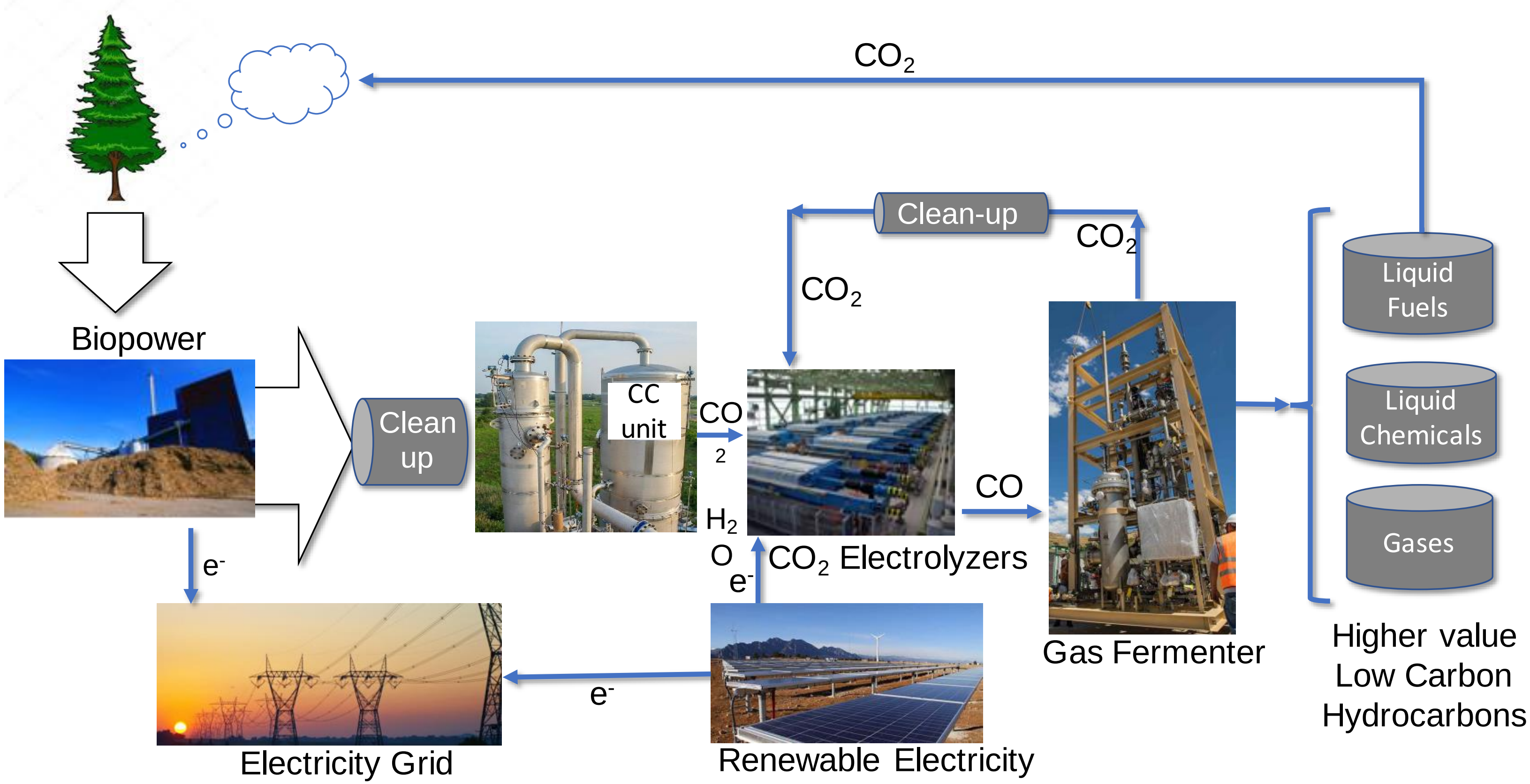
Integration of CO_2 Electrolysis with Microbial Syngas Upgrading to Rewire the Carbon Economy

WBS# 5.1.3.101
3/7/2019
2019 BETO Peer Review
CO_2 Session
PI - Michael Resch, PhD.

Project Overview



To incentivize BioEnergy with CO_2 Capture and Sequestration (BECCS) we will investigate key gas-to-fuels **process integration hurdles**

Project Goals

Goal

- Integration of CO_2 flue gas electrolysis with syngas fermentation

Outcome

- Determine the impact of varied flue gas compositions on electrolyzer efficiency, lifetime, and specificity
- Examine the relationship of electrolyzer produced syngas upon biocatalytic conversion metrics (conversion efficiency and rate)
- Identify key TEA and LCA drivers
  - max electricity cost for process viability
  - carbon intensity of integrated process
  - feedstock inventory requirements

Relevance to Industry

- By producing valuable products out of CO_2 this project will incentivize CCU to realize carbon circular economy opportunities

Quad Chart Overview

Timeline

- Start Date: 10/1/2018
- End Date: 9/30/2021
- 8% Complete

	FY 18 Costs	Total Planned Funding (FY 19-Project End Date)
DOE Funded	$56k (proposal writing)	$1.444k
Project Cost Share*	$0	$860k

•**Partners:** Dioxide Materials ($100k cost share and $334k BETO funding), 3M ($760k cost share), LanzaTech (no cost partner)

Barriers addressed

Ct-A Defining metrics around feedstock quality

Ct-D Advanced bioprocess development

Ct-H Gas Fermentation Development

Objective

Evaluate and overcome key process hurdles associated with the integration of electrocatalytic CO_2 conversion and biological syngas upgrading, in order to achieve economically-viable, sustainable conversion of biopower-derived flue gases to fuels and chemical intermediates.

End of Project Goals

- Run the CO_2 electrolyzer integrated to a bioreactor to determine the CO inventory needed to maintain carbon requirements of the bioreactor.
- Determine the minimum and maximum CO concentration that can maintain the microorganism production rate or maintain a revivable dormant state, as well as determine robustness of microorganism
- Determine the minimum electricity cost and carbon intensity of the process.

Project Overview

History

- Awarded at the start of FY19 as a competitive Biopower Lab Call proposal for Topic 7 *Innovative research to enable economic and impactful biopower with carbon capture in the United States*

Goal

- To incentivize BECCS we will investigate key flue gas-to-fuels **process integration hurdles** such as:
  - CO_2 concentration
  - Flue gas contaminates
  - Scaling the integration of the two technologies
  - Biocatalyst performance

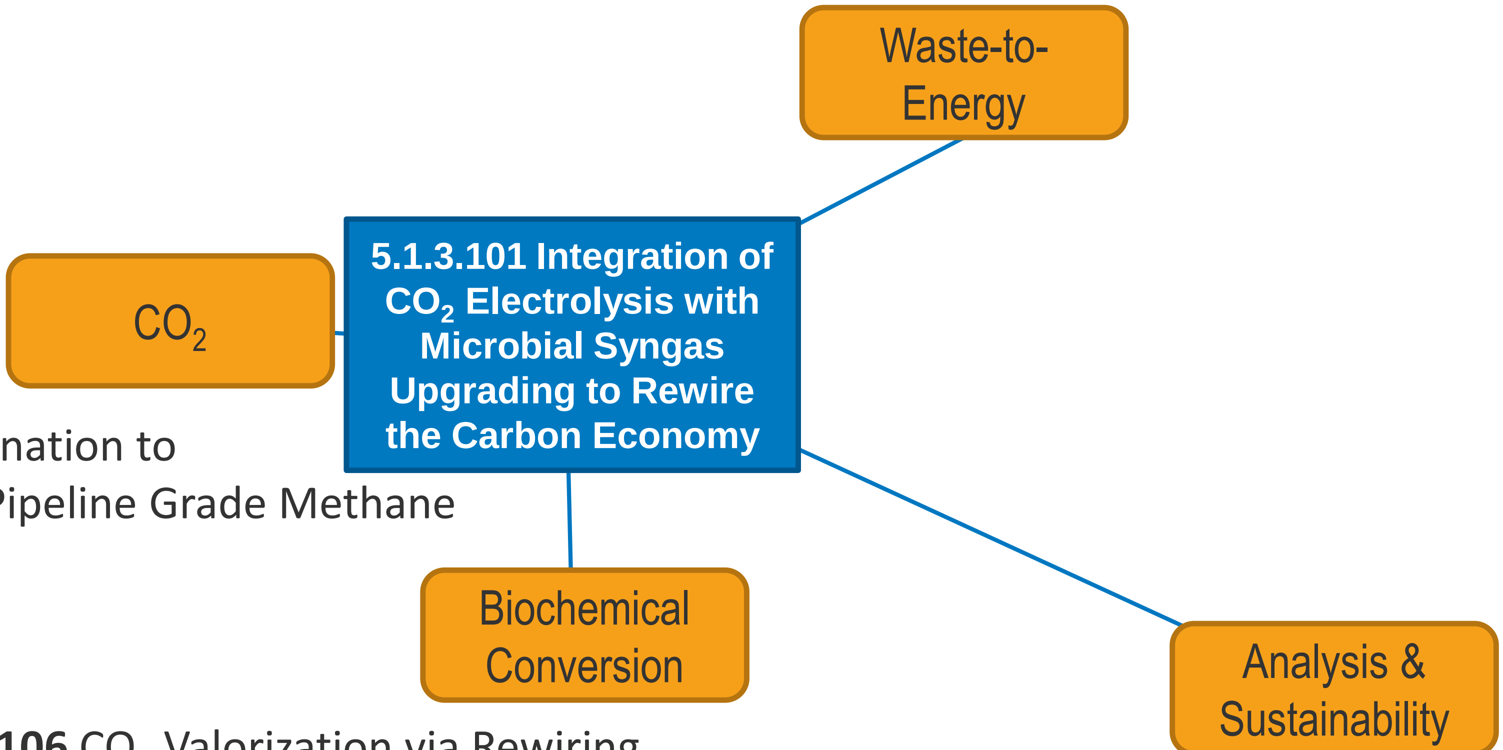
Leveraging Work at NREL

5.1.3.101 Integration of CO_2 Electrolysis with Microbial Syngas Upgrading to Rewire the Carbon Economy

- Agile BioFoundry
- Lignin
- Feedstock Logistics
- Algae
- Waste-to-Energy
- CO_2
- ADO Analysis/ Modeling
- Catalysis
- ADO Integration Scale-up
- Biochemical Conversion
- PABP/ Separations
- Analysis & Sustainability
- Co-Optima
- FCIC

Leveraging Work at NREL

2.3.2.102 Biogas to Liquid Fuels and Chemicals using Methanotrophic Microorganisms



5.1.3.102 Biomethanation to Upgrade Biogas to Pipeline Grade Methane

2.3.2.106 CO_2 Valorization via Rewiring Carbon Metabolic Network.

2.1.0.304 Feasibility Study of Utilizing Electricity to Produce Intermediates from CO_2 and Biomass

Approach - Management

Dioxide Materials™

Transforming ENERGY

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Task 1 - Liu (DM)	Task 2 - Guarnieri	Task 3 - Resch
CO_2 Electrolyzer performance optimization	**Gas fermentation Process Development and Strain Optimization**	**Analysis and Integration of Combined CO_2 electrolysis with gas fermentation**
Design and fabricate a carbon- and energy-efficient CO_2 electrolyzer with optimized functionality on biopower-derived effluent gas streams.	Define microbial and gas fermentation requirements to maximize the carbon uptake and conversion efficiencies.	Integrate technologies to increase the carbon efficiencies of BECCS and other industrial processes by creating valuable products from waste gas sources.

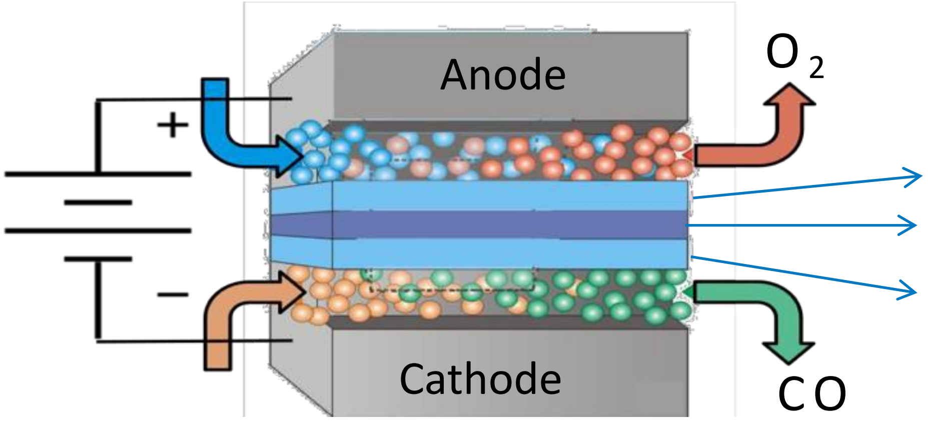
Technical Approach

Integration of CO_2 electrolysis with gas fermentation

CO_2 Electrolysis

CO_2 + electricity → CO + ½ O_2

$2OH^- \rightarrow H_2O + 2e^- + \frac{1}{2} O_2$



$CO_2 + H_2O + 2e^- \rightarrow CO + 2OH^-$

The DM/3M Team's Effort: Converting CO_2 Electrolysis From A Laboratory Curiosity To Real Technology

Biological Conversion of Syngas

Diversity of *Clostridia autoethanogenum*

Rigorous Development and Modeling Enabled Wide Range of Feedstock

Feedstock	Reaction	H_2:CO ratio	
CO	$6\,CO + 3\,H_2O \rightarrow$ <u>EtOH</u> $+ 4\,CO_2$	0:1	**High CO off-gas (e.g. steel)** Demonstrated at scale
CO + H_2	$3\,H_2 + 3\,CO \rightarrow$ <u>EtOH</u> $+ CO_2$	1:1	**Syngas (e.g. MSW)** Demonstrated at scale
CO + H_2	$4\,H_2 + 2\,CO \rightarrow$ <u>EtOH</u> $+ H_2O$	2:1	
CO + H_2 + CO_2	$5\,H_2 + 1\,CO + 1\,CO_2 \rightarrow$ <u>EtOH</u> $+ 2\,H_2O$	5:1	**High H_2 off-gas (e.g. refinery)** Demonstrated at pilot, allows CO_2 fixing in products

Any combination or interpolation of these can be used for ethanol production with only a change in operating conditions

No Carbon Left Behind™

LanzaTech

2 – Approach (Technical)

Critical Success Factors

- Identify flue gas contaminants and toxicity to electrolyzer catalysts
- Flue gas contaminants toxic to electrolyzer membranes
  - Implement gas clean-up strategies
- Poor biocatalyst conversion rate
  - Generate variants with enhanced CO conversion capacity via random and targeted mutagenesis.

2 – Approach (Technical)

Potential Challenges

- Electrolyzers unable to reach 200 mA/cm² at high selectivity on low concentration CO_2
  - Build a larger electrolyzer to meet needs of fermenter.
  - Increase CO_2 concentration into electrolyzer
- Flue gas contaminants toxic to electrolyzer membranes
  - Implement gas clean-up strategies
- Poor biocatalyst conversion rate
  - Generate variants with enhanced CO conversion capacity via random and targeted mutagenesis.

Progress

Integration of CO_2 electrolysis with gas fermentation

Lab Set-up Progress

- Safely Integrate electrolysis with CO gas fermentation at NREL
- Scale matching and gas compatibility

✓ P&ID
✓ Electrical
✓ Hazard Review
➢ Lab Set up

➢ Integration
➢ Industrial flue gas analysis

Investigating Industrial Flue Gas

Relevance

Industrial Relevant CO_2 Feedstocks

Process	CO_2 concentration in gas stream % by vol.	Number of sources	Emissions ($MtCO_2$)	% of total CO_2 emissions	Cumulative total CO_2 emissions (%)	Average emissions/source ($MtCO_2$ per source)
CO_2 from fossil fuels or minerals						
Power						
Coal	12 to 15	2,025	7,984	59.69	59.69	3.94
Natural gas	3	985	759	5.68	65.37	0.77
Natural gas	7 to 10	743	752	5.62	70.99	1.01
Fuel oil	8	515	654	4.89	75.88	1.27
Fuel oil	3	593	326	2.43	78.31	0.55
Other fuels[a]	NA	79	61	0.45	78.77	0.77
Hydrogen	NA	2	3	0.02	78.79	1.27
Natural-gas sweetening						
Petrochemical industry						
Ethylene	12	240	258	1.93	98.85	1.08
Ammonia: process	100	194	113	0.84	99.70	0.58
Ammonia: fuel combustion	8	19	5	0.04	99.73	0.26
Ethylene oxide	100	17	3	0.02	99.75	0.15
Other sources						
Non-specified	NA	90	33	0.25	100.00	0.37
		7,584	**13,375**	**100**		**1.76**
CO_2 from biomass[e]						
Bioenergy	3 to 8	213	73			0.34
Fermentation	100	90	17.6			**0.2**

CO_2 from biomass[e]

Bioenergy	3 to 8	213	73
Fermentation	100	90	17.6

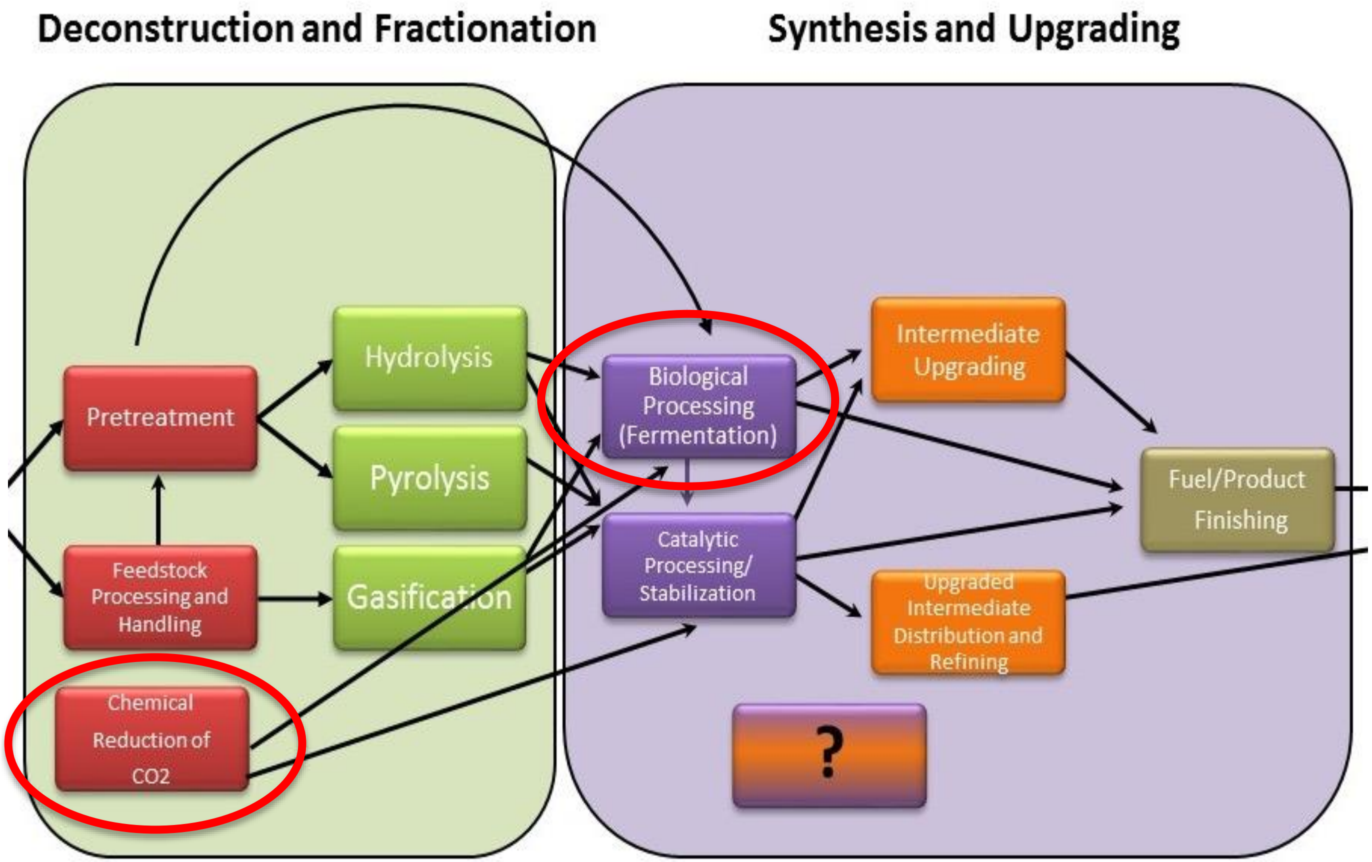
Gale *et.al. IPCC Special Report on Carbon dioxide Capture and Storage.* (2005)

Compositions of Biopower Facility Flue Gas

Biopower from biomass could include Combustion, Co-firing, Gasification, Pyrolysis, and Anaerobic Digestion

1. Gasifier from waste wood to power 1.5 gen facility
   - ~65% N
   - 14-17% CO_2
   - ~2% O^2
   - 15-30 ppm VOCs
   - 30 PPM NO_x
   - VSCs
2. Fermenter Flue Gas Composition
   - 99%+ CO_2
   - ~51000 #/hr CO_2
   - Minimal O_2
   - VOC and VSCs

BETO Conversion Relevance



- This project supports BETO **Conversion R&D** Portfolio which focuses on early-stage technology R&D.
- Use low carbon renewable electricity to catalytically reduce CO_2 into CO intermediate and upgrade into biofuels and bioproducts, to enable BECCS.

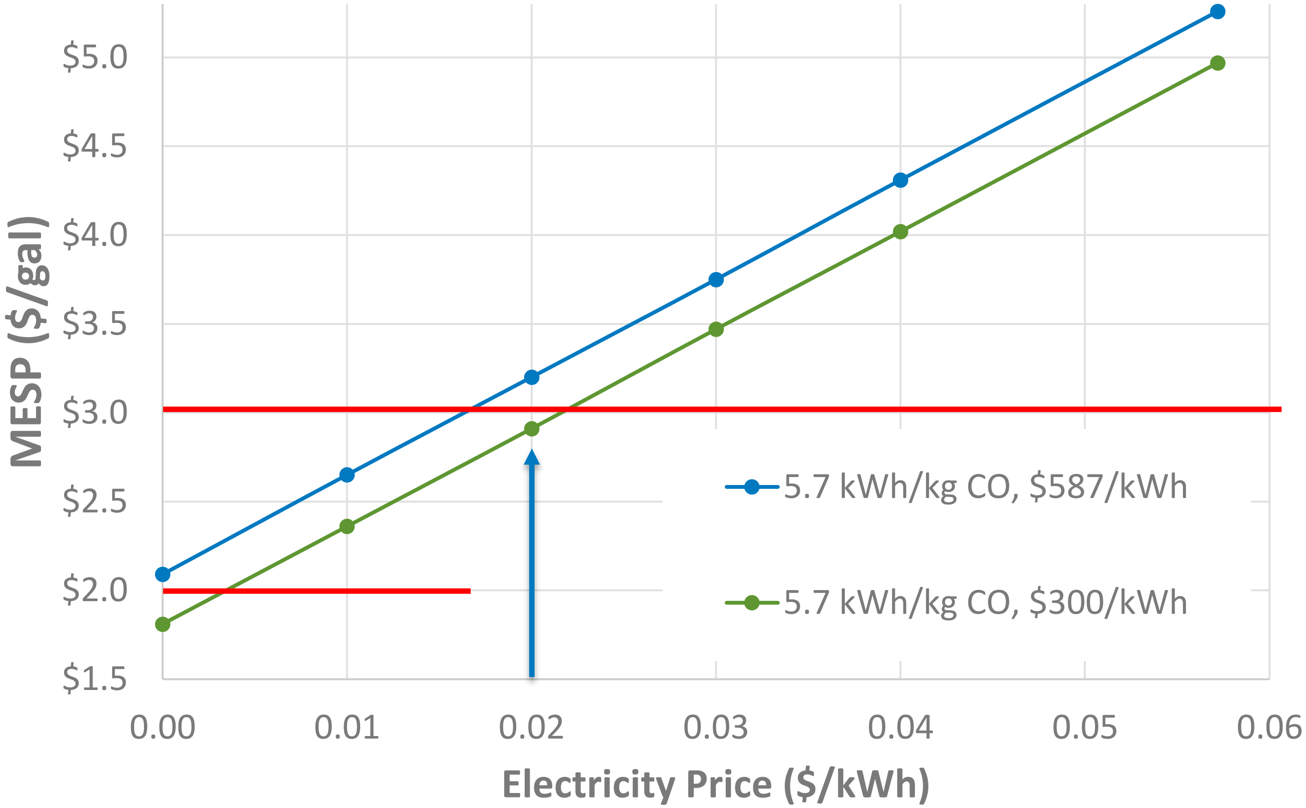
Relevance

Supports BETO's mission to *"develop industrially relevant, transformative, and revolutionary **bioenergy technologies** to enable **sustainable, domestically produced biofuels**, bioproducts, and **biopower** for a prosperous nation."*

Also directly supports BETO's strategic goal to ***enable** use of America's abundant biomass and **waste resources** for advanced biofuels, biopower, and bioproducts by:*

- Identifying and developing biofuel pathways and innovative end uses;
- Completing applied R&D on complex, **real world systems**, and integrating engineering processes for promising new advanced bioenergy technologies;
- While maintaining or enhancing economic, environmental and **social sustainability**.

Preliminary TEA



Current SOT and impacts of electricity price and electrolyzer capital costs to minimum ethanol selling price (MESP).

Future Work

Integration of CO_2 electrolysis with gas fermentation

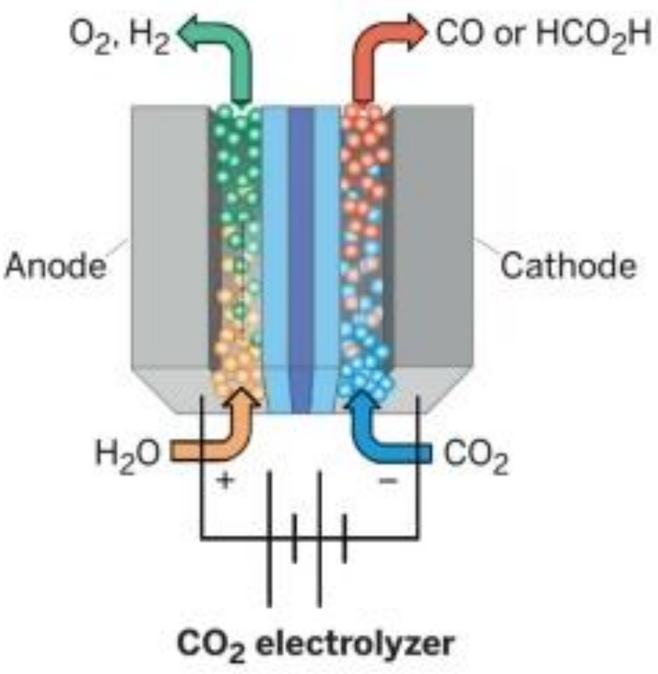
Electrolytic Gas Stream Evaluation

Goal:

1. Identify filtration, purification, and concentration impacts upon performance metrics for electrolyzer output stream composition as well as biocatalyst performance.

Approach:

1. Establish integrative electro-biocatalytic fermentation capacity.
2. Evaluate gas streams from diverse points sources; conduct off gas analyses to establish conversion efficiencies on varied CO_2 concentrations and trace compositions.
3. Define biocatalyst growth capacity and productivity in 0.1-5L gas fermenters as a function of input gas composition.
4. Develop smart control systems to maximize performance.



Systems Integration (3/31/20): Set-up an integrated 25 cm^2 CO_2 electrolyzer feeding syngas into a 2-5L gas fermenter and run for 24 hours

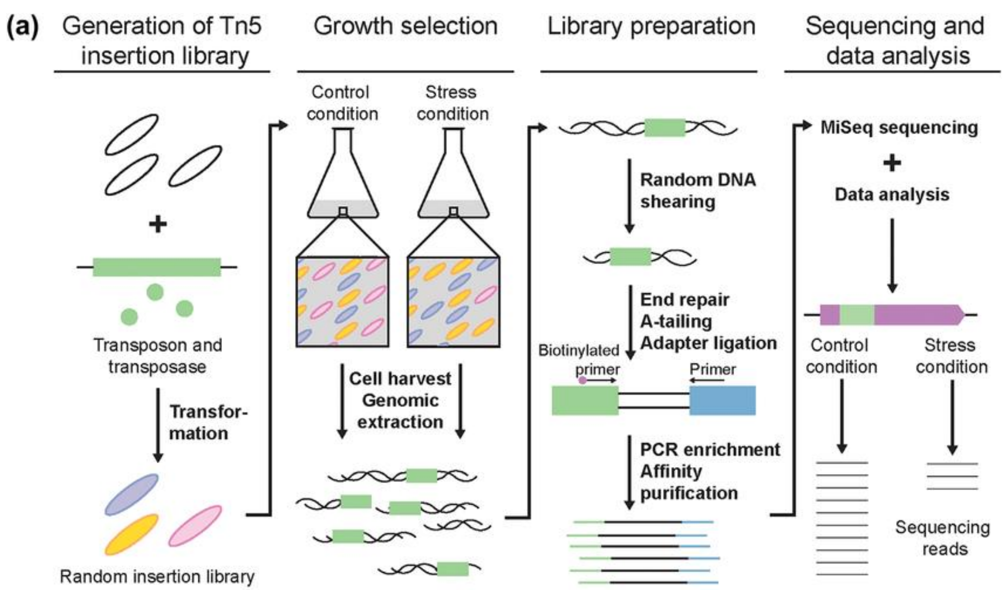
Strain Engineering

Goals:

1. Generate a minimal *Clostridia autoethanogenum* genome with maximal fitness (growth rate, carbon efficiency, flux to product)
2. Adapt strain(s) to electrolysis-derived syngas stream(s).

Approach:

1. Generate a genome-wide transposon library.
2. Conduct next-gen sequencing to define insertional frequency and essential genes.
3. Chemostat+adapted evolution on top-candidate strain variants.



9/30/2019 Generate and screen >1,000 biocatalyst variants for enhanced conversion.

Year 1

Start Q1 FY19

- Electrolyzer fabrication and evaluation on CO_2
- Determine flue gas composition from two industrial sources
- Electrolyzer performance on BECCS CO_2 streams
- Biocatalyst performance on syngas feeds
- Baseline TEA and LCA (partner AOP)

Year 2

- Electrolyzer evaluation on mixed typical flue gas components
- Biocatalyst performance on syngas on electrolyzer flue gas mixtures
- Biocatalyst strategies to increase carbon efficiency
- Integrate system with GC for real time gas monitoring
- Match scale of electrolyzer with bioreactor needs
- Update TEA SOT and R&D targets

Year 3

End Q4 FY21

- Run electrolyzer and bioreactor on representative industrial flue gas mixtures for 100 hours
- Determine the impact electricity costs have on economic viability
- Identify key cost drivers for future R&D commercial deployment
- Determine economic and environmental benifits by integration of this CO_2 upgrading strategy with BECCS

Summary

1. **Overview** - This project will determine the viability of converting CO_2 into fuels and chemicals
2. **Approach** – Integration and optimization of electrolysis with gas fermentation
3. **Technical Accomplishments/Progress/Results** – Establishing core capabilities at NREL
4. **Relevance** – Innovative research to enable economic and impactful biopower with carbon capture in the United States
5. **Future work**
   - Evaluate Biopower flue gas streams
   - Electrolyzer compatibility and scaling
   - Strain Engineering and assimilation improvements
   - Electrolysis and gas fermentation integration
   - Identification of key technical hurdles for industrial applications

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Thank You

www.nrel.gov

Publication Number

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NREL Transforming ENERGY

Project Milestones

- **Kickoff Meeting (Q1):** Establish lab set-up, safety requirements, tech transfer, and partner deliverables. Identify two industrial biopower flue gas streams and quantify chemical composition.
- **Establish cultivation capacity (Q2):** Establish and demonstrate mid-throughput, 0.1-5L batch and chemostat cultivation capacity for CO gas fermentation
- **TEA/LCA Baseline (Q3):** Provide overall integrated process concept, process conditions and parameters for major unit operations, and support analysis team data for TEA and LCA studies to establish a baseline for the current state-of-the-technology.
- **Biocatalyst and Protein Engineering. (Q4):** Generate and screen >1,000 biocatalyst variants for enhanced conversion.
- **Electrolyzer fabrication and operation. (12/31/2019):** Using a CO_2 25 cm^2 electrolyzer, we will accomplish continuous operation on an influent gas stream with <50% CO_2 content to identify baseline. Identify filtration, purification, or concentration impact upon performance metrics for electrolyzer output stream composition as well as biocatalyst performance on varying syngas mixtures needed on each gas stream input to maintain 100 hours of performance of the CO_2 electrolyzer and bioreactor.
- **Systems Integration (3/31/20):** Set-up an integrated 25 cm2 CO_2 electrolyzer feeding syngas into a 2-5L gas fermenter and run for 24 hours
- **Process Integration (9/30/21):** Run the CO_2 electrolyzer integrated to a bioreactor to determine the CO inventory needed to maintain carbon requirements of the bioreactor. Determine the minimum and maximum CO concentration that can maintain the microorganism production rate over a 100-hour test period. Determine the minimum electricity cost and carbon intensity of the process.