3%	1%	-	76%
13[b]	NEt_3:10Ethanol	4%	4%	-	19%

Reaction conditions: Catalyst=Cu/ZnO/Al_2O_3 (300 mg), CO_2/H_2=60 bar (1:2), T=170 °C, t=16h. [a]40h, and [b]120°C

Continuous Flow Reactor System – CO_2 Hydrogenation, continued

Pre-combustion solvent system evaluation under continuous flow.



170 °C, 60 bar, 1.0 g Catalyst A

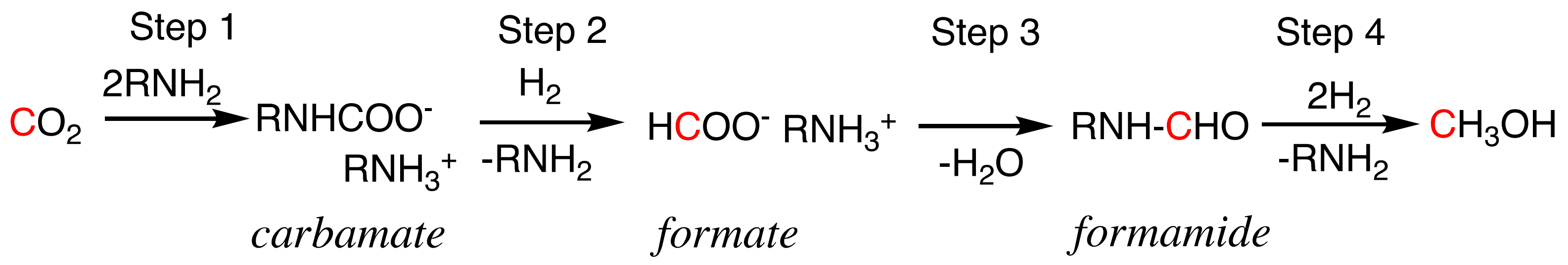
Continuous Flow Reactor System

- Higher reactivity demonstrated when CO_2 is captured in feed prior to reaction.
- Captured CO_2 reacts differently in the condensed phase than gaseous CO_2, opening new doors for reactivity.

The Disconnect: Reacting Captured CO_2 in Viable post-Combustion Solvents

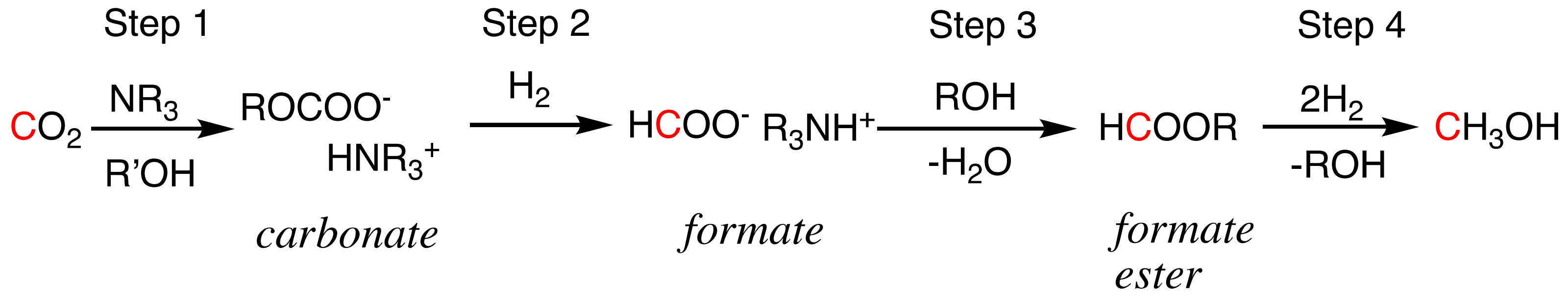
- 1°, 2° and °3 amines and alcohols used in conversion are too volatile for capture
- Weaker binding (-60 kJ/mol vs -75 kJ/mol) enables conversion, but too weak for capture
- Aqueous solvents can’t work due to thermal condensation (C-O cleavage) step in our mechanism

Pathway (a)



$$CO_2 \xrightarrow{2RNH_2} RNHCOO^- \; RNH_3^+ \xrightarrow[-RNH_2]{H_2} HCOO^- \; RNH_3^+ \xrightarrow[-H_2O]{} RNH\text{-}CHO \xrightarrow[-RNH_2]{2H_2} CH_3OH$$

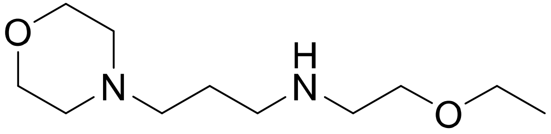
Pathway (b)

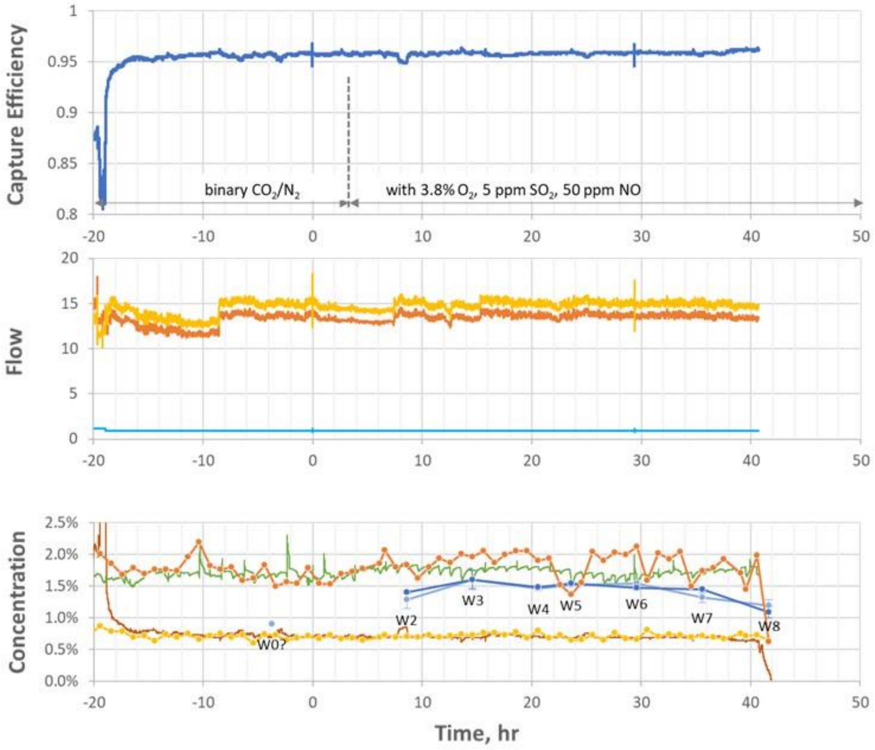


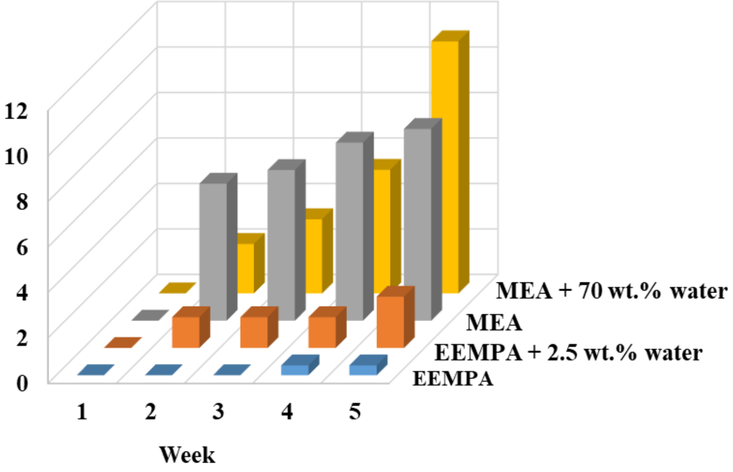
$$CO_2 \xrightarrow[R'OH]{NR_3} ROCOO^- \; HNR_3^+ \xrightarrow{H_2} HCOO^- \; R_3NH^+ \xrightarrow[-H_2O]{ROH} HCOOR \xrightarrow[-ROH]{2H_2} CH_3OH$$

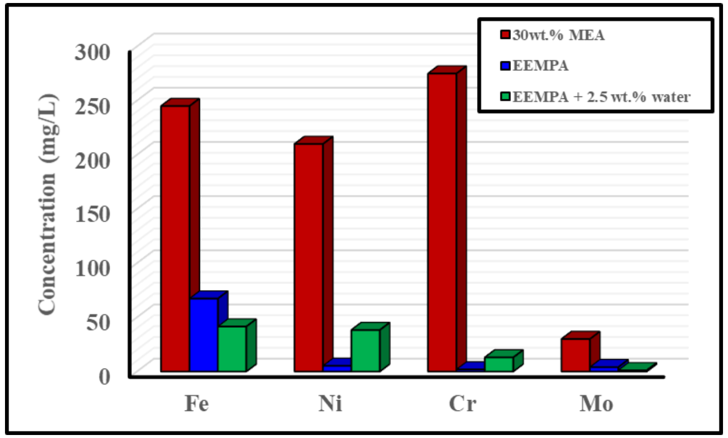
Moving to Post-Combustion Solvents: 2-EEMPA

EEMPA has lowest energy solvent (2.0 GJ/tonne CO_2) and lowest total cost of capture $37.6/tonne CO_2 of any capture tech.









- 50-L scale testing recently completed by RTI International 2/2/21
- 90% lower corrosion and degradation than 5M MEA

Zheng et al. *Energy Environ. Sci.*, **2020**,*13*, 4106-4113. Jiang et al. *IJGHGC*, **2021**, *106*, 103279.

Post-Combustion Solvent Updates: Hydrogenation of EEMPA-carbamate

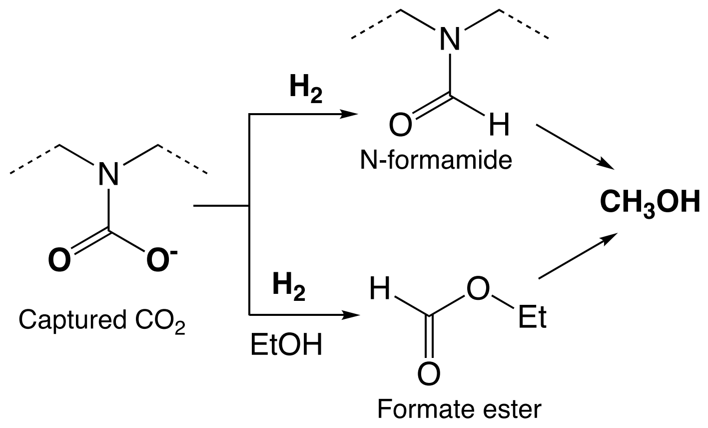
Entry	Catalyst	CO_2 captured	CO_2 conv. (%)	EEMPA-N-CHO selectivity (%)	EEMPA N-Me selectivity (%)	Methanol selectivity (%)	Methanol yield (%)
1	Catalyst A2	10 wt%	27.5	traces	75.1	24.9	6.8
2	Catalyst B1	10 wt%	11	8.7	69.8	21.5	2.4
3	Catalyst B2	10 wt%	40.3	26.8	60.9	12.2	4.9
4	Catalyst B3	10 wt%	24.4	55.0	40.9	4.1	1
5[a]	Catalyst B2	10 wt%	22.5	7.9	67.7	24.4	5.5
6	**Catalyst A2**	**5 wt%**	**50.5**	**traces**	**77.5**	**22.5**	**11.3**
7	Catalyst B3	5 wt%	59.0	traces	95.6	4.4	2.5
8	Catalyst B2	5 wt%	36.1	17.9	68.6	13.6	4.9
9	Catalyst A3	5 wt%	54.0	34.9	65.1	traces	traces

Time=12h, EEMPA=5g (CO_2 loaded EEMPA used), initial $P(H_2)$ = 60 bar, [a]Ethanol-10.6 g.

- Higher conversion demonstrated at lower CO_2 loading.
- The methanol selectivity compared to EEMPA N-Me was <25% in all these cases.

Post-Combustion Solvent Updates: Batch Reactor

Ethanol co-feed facilitates methanol production.



Entry	*Capture solvent*	*Exp. No*	*CO_2/H_2 bar*	*time (h)*	*Formamide mmol*	*N-methyl amine mmol*	*CH_3OH mmol*	*CH_3OH Selectivity (%)*
1	EEMPA	62711-153	15/45	12	0.8	2	0.65	24.5
2	EEMPA	62711-148	15/45	48	0.45	5.1	1.23	19.4
3	EEMPA	62711-147	5/55	48	0.04	5.85	1.19	16.9
4[a]	EEMPA + ethanol	62711-150	5/55	48	traces	1	2.4	70.6

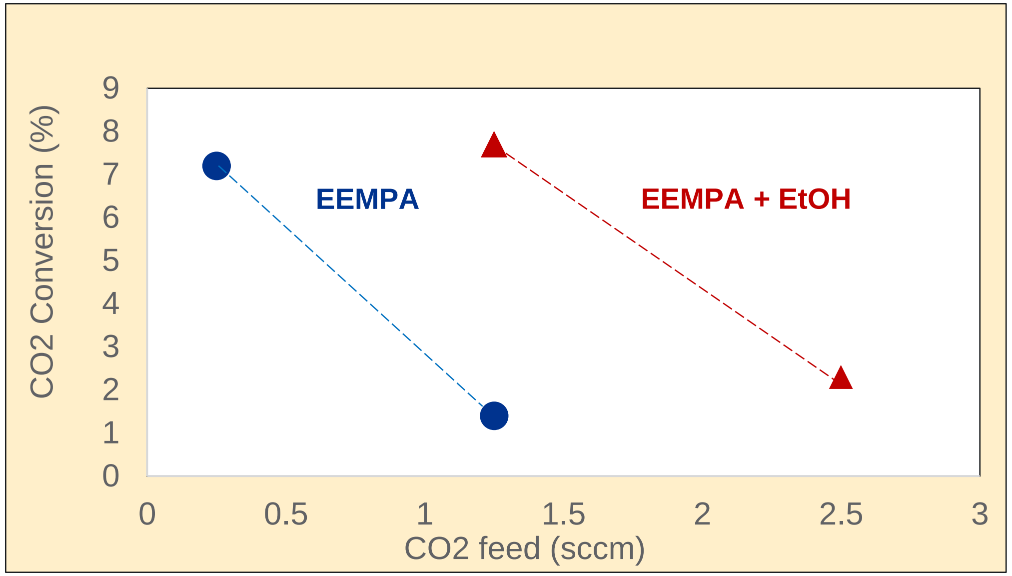
Catalyst A=200mg, 100 mL reactor, EEMPA=23mmol, P=60 bar (CO_2:3H_2), T=170 °C, t=12 h, [a] ethanol=200 mmol.

- Ethanol co-feed facilitates the reaction through formate ester intermediate which is more selective to methanol than the N-formamide intermediate.
- With the leading PNNL post-combustion solvent system, process conditions were tailored to convert CO_2 and H_2 to **methanol** with **71% selectivity.**
- The formation of methanol in the presence of a **post combustion** solvent is, we believe, the first time this has been demonstrated in the presence of a heterogenous catalyst.

Continuous Flow Reactor System Updates

Post-combustion EEMPA captured solvent integrated with catalyst testing.

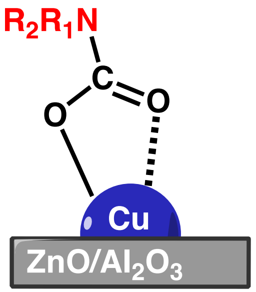
- Best catalysts identified from batch reactor testing being evaluated under continuous flow and varying:
  - CO_2 loading, alcohol or water co-feeds, temperature, space velocity
- Ethanol co-feed improves conversion
- At least up to 3 wt.% water in feed had no effect on methanol yield
- Best results obtained to-date:
  - 8% single pass CO_2 conversion (170°C, 60 bar, 0.15 g_{CO2}/g_{cat}/hr).



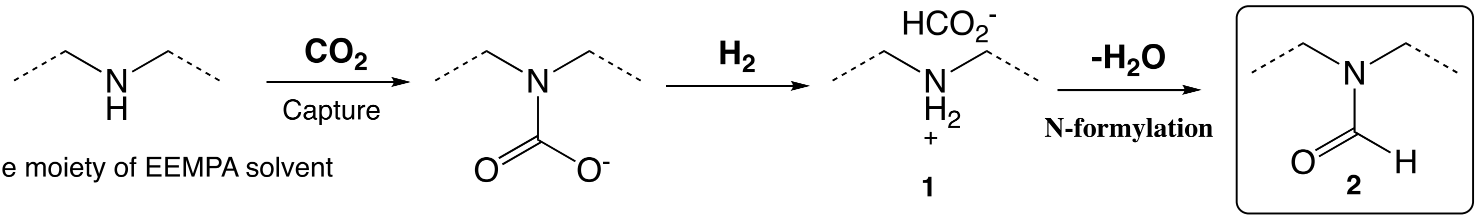
0.05 ml/min EEPA - 10 wt.% CO_2; EEMPA/ EtOH = 1/3 (mol);170 °C, 60 bar; TOS 10 hrs

Post-Combustion Solvent Updates: Reaction Mechanism

Screening EEMPA as a post-combustion solvent with leading catalyst and varying conditions.

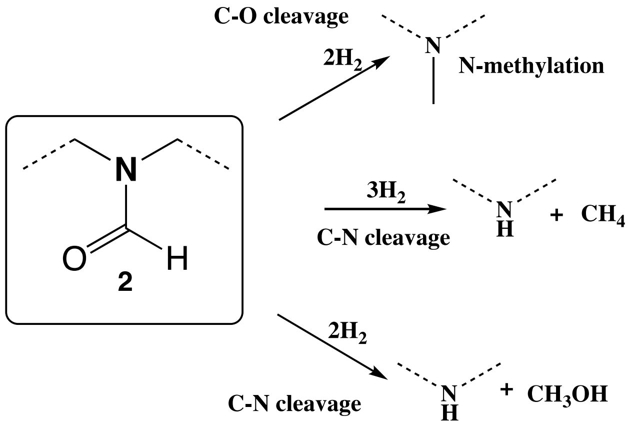


(a)

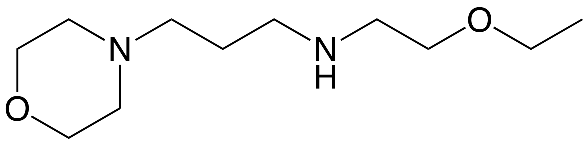


N-formylation

(b)



(c)



Chemical structure of EEMPA

- Solvent is deactivating via N-methylation of EEMPA's 2˚ amine with Catalyst A
- Need catalysts/ conditions to facilitate the last step in the mechanism, amide to methanol
- Selective C-N cleavage is the goal as it prevents solvent deactivation and improves the targeted product selectivity

Post-Combustion Solvent Updates – Hydrogenation of EEMPA-carbamate

Evaluating heterogeneous catalyst systems with metal-base pairs.

Entry	Catalyst	Solvent	CO_2 captured	CO_2 conv. (%)	EEMPA-N-CHO selectivity (%)	EEMPA N-Me selectivity (%)	Methanol selectivity (%)	Methanol yield (%)
1	Catalyst X	EEMPA	5 wt%	12.8	59.2	ND	40.8	5.2
2[a]	Catalyst X	EEMPA + EtOH	5 wt%	20.9	72.5	ND	27.5	5.8

Time=12h, EEMPA=5g (CO_2 loaded EEMPA used), initial $P(H_2)$ = 60 bar, [a]Ethanol-10.6 g, ND =not detected in the ^1H NMRq

- A **base supported catalyst** formed methanol with **high C-N cleavage selectivity**.
- 41% methanol selectivity was achieved (versus 24% before) even without base or ethanol in solvent feed.
- Currently optimizing the catalyst/support ratio to improve the methanol rate.

Techno-economic Assessment (TEA) for IC^{3}M

Integration enables competitive market pricing with 45Q and renewable fuel standards.

- **Preliminary** TEA performed on **two different flue gas sources**:
  - 50 MW SOFC power plant
  - 550 MW NGCC plant,
  - Baseline **natural gas-to-methanol plant.**
- H_2 price set at $2/kg

	Reference Technology	Proposed Technology(2)	
	Conventional Natural Gas based Syngas(1)	**NGCC-Based Flue Gas (550 MW)**	**SOFC-Based Flue Gas (50 MW)**
Capacity (millions of gallons MeOH /yr)	329	329	23
Energy into system (%, HHV)			
Natural gas	99.6		
Hydrogen		77.4	83.2
Steam	0.0	13.2	15.0
Electricity	0.4	9.4	1.8
CO_2 concentration at inlet (mol %)	NA	4.0	29.0
CO_2 conversion in reactor (%)	NA	70	70
H_2 consumption (mol H_2/mol MeOH)	NA	3.1	3.1
Equivalent work of capture/ conversion (kJ_e/mol CO_2)(3)	NA	43.9	35.4
Overall energy efficiency (%, HHV)(4)	65.4	58.3	66.4
Production costs ($/gallon MeOH)			
Raw Materials (5)	0.53	1.27	1.27
Carbon Credits(5)	0.00	0.15	0.15
Utilities	0.02	0.20	0.16
Total Fixed Capital ($/gal MeOH)(6)	0.32	0.22	0.28
Minimum MeOH Selling Price ($/gal)(7)	**1.29(5)**	**1.89**	**2.05**

1) Methanol from natural gas by the ICI copper-based catalytic process (PEP Yearbook, 2014).
2) Key modeling assumptions: 90% capture of CO_2 from flue gas, 5.3 mol/mol H_2/CO_2 target at reactor inlet, 120 °C reactor temperature, 25 bar reactor pressure, equilibrium reactor performance and methanol selectivity of 100%, reactor space velocity of 0.9 kg/h MeOH/ liter of catalyst, flue gas compositions reported by [8] and [9] used for the respective SOFC and NGCC cases.
3) Carnot efficiency is used to convert thermal energy to electricity.
4) Defined as heating value of methanol over total energy fed into the system (H_2, steam and electricity). Carnot cycle efficiency is used to convert electricity to thermal energy.
5) Current industrial price of methanol. H_2 price and 45Q carbon credit are set to \$2/kg (DOE, 2015) and \$35/tonne CO_2 [10].
6) Based on Aspen Process Economic Analyzer.
7) Assuming 15% ROI.

Commercial Viability for IC^{3}M

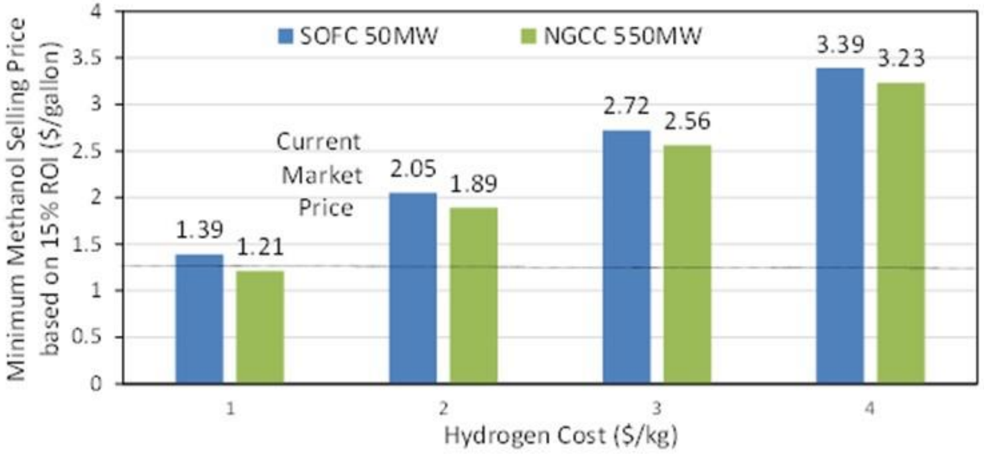
Reagent (H_2) costs drive economics and market competitiveness.

- \$1/kg H_2 both ICCCM processes competes with current methanol market prices
- Q45 carbon credit (\$35/tonne CO_2) drives the economics
  - Additional carbon taxes further facilitate gains

Low Carbon Fuel Standard

CALIFORNIA AIR RESOURCES BOARD

H_2 cost sensitivity analysis

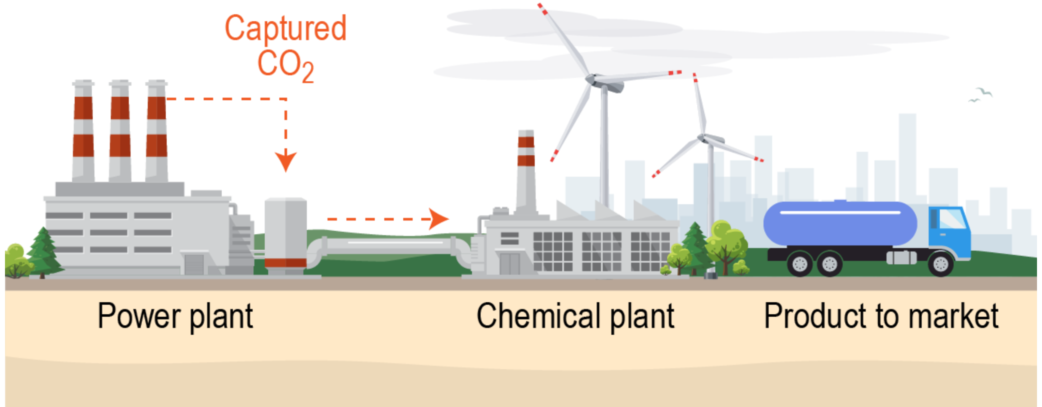


- **H_2** is expensive, but serves an indirect energy source to drive CCS, VS steam or electricity
- ICCCM becomes a viable technology for **modular distributed-scale processing platforms** by removing additional energy inputs and equipment
  - landfill gases
  - waste-water treatment gases
  - manure off-gas
- Stranded H_2 can be co-sourced, enabling lower cost/ renewable H_2 supplies

Commercial Viability for IC^{3}M

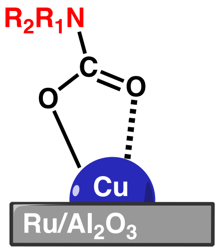
Adapting the technology to make other products.

- CO_2 reduction can produce other chemicals such as formic acid, methylformate, and methane.
- IC^{3}M being evaluated for producing multiple products.
- Methane, for example if made using waste CO_2 and renewably sourced hydrogen, could offer an alternative for utilities and consumers looking for natural gas with a renewable component and a lower carbon footprint.



Post-Combustion Solvent Updates, continued

Alternative catalyst to bypass N-methylation makes a different product, CH_4.



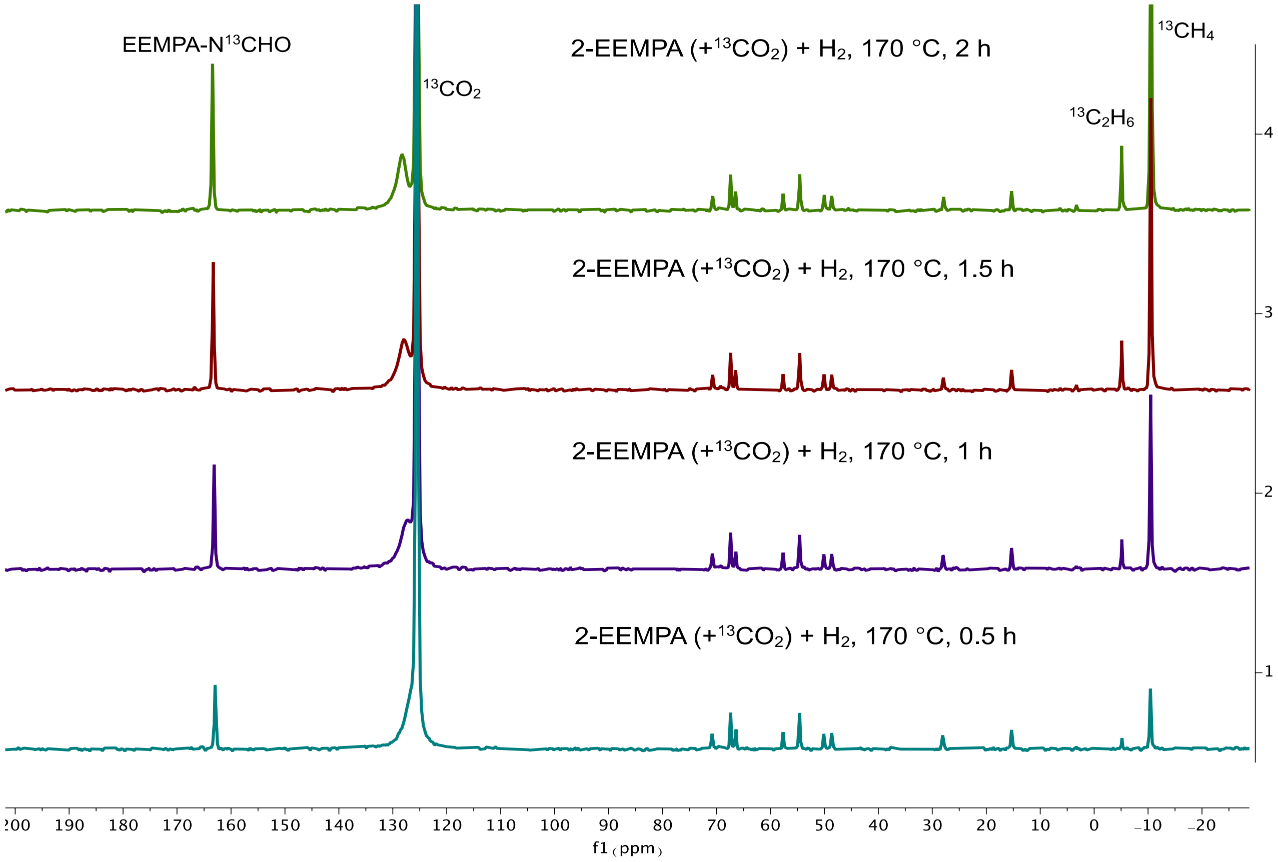
Exp. no	CO_2 (mmol)	T °C	P_{H2} (bar)	CH_4 Yield(%)	C_2H_6 Yield(%)	Higher HC Yield(%)	CH_4 Sel.(%)	C_2H_6 Sel.(%)	Higher HC Sel.(%)
166[a]	14.3 (captured)	170	14	53.1	2.8	4.9	87.4	4.6	8
167[a]	14.5 (captured)	145	14	17.2	0.4	0.7	94	2.2	3.7
168[a]	14.7 (captured)	120	14	3.4	0.1	0	98	2	0

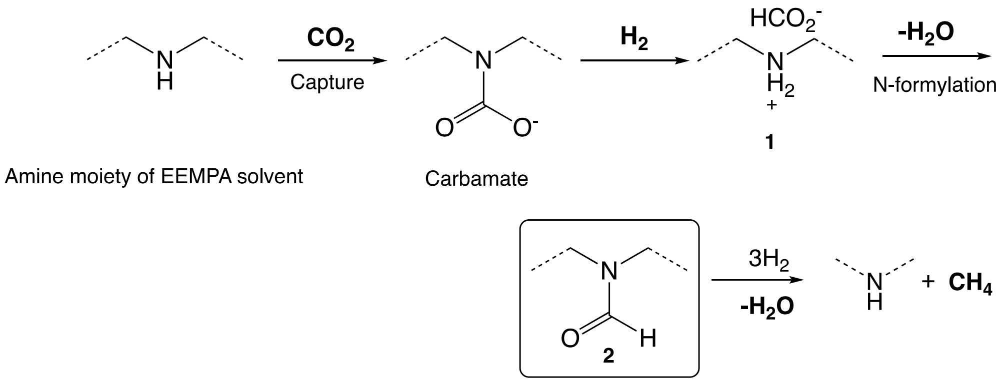
CO_2:H_2 = 1:~4, time = 3 h, 200 mg of [a]5wt% Ru/Al_2O_3, EEMPA=5 g (23 mmol).

- Ru in place of previous catalysts produces methane with high selectivity (98%)
- Product flexibility thus demonstrated by adjusting catalyst and conditions
- Selective production of either methanol or methane has been demonstrated
- Demonstrates that IC^3M can be a platform technology for multiple products

U.S. Patent Application US20210214287A1 *ChemSusChem 2021, 10.1002/cssc.202101590*

Operando MAS ^{13}C NMR – Hydrogenation of captured CO_2 to Methane





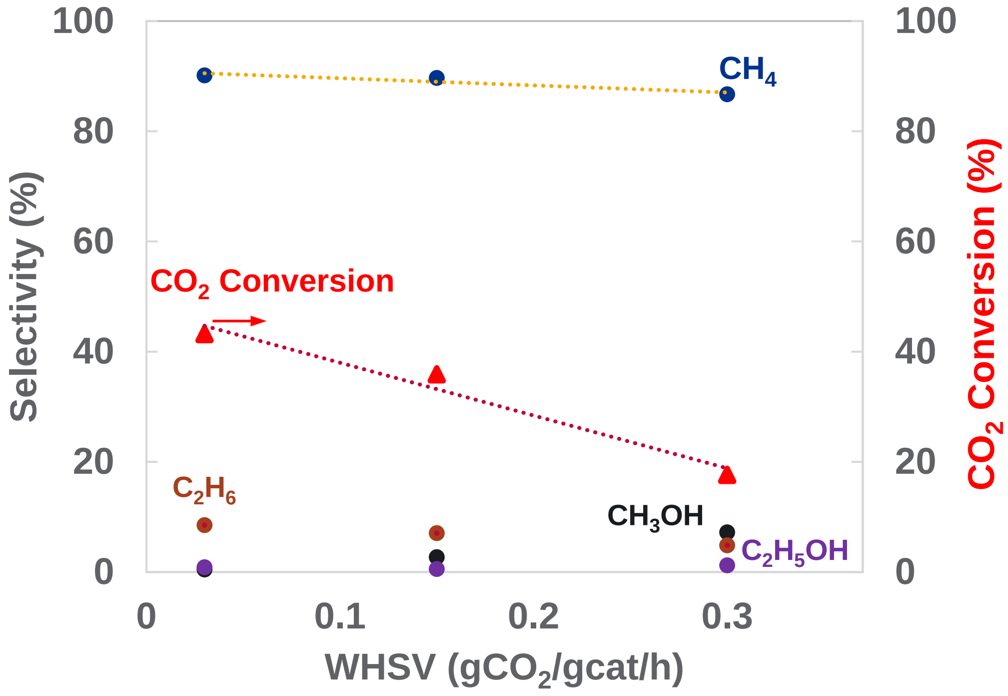
NMR showed in-situ formation of EEMPA N-CHO (**2**) and simultaneous formation of methane and ethane

To the best of our knowledge, this is the first demonstration of integrated, low temperature capture and conversion of CO_2 to methane in a post-combustion solvent.

ChemSusChem 2021, 10.1002/cssc.202101590

IC3M technology for Methane using a Water-lean, Post-Combustion CO_2 Capture Solvent

Continuous flow reactor demonstrated for methane production.



2-EEMPA solvent (10 wt% CO_2 loaded) in H_2, 170 ºC, 60 bar, 1.0 g 5 wt% Ru/Al_2O_3.

Increased contact time and higher temperature, decreased the selectivity to alcohols and increased the selectivity to methane and ethane

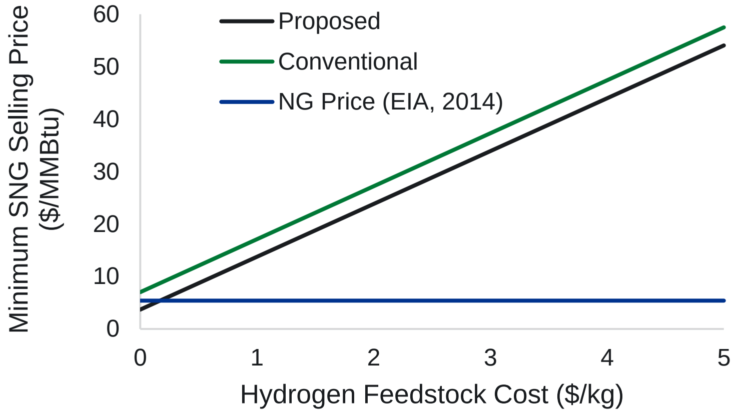
Entry	WHSV ($g_{CO2}/g_{cat}/h^{-1}$)	T ºC	CO_2 conversion (%)	Selectivity (%)			
				CH_4	C_2H_4	CH_3OH	C_2H_5OH
1	0.30	170	17.6	86.7	4.8	7.2	1.2
2	0.03	170	43.2	90.1	8.5	0.4	0.9
3	0.30	190	52.1	87.7	9.1	2.7	0.6

ChemSusChem 2021, 10.1002/cssc.202101590

Methane production Comparison between IC^{3}M and conventional FG-to-NG processes - TEA

Process	Proposed	Conventional
Scale (Million MMBtu SNG/year)	33.8	33.8
Carbon Capture Condition		
Lean / Rich Loading (mol CO_2/mol solvent)	0 / 0.136	
Regeneration Heat Duty (GJ/tonne CO_2)	≈ 2.5	2.65
CO_2 Capture Cost ($/tonne CO_2)		71
Methanation Condition		
Temperature (°C)	170	350
Pressure (bar)	15	30
CO_2 Conversion (%)	99.8	99
Heat of Reaction (GJ/tonne CO_2)	-3.75	-3.75
Key Performance Measures		
Thermal Efficiency (%, HHV)	79.75	76.14
Hydrogen Consumption (kg/kg SNG)	0.503	0.505
CO_2 Compression/Pump (kWh/tonne CO_2)	18.33	57.95
Key Economic Measures		
Total Plant Cost (MM$)	556.2	823.0
Minimum SNG Selling Price ($/MMBtu)	25.0	28.4
Cost Distribution		
H_2 Cost ($/MMBtu SNG)	20.2	20.2
Carbon Credit ($/MMBtu SNG)	-1.8	-1.8
O & M and Other Cost ($/MMBtu SNG)	4.1	6.3
Capital Cost ($/MMBtu SNG)	2.5	3.7

ChemSusChem 2021, 10.1002/cssc.202101590



- The proposed technology can potentially reduce the energy consumption for CO_2 pressurization, total capital investment, and minimum SNG selling price of FG-to-SNG process by 68%, 32%, and 12%, respectively.

- The benefits of the proposed IC^{3}M process over conventional process increases as the H_2 price decreases.

Conclusions/ Future Work

Conclusions

- Catalytically reacting CO_2 in capture medium can bypass energy associated with CO_2 release and compression
- The combination of alcohols and 3° amines favors methanol formation, but these amines are not post-combustion solvents
- Captured CO_2 reacts differently in the condensed phase than gaseous CO_2, opening new doors for reactivity
- Production of methanol or methane demonstrated; product flexibility enabled by changing catalyst and conditions
- Selective C-N cleavage to methanol achieved with a base supported catalyst or by using base as an additive
- The IC^3M process for methanol production has been patented, the route to methane is patent pending, and techno economic analysis suggests the potential for economic feasibility for both pathways.

Future Work

- Increase activity in our *post-combustion* solvent system by altering catalyst, process conditions, and through addition of alcohols (if needed) to enhance reaction kinetics.
- Demonstrate integrated capture and conversion (2-step)

Thank you!

U.S. DEPARTMENT OF ENERGY | NATIONAL ENERGY TECHNOLOGY LABORATORY

Pacific Northwest
NATIONAL LABORATORY


Robert A. Dagle


David J. Heldebrant


Jothi Kothandaraman


Johnny Saavedra-Lopez


Richard Zheng


Yuan Jiang


Ron Kent

SoCalGas

Appendix

Organization Chart

Organization	Personal	Task
PNNL	**Robert Dagle** has 20 years of catalyst and process R&D experience and currently manages ~$2M per year in DOE-EERE funded research in the area of thermocatalytic conversions. Mr. Dagle's technical expertise lies in the upgrading of bio- and fossil-derived oxygenated intermediates (e.g., ethanol, syngas) to fuels and chemicals, and with microchannel process technology. In addition to this project, Robert collaborates with project partner SoCalGas in developing a process for the conversion of methane to solid carbon and hydrogen. Mr. Dagle has over 50 peer reviewed publications and 14 U.S. patents (Battelle Distinguished Inventor Status). Mr. Dagle will manage the overall project and assist with catalyst and reactor development.	PI, catalyst development, flow system development
PNNL	**Dave Heldebrant** is the inventor of the CO_2BOL solvent platform, with over 12 years of experience on water-lean solvent systems for CO_2 capture, including 8 US patents filed and over 24 publications in CCS and 16 years of experience on catalytic transformations of CO_2, with 12 publications in this field. Dr. Heldebrant currently manages ~$3M per year in DOE-FE and BES funded research in the fields of carbon capture and conversion. Dr. Heldebrant will oversee the solvent and catalyst development as is a co-PI for the project.	Co-PI, capture solvent and catalyst integration
SoCalGas	**Ron Kent** has 30+ years of energy industry experience managing energy technology projects. He is currently an advanced technologies development manager at SoCalGas. His focus is on energy conversion technologies, major demonstrations of low carbon energy resources and business strategy and development. Ron will assist with tech-to-market assessment and help identify future potential commercial partners.	Commercial development
PNNL	**Jotheeswari Kothandaraman** has over five years of experience in the synthesis and testing of catalysts for CO_2 reduction and will experimentally evaluate the compatibility of capture solvents with catalyst. Having received her PhD in Chemistry from USC, Dr. Kothandaraman studied in the group led by the late George Olah, who won a Nobel Price in Chemistry for contribution to carbocation chemistry and was a well-known proponent and author of the "methanol economy". Dr. Kothandaraman will lead development activities for the solvent and catalyst development.	Capture solvent and catalyst integration
PNNL	**Johnny Saavedra Lopez** has 10 years of catalyst and process development experience at the Institute of Chemical Technology in Valencia, Spain working with Professor Avelino Corma, and 5 years of experience at PNNL. Dr. Saavedra Lopez has expertise in catalysis, reaction engineering, and process development. Dr. Saavedra Lopez will assist with catalyst and reactor development and oversee continuous flow testing activities.	Catalyst and reactor development and testing
PNNL	**Richard Zheng** has over 20 years of experience of developing advanced processing technologies in areas of separations and chemical conversions. His expertise areas are lab-scale and bench-scale system design, control system integration, and testing. His research has won two R&D 100 awards and he has published over 30 journal articles and holds 6 U.S. patents in areas of adsorption separation processes, hydrogen storage, and advanced nanomaterials. Dr. Zheng will oversee reactor design and fabrication.	Reactor design and system fabrication and testing
PNNL	**Yuan Jiang** has 7+ years of experience in process design and techno-economic modeling. Dr. Jiang currently supports PNNL's economic analysis projects and tasks for the BETO and FE portfolios. She has published 10 peer-reviewed publications in the field of process engineering. Dr. Jiang will oversee process modeling and techno economic analysis.	Process design and TEA

Gantt Chart

	◆ Milestone - Progress Measure	<	Year 1		>	<	Year 2		>
	♦ Deliverable	Y1				Y2			
		Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Task	**Task/Activitiy Description**	M1	M4	M9	M12	M15	M18	M21	M24
1	**Catalyst/Sorbent Development**	◆		◆					
2	**Continuous Flow System**		◆		◆				
3	**Reactor Design, Development, and Fabrication**						◆		
4	**TEA and Technology-to-Market**							◆	
5	**Bench Scale Integrated System Fabrication and Demonstration**								◆
6	**Proof of Concept for Extension of the Methanol-Based Modular Unit to Poly/Cyclic Carbonates**					◆			
7	**Project Management and Reporting**	◆	◆	◆	◆	◆	◆	◆	♦