Integrated Capture and Conversion of CO_2 to Methanol (ICCM) Process Technology

(TCF-19-17862)

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National Energy Technology Laboratory
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Project Objectives

DOE Funding: $600K / 24 months

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

Start: 2/2/2020

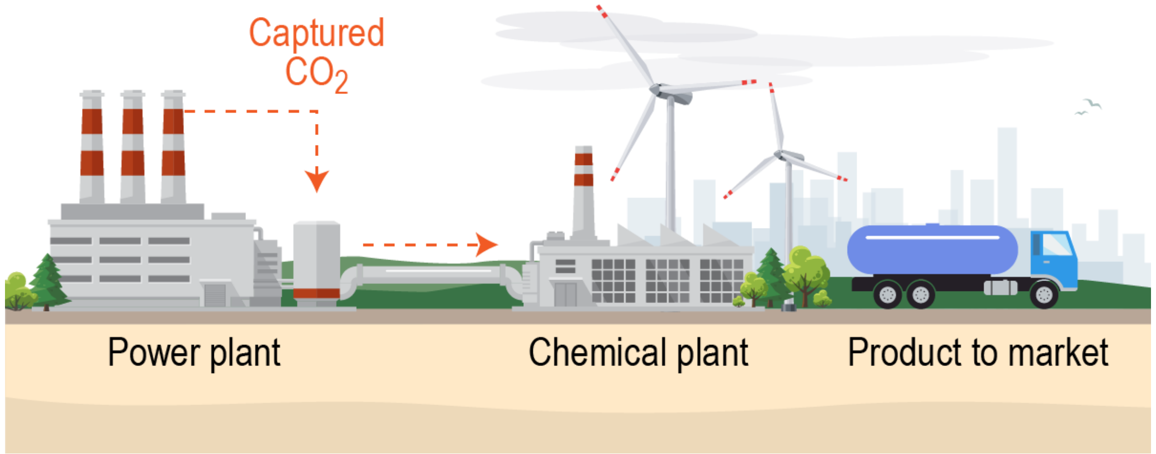
End: 4/30/2022

(3 month no-cost extension due to Covid shutdown)

The goal of this project is to develop a prototype system that integrates the capture and catalytic hydrogenation of CO_2 into methanol in the condensed phase using CO_2 capture solvent.

Technology Description

Integrated CO_2 Capture and Conversion to Methanol (ICCCM) Process Technology.



- **Objective:** Design and demonstrate effectiveness for a modular, integrated ICCCM 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: A modular unit will be designed that can subsequently be installed at an industrial CO_2 source (e.g. for power generation or anaerobic digestion).

TEA confirmed market viability against conventional methanol synthesis.

Technical Approach/ Project Scope

- This project leverages the CO_2BOL **capture solvent technology** developed at PNNL (and associated bench-scale equipment)
- PNNL demonstrated the **proof-of-concept** for batch-wise integration of CO_2BOL solvents promoting **conversion of CO_2 into methanol**
  - Demonstrated methanol synthesis can be performed in the condensed-phase at lower temperature and pressure (125 °C, 25 bar), compared to conventional syngas conversion (250-300 °C, 50-100 bar)
- The **CO_2 into methanol conversion** technology needs further development
  - Develop a process using the leading PNNL *post-combustion* capture solvent
  - Develop the process using scalable, continuous flow reactors
  - Design and build a modular, microchannel reactor with active heat management
- Demonstrate integrated **capture** and **conversion** at the bench scale
- Refine the **TEA** and develop a **conceptual design** for a pre-commercial system that targets a specific market opportunity

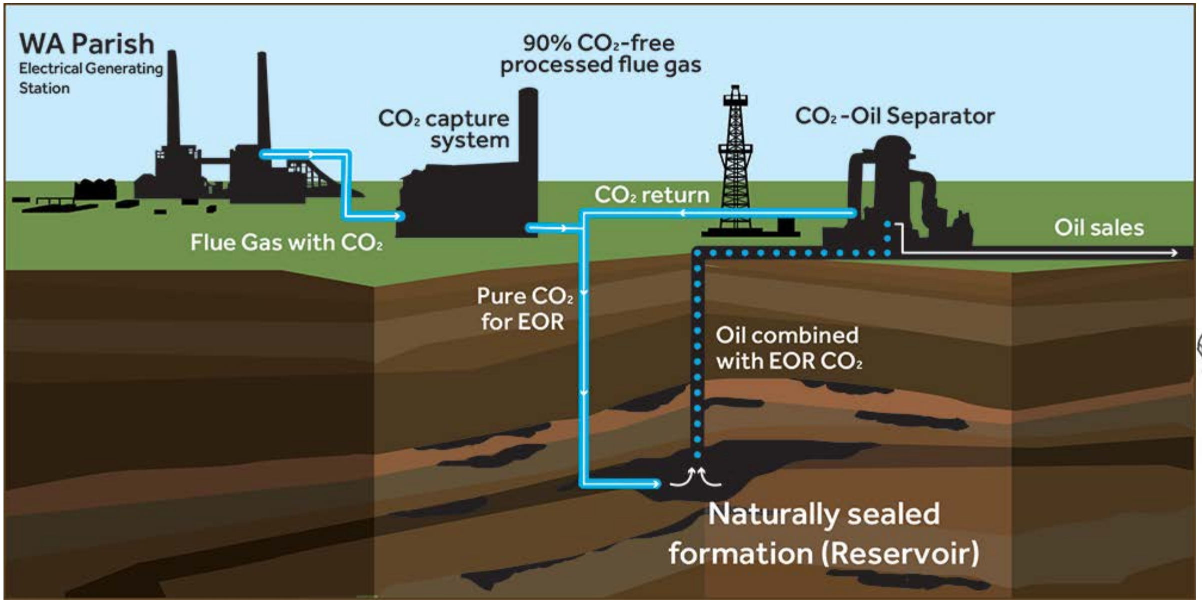
Project Scope – Remaining Milestones

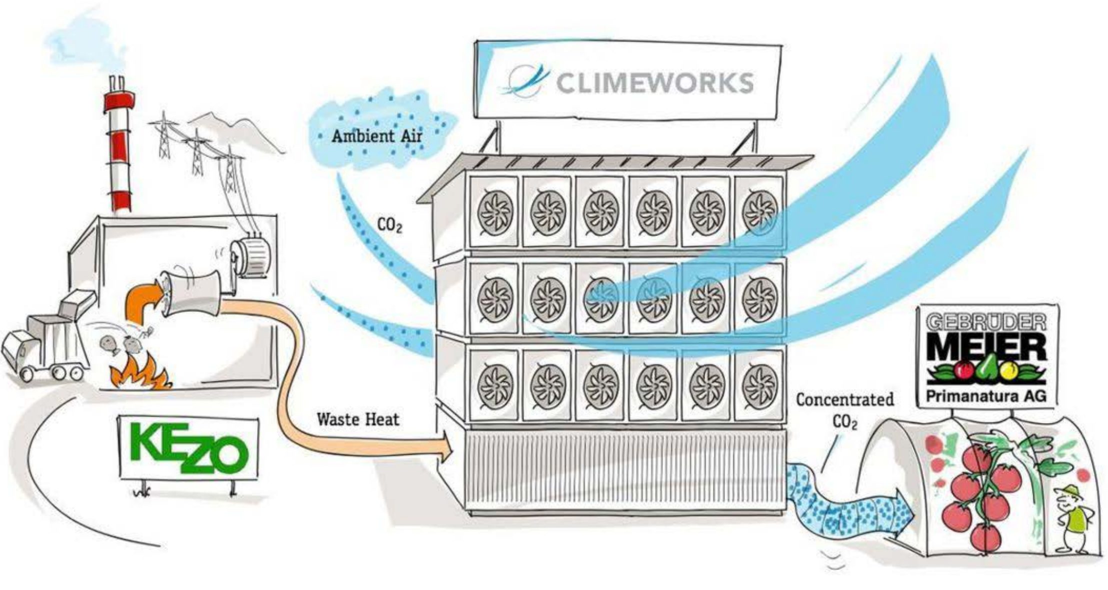
Type	Description	Date
Milestone	**(Task 1) Catalyst/CO_2 capture solvent evaluations–** using batch reactors assess catalytic performance using at least one solvent evaluate catalytic performance of at least five alternative catalyst formulations that may offer improved catalyst performance. Comparatively evaluate catalyst performance operating in the condensed phase temperature and pressure regime (e.g., 100-180 ˚C, 10-60 atm). The best improved catalyst system identified will be further evaluated under continuous flow.	1/31/21
Milestone	**(Task 2) Continuous flow reactor evaluations** – evaluate at least one improved candidate catalyst/sorbent combination under continuous flow operation. Evaluate catalyst performance for a least three solvent/catalyst feed ratios, one temperature and pressure, and at least 10 hours' time-on-stream. This information will be used to design and operate the bench-scale reactor to be designed and operated with active heat removal.	04/30/21
Milestone	**(Task 6) Proof of concept for poly/cyclic carbonate formation from captured CO_2** – Using the knowledge obtained from previous milestones/tasks, selected capture solvent(s) will be screened for its compatibility with catalysts for the coupling of CO_2 and epoxide to poly/cyclic carbonates. Evaluate the potential for carbonate formation by evaluating at least three combinations of catalyst and/or solvents and with expoxide co-feed (instead of H_2 as for methanol production).	07/31/21
Milestone	**(Task 3) Reactor Design and Fabrication** – design and fabricate the bench scale reactor utilizing active heat exchange that will be utilized for the integrated demonstration. Isothermal reaction conditions will be obtained with the use of integrated heat exchange. The reactor will be evaluated for performance using the chosen catalyst/solvent and at least one temperature, pressure, and throughput identified in the microscale testing. Gas and liquid feeds will be deployed at pressure in order to maintain condensed phase operation. Reactor performance information will be used as inputs for updating the TEA for the process.	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. Overall market viability will be assessed using analysis input from SoCalGas. Depending on the eventual market application assess feasibility of using microchannel technology as a viable platform technology. Identification of additional project partners for technology demonstration using real off gas will be identified.	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 modular reactor system (scalable) that could be subsequently installed at an industrial CO_2 source (e.g. for power generation or anaerobic digestion).

CO_2 Capture and Utilization Today

All CO_2 capture and utilization deliver concentrated CO_2 streams for utilization, but why?





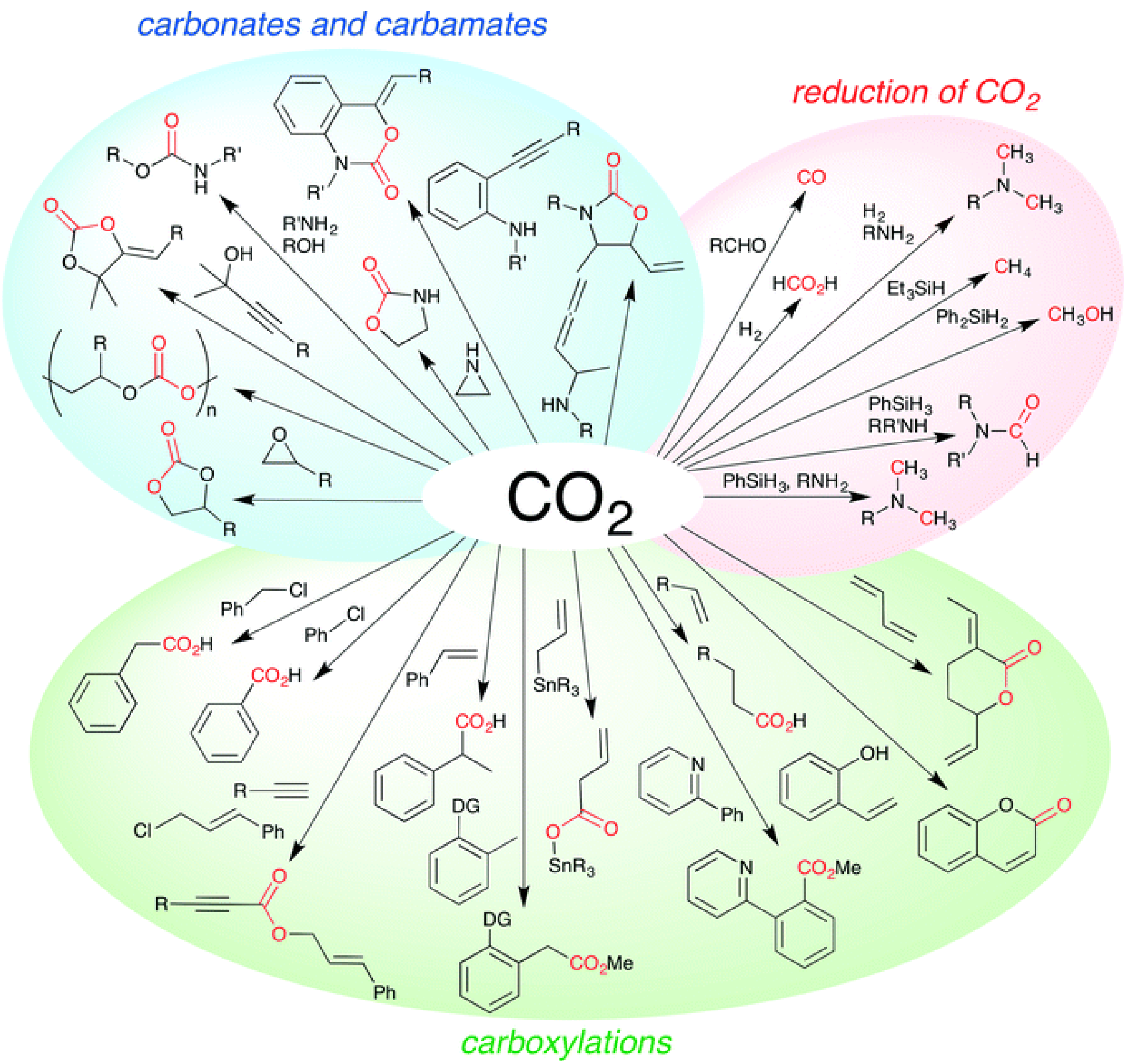
EOR and agriculture are moderate uses, but less efficient end use due to thermal regeneration of sorbent.

Products That Can Be Made From CO_2

Valorizing CO_2 introduces market drivers to implement CCS.

O=C=O

- Numerous products can be made from CO_2, but reactive pathways are limited.
- All chemical reactions of CO_2 proceed via nucleophilic attack on the central carbon or electrophilic coordination to the oxygens.
- Majority of thermochemical or catalytic conversions are done in gas phase or in organic solvents.



Catal. Sci. Technol., 2014, **4**, 1482-1497

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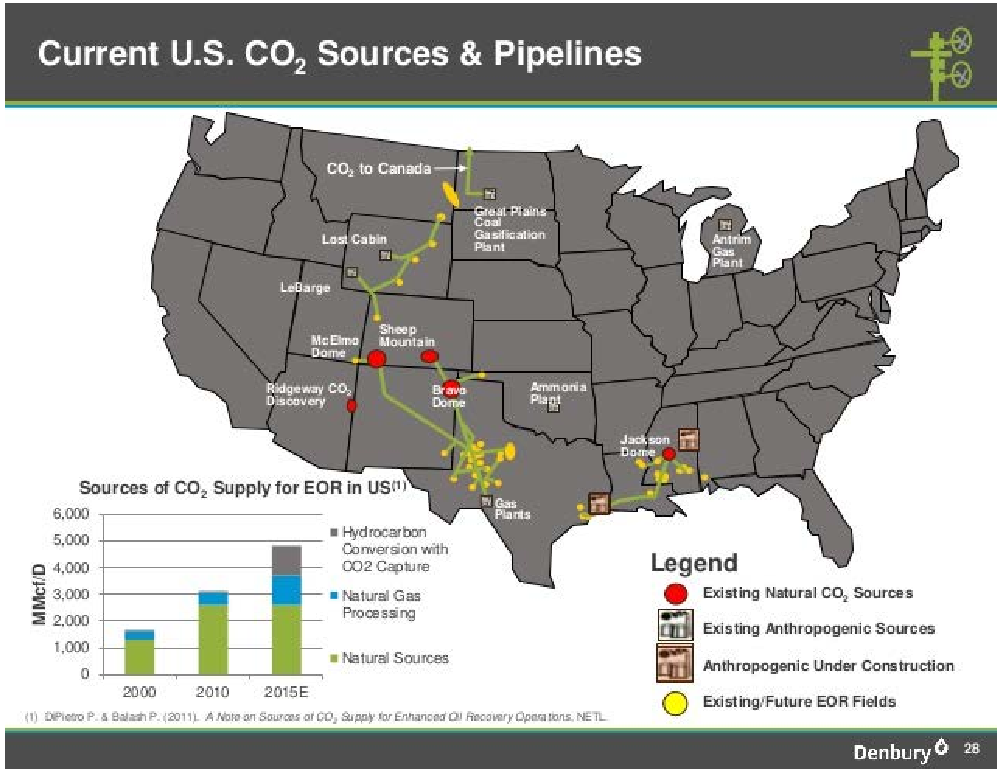
The Case for Integrating CO_2 Capture with Conversion

The energy cost of collecting, concentrating and purifying CO_2 is not free.



Current U.S. CO_2 Sources & Pipelines

(1) DiPietro P. & Balash P. (2011). *A Note on Sources of CO_2 Supply for Enhanced Oil Recovery Operations*, NETL.

Denbury 28

When natural supplies are exhausted, CO_2 must be captured before use.

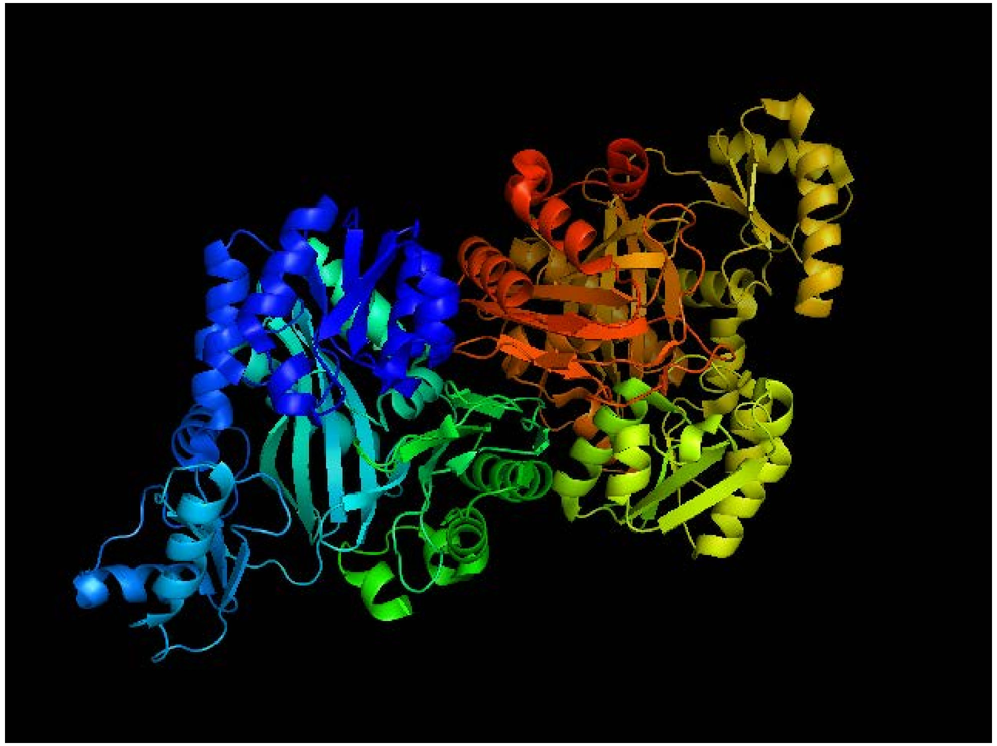
- Natural CO_2: \$20/tonne[2]
- Direct air capture: \$1,000-100/tonne[2,3]
- Flue gas: \$100/tonne[2]
  - Capture: **-85 kJ/mol**
  - Compression: **-12 kJ/mol**
  - Transport: **Variable**

1) "*Accelerating the uptake of CCS: industrial use of captured carbon dioxide*." Global CCS Institute, **2015**

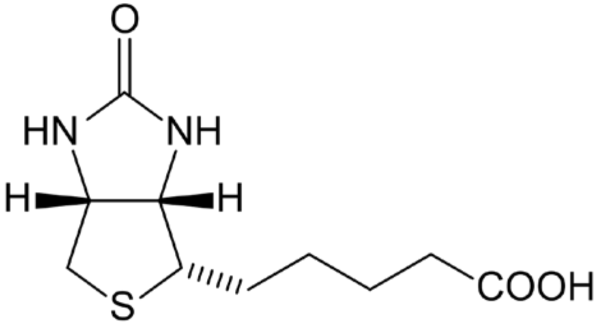
2) Herzog et al. PNAS, **2011**, 108, 20428–20433. 3) *Joule*, **2018**, 2, (8), P1573-1594, 4) Image from NETL.gov

Nature Has Long-Perfected CO_2 Capture and Conversion

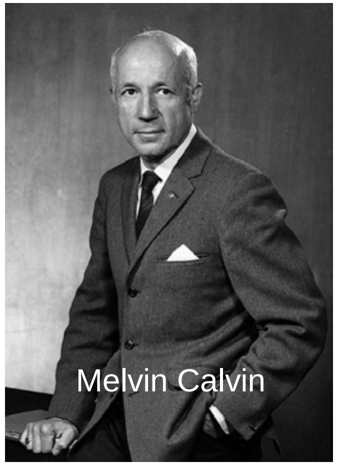
Biotin transfers anionic carboxylates in solution to grow fatty acids via the Calvin cycle.

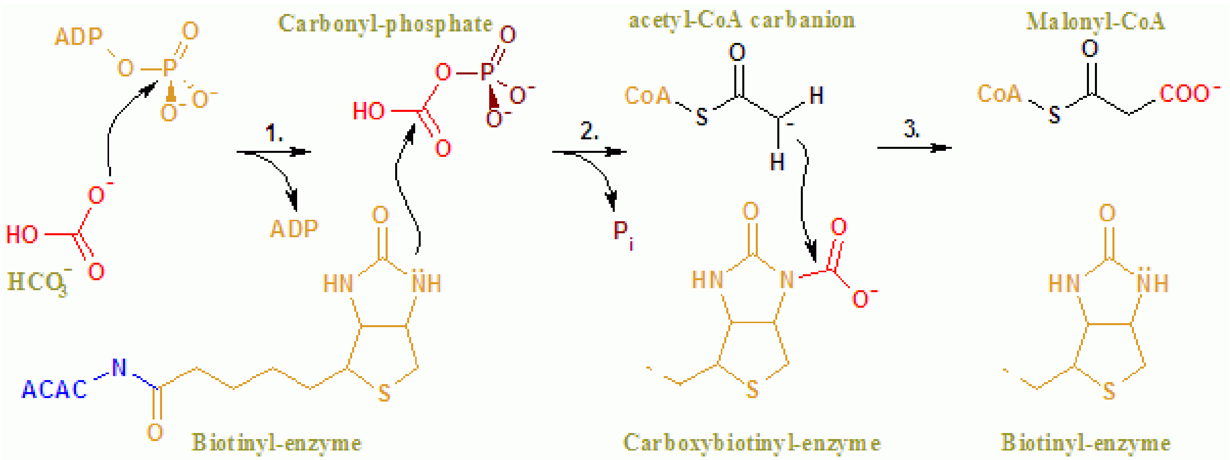


Biotin carboxylase subunit of *E. coli* acetyl-CoA carboxylase



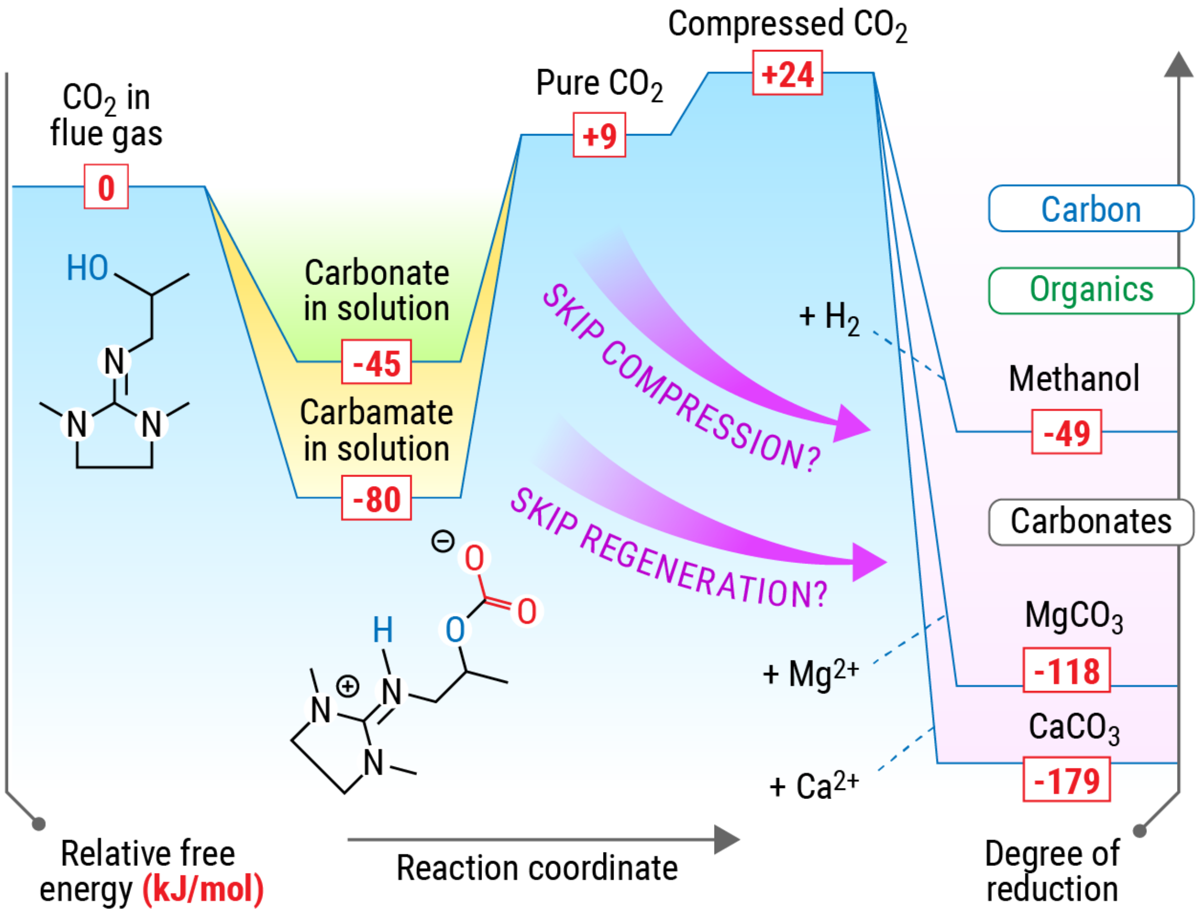
Biotin co-factor





The Case for Integrating CO_2 Capture With Conversion

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



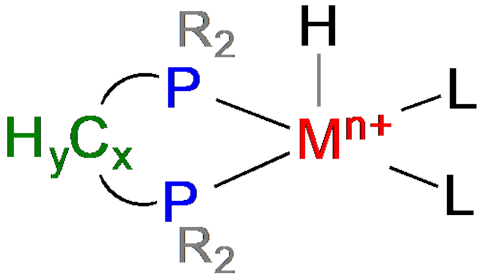
ICCCM Platform:

- 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

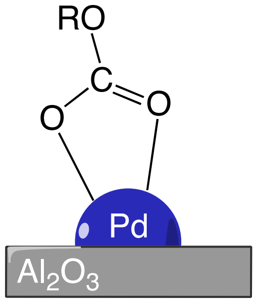
Reaction Advantages of Converting Captured CO_2

Condensed-phase reactions provide energy and cost benefits and new reactive landscapes.

- Same solvent used for both steps
  - Currently limited to water-lean solvents
- Catalysis at atmospheric (CO_2) pressures
  - CO_2 concentration >5 wt.% in solution at 1 atm
  - Potentially faster liquid phase kinetics
- Potentially lower free-energy pathways
  - Rehybridization complete, similar intermediates
  - High dielectric provides stabilization for polar transition states
- Heterogeneous or homogeneous pathways viable
  - Direct coordination to catalysts



Inner-sphere chelation of “captured” CO_2 (**L**)

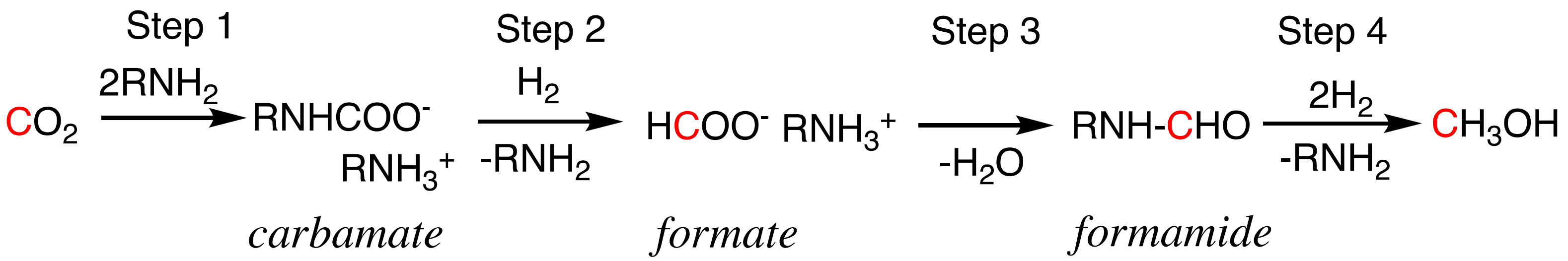


Chelation of “captured” CO_2 to metal surfaces

Condensed-Phase Methanol Synthesis Exploits Similar Chemical Reactivity

The same chemicals that capture CO_2 also promote conversion.

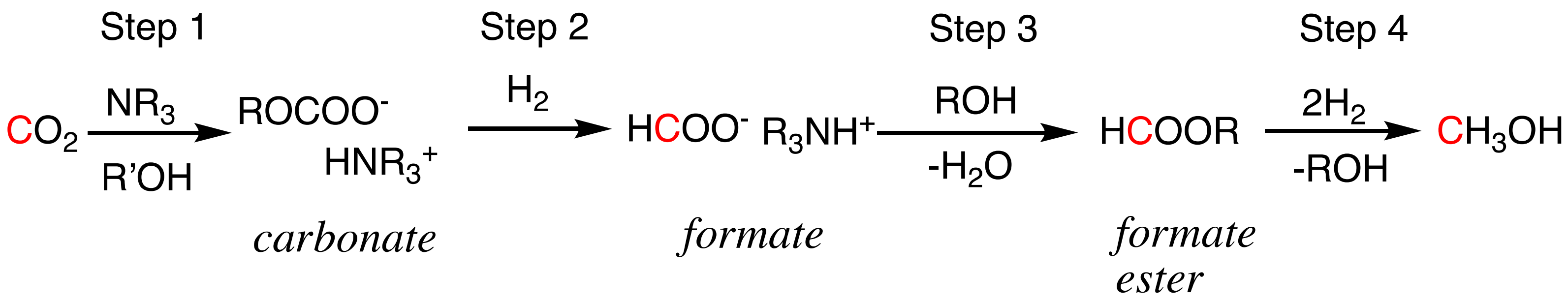
Pathway (a)



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

carbamate *formate* *formamide*

Pathway (b)



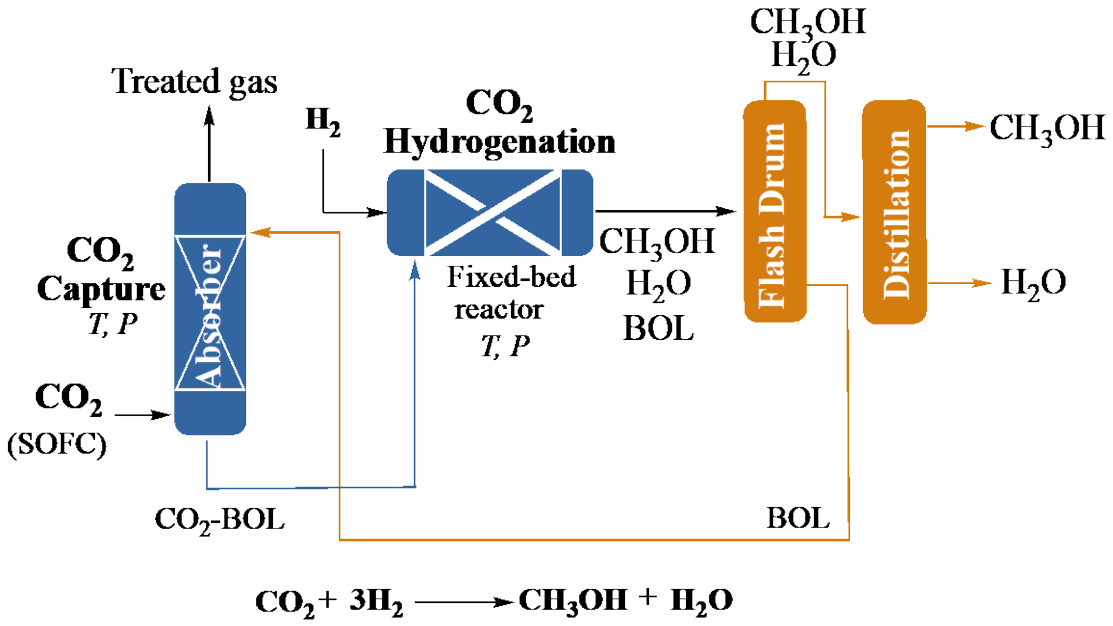
$$CO_2 \xrightarrow[R'OH]{\overset{\text{Step 1}}{NR_3}} ROCOO^-\ HNR_3^+ \xrightarrow{\overset{\text{Step 2}}{H_2}} HCOO^-\ R_3NH^+ \xrightarrow[-H_2O]{\overset{\text{Step 3}}{ROH}} HCOOR \xrightarrow[-ROH]{\overset{\text{Step 4}}{2H_2}} CH_3OH$$

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. Technol. **2018**, *8*, 5098-5103

Process configuration for ICCCM

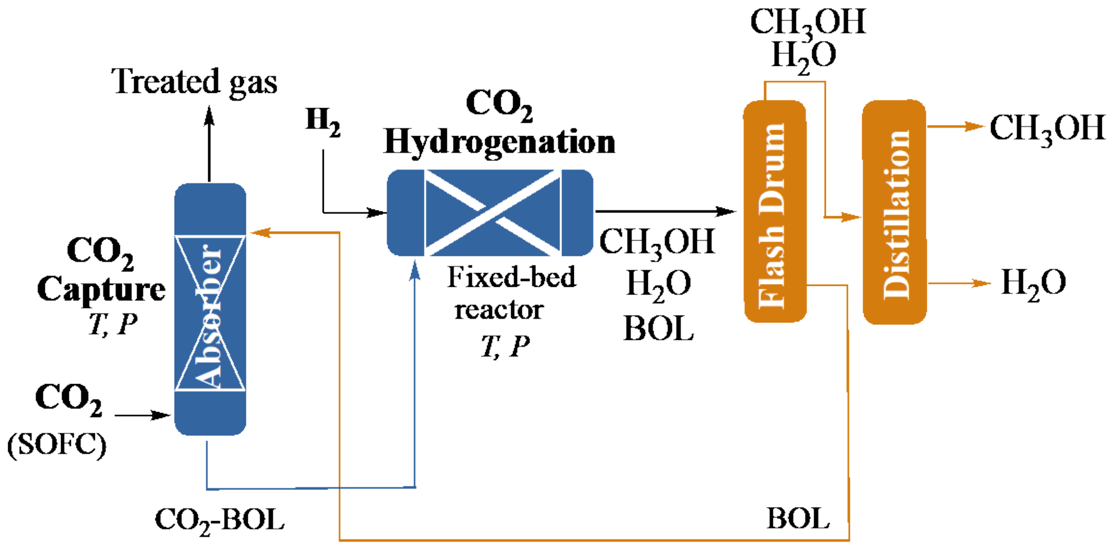


$$CO_2 + 3H_2 \longrightarrow CH_3OH + H_2O$$

- Flue gas from a power generation is cooled prior to entering the CO_2 absorber
- In the absorber, the water-lean CO_2BOL solvent is used to capture CO_2
- CO_2-rich solvent exiting the absorber is then pressurized to 25 bar and heated to 120 °C before being sent to the main reactor, along with H_2, for methanol production
  - Different products available with different reagent co-feed
- The H_2:CO_2 ratio in the reactor is slightly higher than the stoichiometric ratio in order to shift reaction equilibrium and increase CO_2 conversion

*Jiang *et al. In Preparation, Patent pending*

Process configuration for ICCCM



$$CO_2 + 3H_2 \longrightarrow CH_3OH + H_2O$$

- **Energy saving features of the ICCCM process:**
  - Hydrogenation of CO_2 to methanol is exothermic, thus energy associated with regeneration of the carbon capture solvent is partially offset by the subsequent conversion.
  - Heat recovered from the reactor can be used to generate low-pressure steam which can be used in other parts of the process, and as a utility.
  - Since CO_2 is directly converted to methanol on the ICCCM solvent no mechanical compression of CO_2 is required for the subsequent reaction.

*Jiang *et al. In Preparation, Patent pending*

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Techno-economic Assessment for ICCCM

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

- Preliminary TEA performed on different flue gas sources
    - 50 MW SOFC power plant
    - 550 MW NGCC plant, and
- Baselined against a conventional 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.

*Jiang *et al. In Preparation, Patent pending*

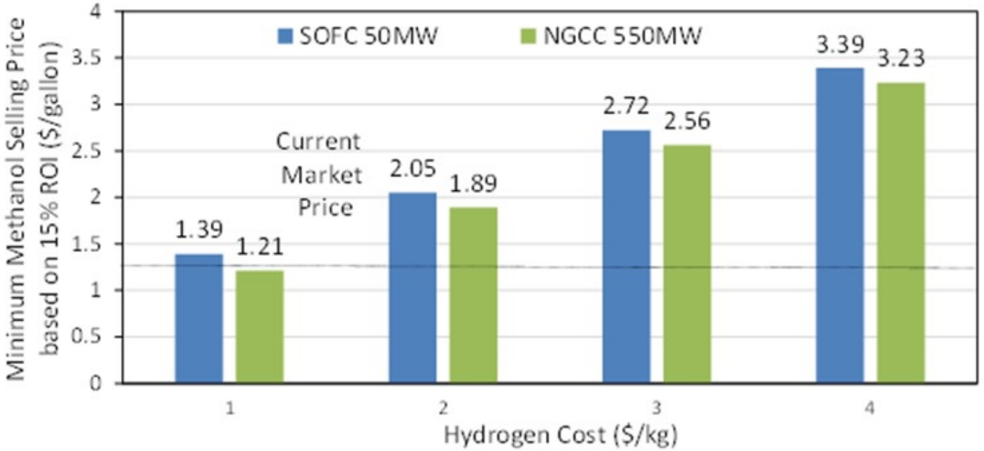
Commercial Viability for ICCCM

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

H_2 cost sensitivity analysis

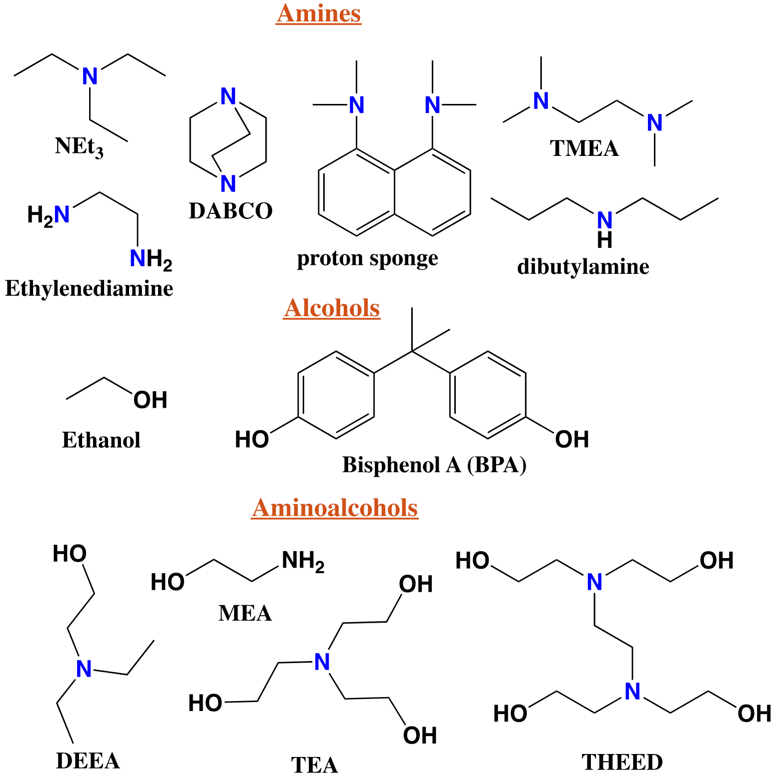


- **H_2** is expensive, but serves an indirect energy source to drive CCS, VS steam or electricity
- ICCCM becomes a viable technology for **modular distributed-scale processing platforms** by removing additional energy inputs and equipment
  - landfill gases
  - waste-water treatment gases
  - manure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

*Jiang *et al. In Preparation, Patent pending*

CO$_2$ Hydrogenation in the Presence of Amines

The combination of alcohols and 3˚ amines is required for 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$_2$O$_3$ (300 mg), CO$_2$/H$_2$=60 bar (1:2), T=170 °C, t=16h. ^{a}40h, and ^{b}120°C

Kothandararaman, J., Dagle, R.A., Dagle, V. L., Davidson, S. D., Walter, E. D, Burton, S. D., Hoyt. D. W. and Heldebrant, D. J. *Catal. Sci. Tech.,* 8 (19), 5098-5103, Patent filed 7, 2020.

*Activity (pre-TCF) limited to pre-combustion (pressure swing) solvents.

Post-Combustion Solvent Updates

Screening EEMPA as a post-combustion solvent with different catalysts.

Entry	*Capture Solvent*	*Exp. No*	*Catalyst*	*Formate mmol*	*Formamide mmol*	*N-methyl amine mmol*	*CH_3OH (desired) mmol*
1	EEMPA	62711-135	A	-	3.7	4.5	traces
2[a]	EEMPA + EtOH	62711-119	A	-	4	-	traces
3	EEMPA	62711-139	B	1.8	traces	traces	traces
4[b]	EEMPA	62711-143	C	-	7.5	traces	traces
5	EEMPA	62711-140	A + C	-	3.1	2.6	traces

Catalyst=200mg, time=12h, 300 mL reactor, P=60 bar (CO_2:$3H_2$), T=170 °C, t=12 h, Concentrations of all the products and intermediates were calculated based on ^1H NMR using 1,3,5-trimethoxy benzene as an internal standard (100 mg), [a]ethanol=200 mmol, [b]48h.

- Initially, little methanol was formed in any cases
- Catalyst B selectively formed formate intermediate (entry 3)
- Addition of ethanol didn’t change the formamide yield (entry 1 vs 2)
- The selectivity to amide intermediate is high with Catalyst A and C
- **Currently working to facilitate the final mechanistic step, amide to methanol**

Post-Combustion Solvent Updates, continued

Screening EEMPA as a post-combustion solvent with "Catalyst A" and varying conditions.

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

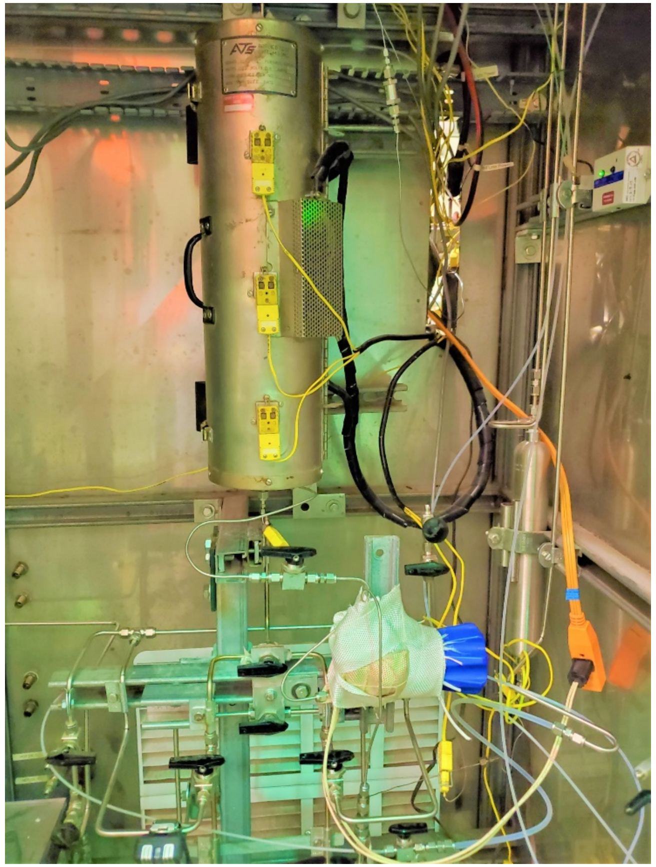
Reaction conditions: Catalyst A=200mg, 100 mL reactor, EEMPA=23mmol, P=60 bar (CO_2:$3H_2$), T=170 °C, t=12 h, concentrations of all the products and intermediates were calculated based on ^1H NMR using 1,3,5-trimethoxy benzene as an internal standard (100 mg), [a] ethanol=200 mmol.

- With decreased CO_2 to EEMPA concentration, methanol was observed (entry 1)
- Longer reaction time increased both methanol and N-methylated amine (entry 2)
- Further decrease in CO_2 concentration and addition of ethanol improved selectivity towards methanol (entry 4)
- **71% selectivity to methanol demonstrated to-date**
- **Currently screening catalysts/ conditions for the final step, amide to methanol**

Continuous Flow Reactor System – CO_2 Hydrogenation

Reactor and flow system apparatus setup.

- Reactor and test configuration set-up
  - Rigorous safety protocols/ approvals made
  - Safety modifications made to lab for high pressure H_2 operation
- Feeds:
  - Liquid amine, ethanol, and CO_2 (simulating capture solvents), and gaseous H_2
- Variables:
  - Parametrics (T, P, SV, feed ratios)
  - Catalyst, solvent system

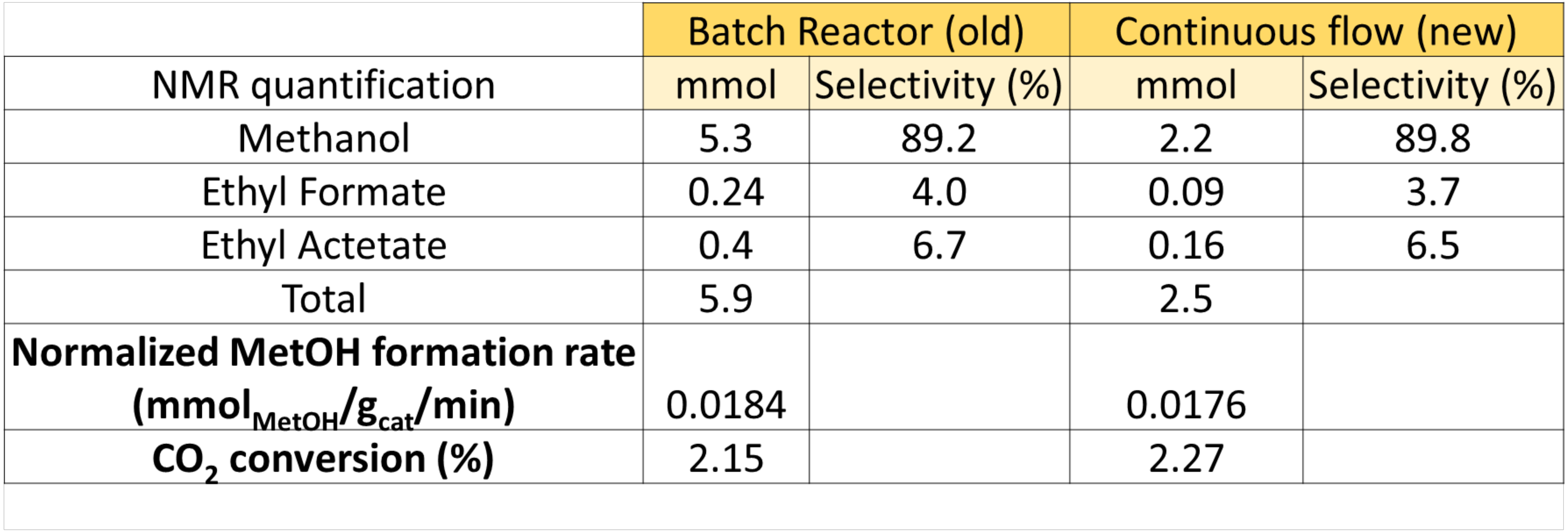


- Currently baselining our continuous flow system by evaluating prior batch rector *pre-combustion* solvent system.
- Once a suitable *post-combustion* solvent system is developed (via batch reactor) we will develop the continuous flow processing (and eventual scale-up) .

Continuous Flow vs. Batch Reactor Results

170 °C, 60 bar, 3700 hr^{-1}, Catalyst A

Pre-combustion solvent system baseline testing.



	Batch Reactor (old)		Continuous flow (new)	
NMR quantification	mmol	Selectivity (%)	mmol	Selectivity (%)
Methanol	5.3	89.2	2.2	89.8
Ethyl Formate	0.24	4.0	0.09	3.7
Ethyl Actetate	0.4	6.7	0.16	6.5
Total	5.9		2.5	
Normalized MetOH formation rate (mmol$_{MetOH}$/g$_{cat}$/min)	0.0184		0.0176	
CO_2 conversion (%)	2.15		2.27	

- Continuous flow results demonstrate similar ***selectivity*** and ***activity*** as prior batch reaction results for pre-combustion system.
- Low initial conversion, however, working to increase activity through parametric evaluation and improved catalyst design.

Continuous Flow vs. Batch Reactor Results, cont.

170 ^{o}C, 60 bar, 1.0 g Catalyst A

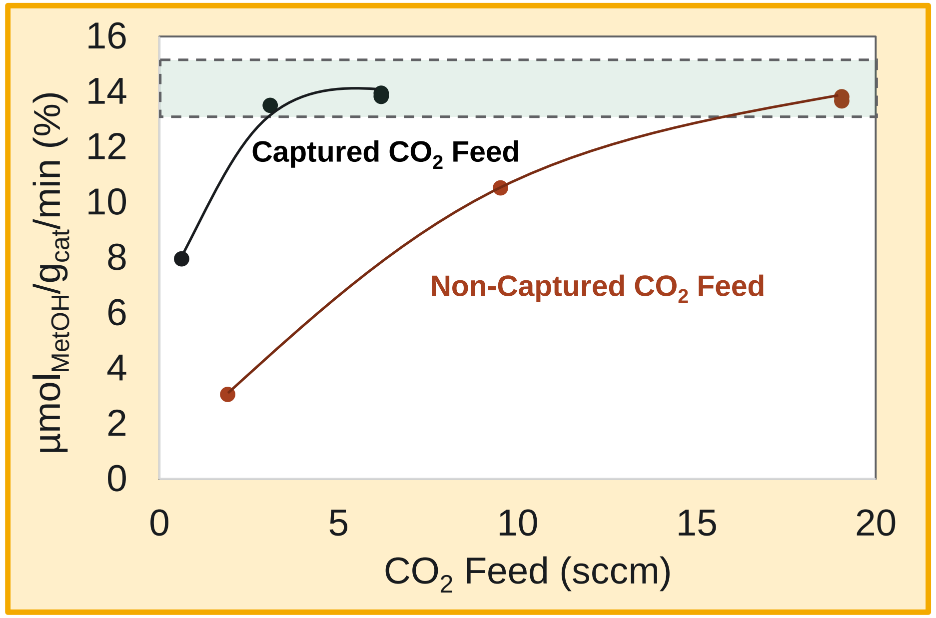
Pre-combustion solvent system evaluation.

- Non-Captured CO_2 Feed

Experiment	$F_{Solvent}$	WHSV (h^{-1})			CO_2 Conversion
#	(mL/min)	EtOH	NEt3	CO_2	(%)
1	0.050	1.92	0.42	0.041	2.2
2	0.050	1.92	0.42	0.020	3.8
3	0.050	1.92	0.42	0.005	5.5

- Captured CO_2 Feed

Experiment	$F_{Solvent}$	WHSV (h^{-1})			CO_2 Conversion
#	(mL/min)	EtOH	NEt3	CO2	(%)
4	0.050	1.92	0.42	0.0134	5.6
5	0.025	0.96	0.21	0.0067	9.8
6	0.005	0.19	0.04	0.0013	31.2



- Higher reactivity demonstrated when CO_2 is captured in feed prior to reaction.
- Working to increase activity/ throughputs via parametric investigation and evaluation of different catalyst formulations.
- Will evaluate *post-combustion* solvent system when identified from batch screening study.

Conclusions/ Future Work

- **Cost benefits to integrating capture and conversion**
  - Proof-of-concept results using *pre-combustion* solvent system ➔ basis for TCF project
- ***Post-combustion* solvent/ catalyst system development ongoing**
  - Investigating multifunctional catalyst system
- **Process development via continuous flow reactor system**
  - Continuous flow reactors offer scalable reaction technology
  - Preliminary results validate prior batch proof of concept experiments when using *pre-combustion* solvent system
  - Working to increase activity, and will explore *post-combustion* solvent system when identified from batch experiments
- **Future Work:**
  - Enhance catalyst activity through parametric optimization and improved catalyst design
  - Develop modular microchannel system with active heat control (next year)
  - Update techno-economics to define the state-of-technology (next year)
  - Demonstrate integrated system for capture and conversion (next year)

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Thank you!

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Robert A. Dagle

David J. Heldebrant

Jotheeswari 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**	◆	◆	◆	◆	◆	◆	◆	♦