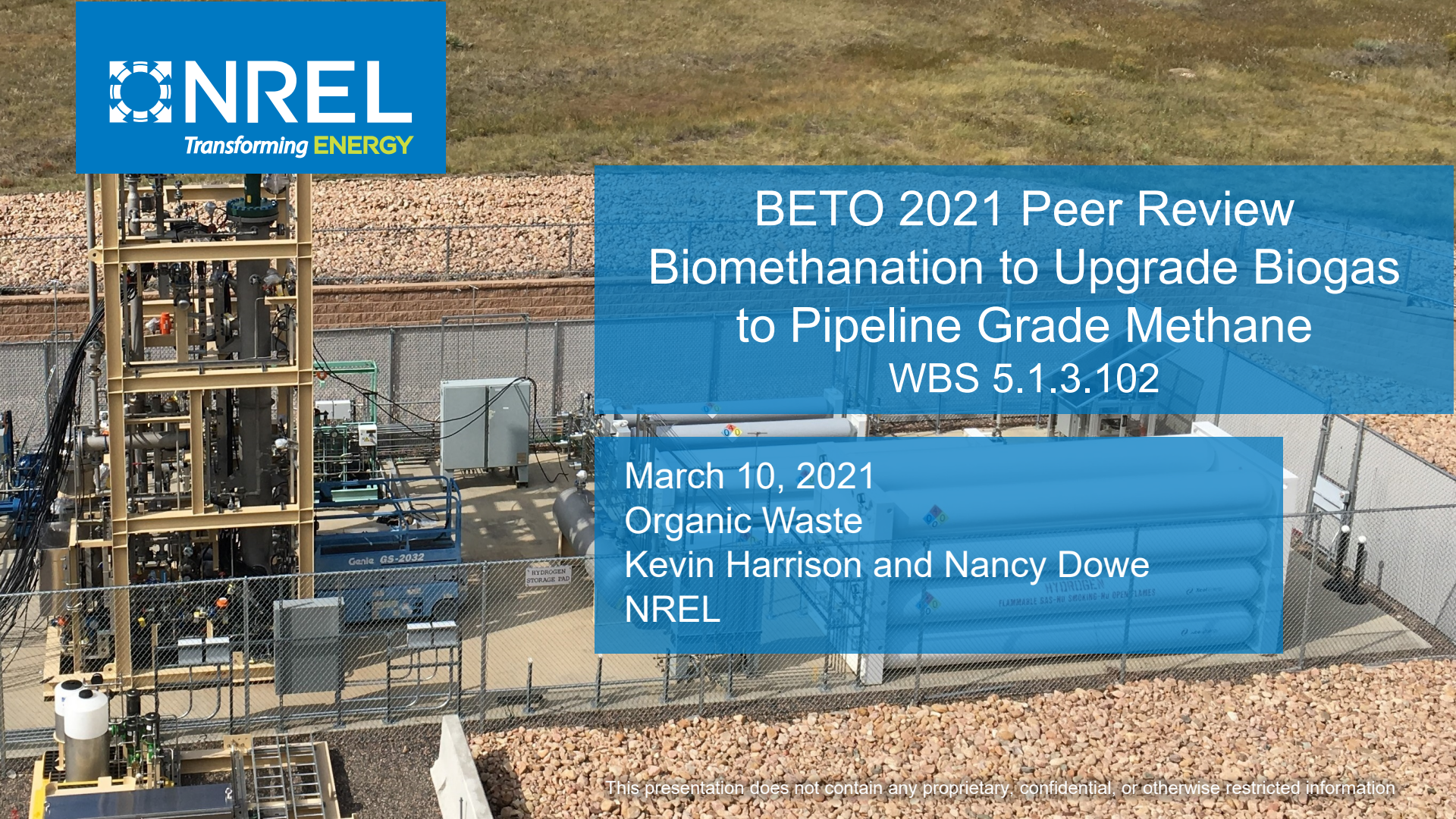


NREL
Transforming ENERGY

BETO 2021 Peer Review
Biomethanation to Upgrade Biogas to Pipeline Grade Methane
WBS 5.1.3.102

March 10, 2021
Organic Waste
Kevin Harrison and Nancy Dowe
NREL

Project Overview

What are we trying to do?

Goal: Develop, innovate, reduce costs and de-risk the biomethanation (Power-to-Gas) process to upgrade biogas sources to pipeline quality natural gas for long-duration energy storage and decarbonization of the transportation sector

How is it done today? Renewable natural gas (RNG) is typically produced from biogas using energy intensive separation technology – keeping the CH_4, but venting the CO_2

Why is it important? This technology upgrades the CO_2 portion of biogas in addition to keeping the CH_4 using natural organisms

What are the risks? Process intensification and scaling of renewable electricity sources and renewable hydrogen technologies require cost reduction at meaningful (utility) scale

The biomethanation process $CO_2 + 4\ H_2 \xrightarrow{\text{Biocatalyst}} CH_4 + 2\ H_2O + \text{Heat}$

Project Overview & History

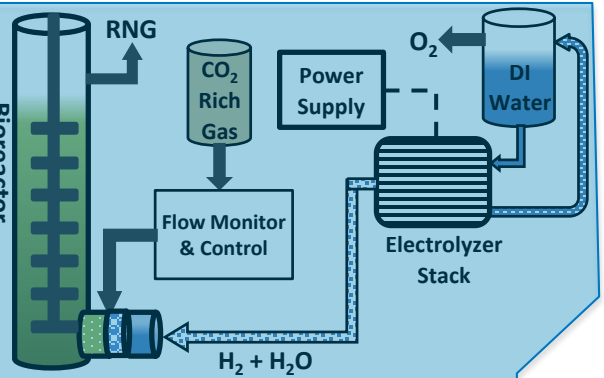
SoCalGas/SETO – Power-to-Gas (P2G)
ESIF-DOE Grid Integration High-Impact Project

Partner: Electrochaea GmbH
CRD 14-567 - Ended in FY20

P2G: Working with partners, design, develop controls, install, commission and characterize 700L bioreactor system from SoCalGas

Electrolyzer/Bioreactor Integration (EBI)
BETO, HFTO and SoCalGas
Partner: Dr. Metz – U of Chicago
CRD 19-809 – Executed in August 2019

EBI: Develop advanced gas mixing and water management techniques to improve hydrogen mass transfer and directly-coupling electrolyzer with bioreactor to advance IP

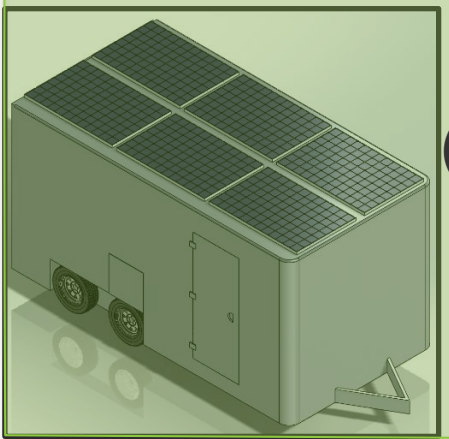


EBI (2.3.2.700)

Biopower BETO/SoCalGas/Electrochaea
CRD 18-775 – Executed July 2020
Biopower: Upgrade biogas waste streams to pipeline quality RNG

Biopower: TEA, LCA, analytical, mobile scale-down of bioreactor and field trials

New Funding Biopower Task 1: Provide R&D to create blueprint with utilities with carbon intensity within existing carbon markets



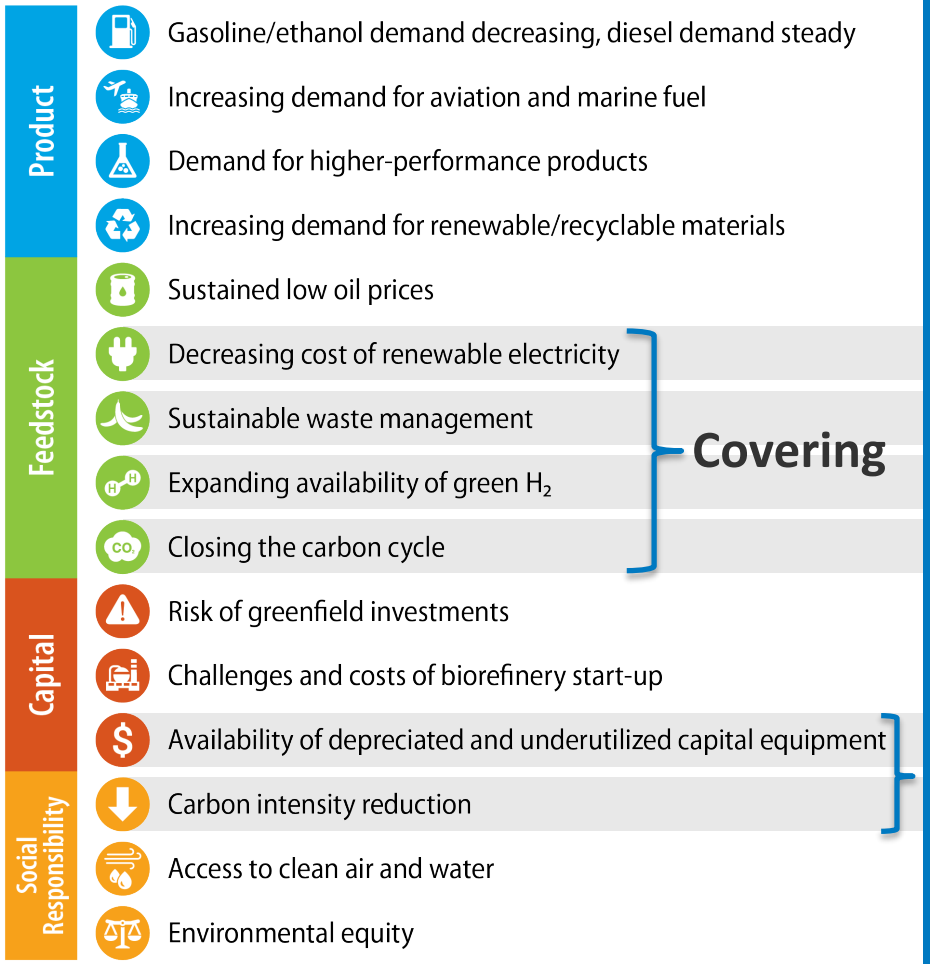
Biopower (5.1.3.102)

TSAs with Summit Utilities, Portland General Electric, Jonah Energy and National Grid (pending)

NREL P2X Program Goal

Lead the U.S. in the advancement and deployment of CO_2 utilization, integration with renewable electricity, hydrogen systems integration and bio-derived high-value products

Market Trends



NREL's Bioenergy Program Is Enabling a Sustainable Energy Future by Responding to Key Market Needs

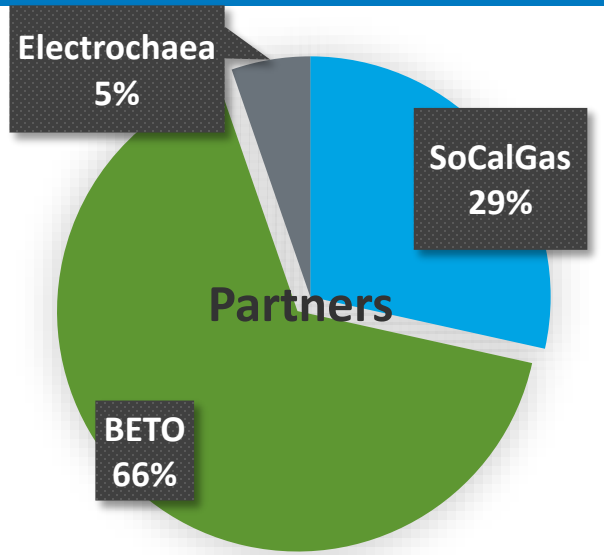
Value Proposition

- Biomethanation can produce a zero to net-negative carbon fuel from waste CO_2
- Sector coupling technology (P2X, E2M)
- Enables higher penetration of solar/wind electricity and accelerates deployment of green renewable hydrogen production

Key Differentiators

- Direct replacement fuel utilizing the existing natural gas infrastructure
- Minimal gas cleanup before pipeline injection
- Low-cost electricity and CO_2 feedstocks

1. Management



(1000 dollars)	SoCalGas	BETO	Electrochaea
*FY20	$602	$628	$57
FY21	$22	$400	$32
FY22	$22	$472	$32
Contributions	$645	$1,700	$120

*Funded in FY19 – Project started FY20

- Project managed and scheduled by PIs at **NREL**
- **SoCalGas** provides guidance for market and commercial deployment
- **Electrochaea** provides design, process development and operational support leveraging their experience at BioCat

Overall Project Total $2.85M

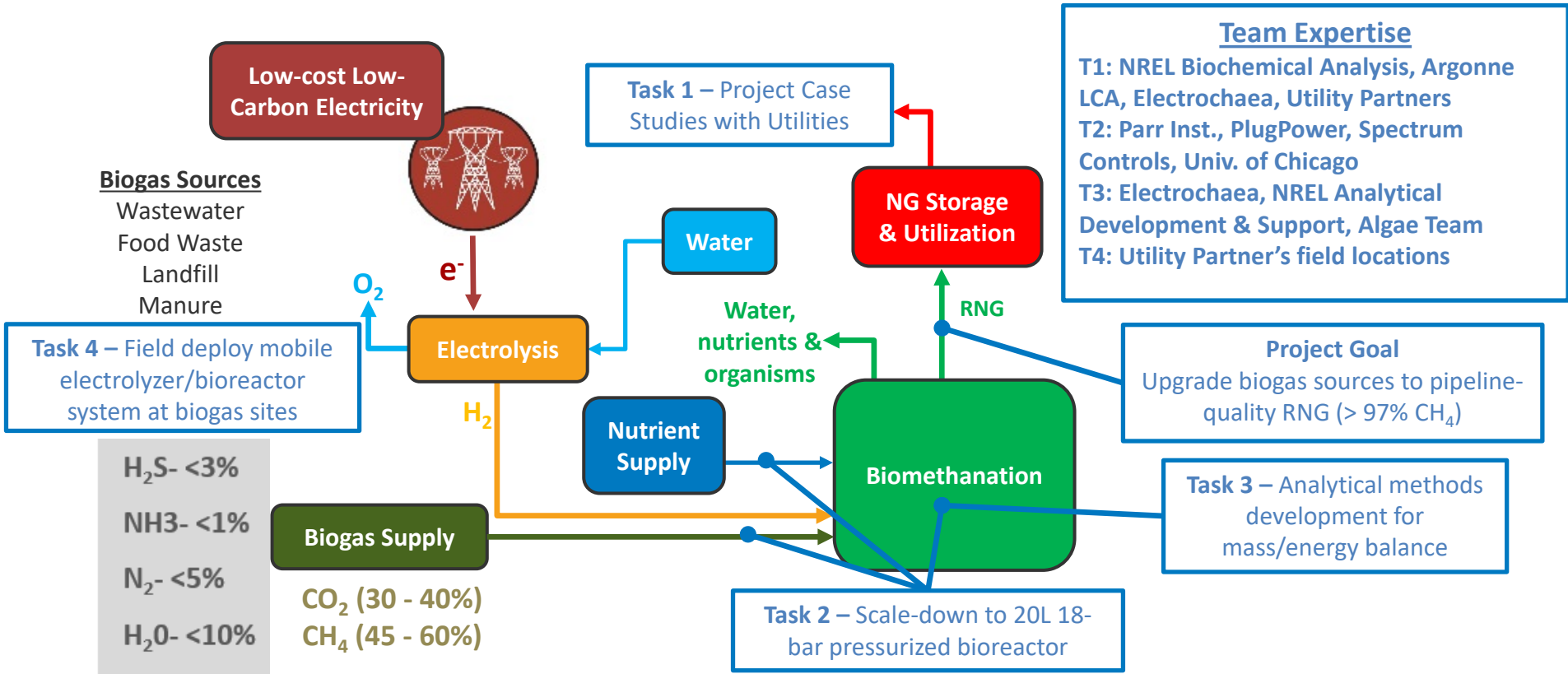
- $580K bioreactor (of $3M cost to SoCalGas)
- $25K Licensing Fee for the organism

Project Management

- Standing bi-weekly calls with partners
- New P2G quarterly with wide group of stakeholders, including new utility partners

1. Management

P2G - The biomethanation process: $CO_2 + 4\ H_2 \xrightarrow{\text{Biocatalyst}} CH_4 + 2\ H_2O + \text{Heat}$



Team Expertise

T1: NREL Biochemical Analysis, Argonne LCA, Electrochaea, Utility Partners
T2: Parr Inst., PlugPower, Spectrum Controls, Univ. of Chicago
T3: Electrochaea, NREL Analytical Development & Support, Algae Team
T4: Utility Partner's field locations

2. Approach – Work Breakdown: Tasks 1 - 4

Focused on Systems Integration to Reduce Costs

Task 1: Complete a technical feasibility and carbon-market based blueprint for utility-scale deployment of hydrogen-to-biomethanation for RNG production

- **Challenge/Opportunity: What's the business case for RNG in light of existing carbon markets and region-specific use cases for the product?**

- **Task 2:** Develop scientifically-based scaling functions using a scaled-down bioreactor that can operate at pressures up to 18-bar, temperatures up to 70C and capable of upgrading gas mixtures containing CO_2, CH_4, H_2 and H_2S in order to understand the effects of gas mixing and the organism's productivity.
  - **Challenge: Improve organism productivity through pressure, gas mixing and bioreactor design.**
- **Task 3:** Develop analytical methods for mass balances (e.g., C, N, S, H and P) to guide nutrient additions and look for potential co-products produced by the methanogens.
  - **Challenge/Opportunity: How can critical nutrient additions be optimized to reduce operating costs and inform TEA/LCA? If cell mass is not retained in the bioreactor, is there a co-product opportunity for discarded cells?**
- **Task 4:** Deploy mobile R&D electrolyzer/bioreactor platform at utility partner field locations to demonstrate upgrading biogas to pipeline quality RNG.
  - **Challenge: Upgrading different compositions of biogas feedstocks at field locations with different infrastructure.**

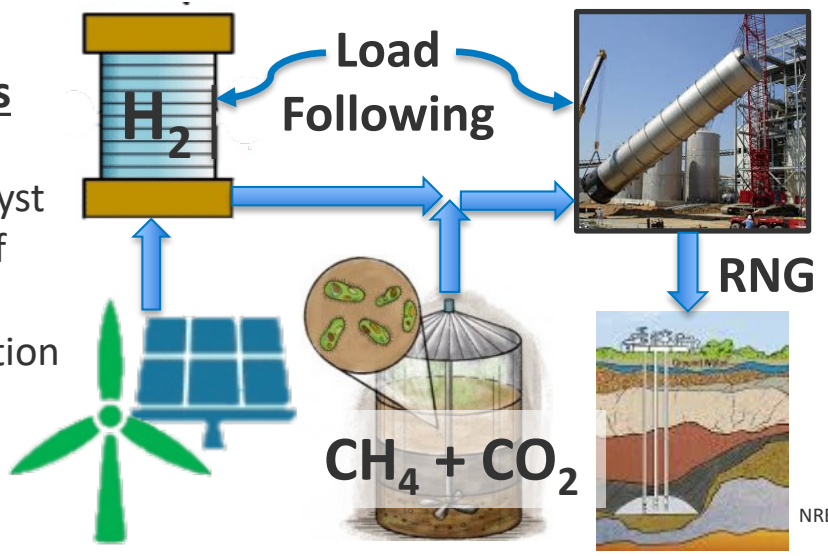
3. Impact

Impact on state-of-technology and industry

- **Provides long-duration energy storage** of low-cost, low-carbon electricity in the form of molecules
- **Recycles CO_2 waste streams** to produce a carbon-neutral to carbon-negative fuel (RNG) to start decarbonizing transportation, heat and power sectors **at meaningful scale**
- Improvements in bioreactor design, NREL IP and dosing systems will **improve biocatalyst productivity and reduce cost**
- Upgrading CO_2 from biogas digesters to methane **nearly doubles digester CH_4 output over separation technology**

Industry engagement/commercialization plans

- Partnerships with utilities (SoCalGas, Summit, Portland General Electric, Jonah Energy), biocatalyst developer Electrochaea, water management U. of Chicago, and compressor technology Sundyne
- Near-term plans to build a U.S.-based demonstration system at a biogas facility to inject RNG into a pipeline for **RIN and LCFS pathway qualification needed for commercialization**



3. Impact

Intellectual Property & Patent Applications

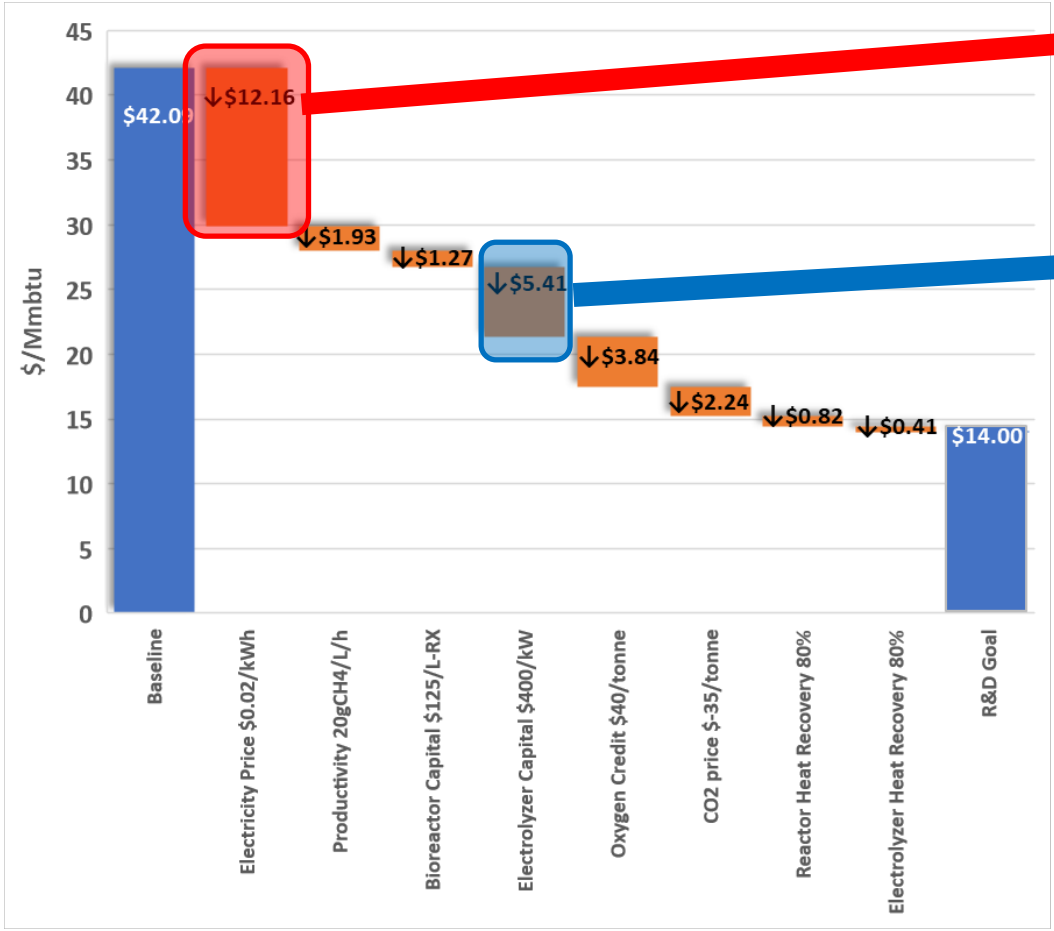
- IP development to reduce electrolyzer capital costs, improve system efficiency, and improve safety
  - PCT application corresponding to NREL ROI No's. 18-48 and 18-48A, Application No. PCT/US19/42861 (7/2019)
  - SoCalGas entered into licensing agreement with NREL (5/2020)
  - U.S. provisional patent application corresponding to NREL ROI No. 19-140, Application No. 63/063,000 (8/2020)

Communication and Outreach

Mobile system design, specification and procurement (2020), fabrication and commissioning (2021) and field trials at partner biogas sites (2022)

- https://www.powermag.com/why-power-to-gas-may-flourish-in-a-renewables-heavy-world/
- https://denver.cbslocal.com/2019/03/03/nrel-archaea-renewable-natural-energy/ *(CBS Video)*
- https://www.greentechmedia.com/articles/read/are-ancient-bugs-the-key-to-storing-wind-and-solar *(podcast)*
- https://www.epa.gov/natural-gas-star-program/2019-renewable-natural-gas-workshop

4. Progress and Outcomes – Pathway to $14/MMBTU



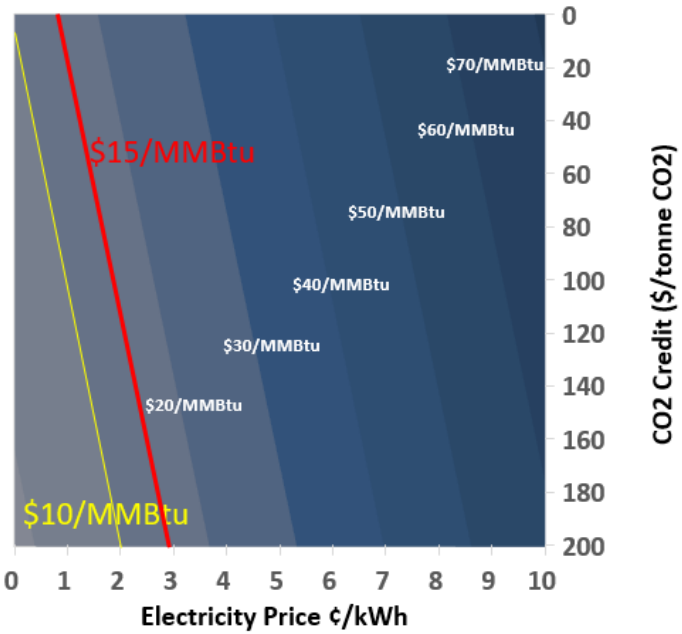
1. **Low-cost renewable electricity ($0.04→$0.02/kWh)**
2. Increase CH4 productivity (13g → 20g CH4/L-h)
3. **Decrease electrolyzer capital cost ($750/ kW→ $400/ kW)**
4. Decrease bioreactor capital cost ($185 /L-RX → $125/L)
5. Oxygen Credit ($0 → $40/tonne)
6. Carbon Credit ($0 → $-35/tonne)
7. Reactor Heat Recovery (0% → 80%)
8. Electrolyzer Heat Recovery (0% → 80%)

NREL TEA Production Costs & CA LCFS for RNG

Near-future scenario assuming;

Electrolyzer cost of $400 / kW

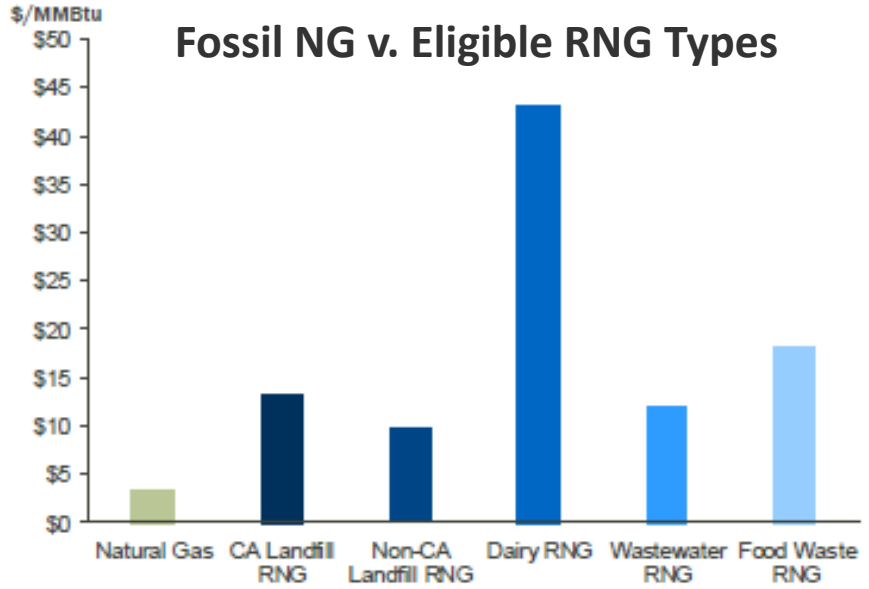
Productivity of 20g CH_4 / L-hr



WBS#5.1.1.102 Biopower analysis NREL

WBS#5.1.1.101 Biopower analysis ANL

Estimated LCFS Credit Value of Fossil NG v. Eligible RNG Types



Source: California ARB LCFS credit price and CI values, MJB&A analysis. LCFS credit price $155/MT. CI values: NG 74.1, CA Landfill 11.3, Non-CA Landfill 33.5, Dairy -178.6, WWTP 19.3, Food waste -19.1.

4. Progress and Outcomes –Task 1 Utility Case Studies

The business case for RNG using existing carbon markets and region-specific use cases

- Utility partners include SoCalGas (CA), Summit Utilities (ME), Portland General Electric (OR), Jonah Energy (WY) and National Grid (NYC, pending)
- Argonne National Laboratory assisting with carbon intensity pathway analysis
- NREL developing TEA for case studies which include feedstock supply and cost, sit evaluation, capital, and market evaluation

Highlight - Summit Utilities

- The goal of the project is to deploy technology to utilize Maine's curtailed renewable energy
- Two case options (plus combination option):
  - P2G using PEM electrolyzer, providing H_2 to support chemical, transport, other
  - P2G / Methanation, using CO_2 from digester, creating an additional ~100,000 MMBTU/year, or ~35% of residential load

75,000 MWh of curtailed renewables per year

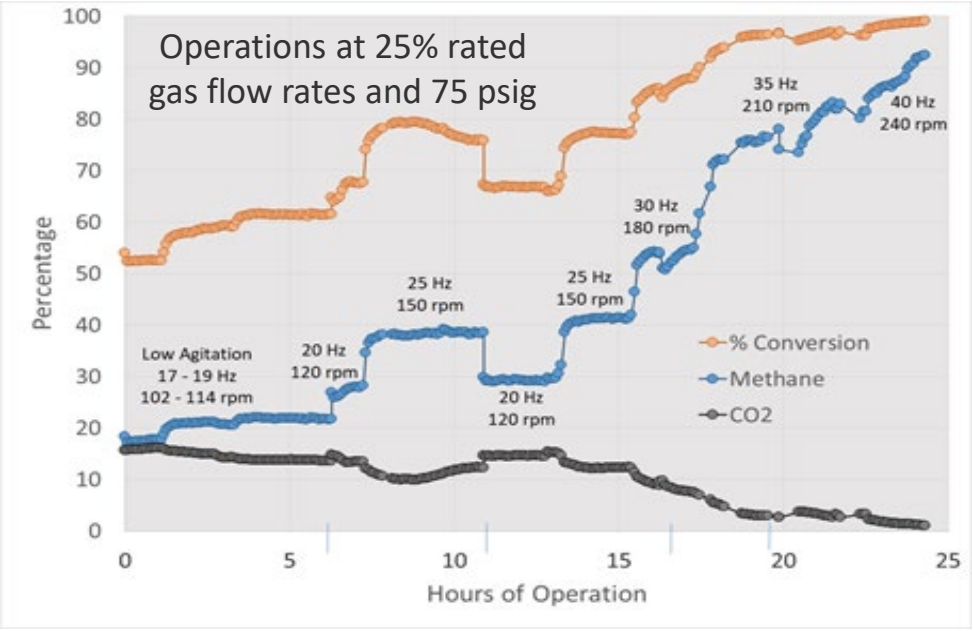
Summit Natural Gas MAINE

New England may be the most viable location for a pilot P2X project. ISO-NE predicts that up to 10% of Offshore Wind will be curtailed by 2030. In just one location, Maine is curtailing ~75,000 MWh of renewables in one year.

4. Progress and Outcomes – Lessons Learned 700L

700L Commissioning Data

1. Showing ramp to 98% conversion of CO_2 to CH_4 within first 24 hours of operation (below)
2. Data highlights the importance of gas mixing
3. Agitator step changes show fast response, repeatability and ability to load follow



Lessons Learned
Informing Scaled-Down System Design

1. Culture circulation returned below liquid level
2. New dosing trials show improved accuracy and repeatability with HPLC pumps (below)
3. pH probes will be installed in 20L vessel
4. Anti-foam addition improved with top entry on scaled-down vessel

Expected Volume (ml)	Graduated Cylinder Measurement (ml)	Pressure (psig)	% Error
2.0	2.0	300	0%
2.0	2.0	50	0%
2.0	2.0	50	0%
2.0	2.0	300	0%
2.0	2.0	150	0%
6.0	6.0	300	0%
3.0	3.0	300	0%
2.0	2.1	300	5%
2.0	2.0	300	0%
2.0	2.0	300	0%
2.0	2.0	300	0%

0.05 mL/min
11 trials
540 min.
0.4% error

4. Progress and Outcomes – Task 2: Scaled Down Bioreactor Vessel Design Basis

Future Work: Sight glasses to study gas mixing, H_2 mass transfer and bubble dynamics using UHS camera up to 1,000,000 frames per second

20L 18-bar Design Basis

- 7.5 ft. height inside trailer
- Vessel: 5'3" T x 6" OD
- Agitation capable of 900 rpm
- Magnetically-coupled agitator w/o pressurized seal-pot
- Diagnostics: Dissolved H_2, pH, Redox, temperature and pressure
- Improved dosing pumps with flowmeter feedback (qualitative)
- 20 kW electrolyzer (0.3 kg H_2/h)
  - Low-cost balance of plant (EBI)

700L 18-bar SoCal Gas Bioreactor

- 125 kW electrolyzer (2.7 kg H_2/h)
- Vessel: 18' T x 18" OD
- 0.25 MMBTU/h methane flowrate

Quad Chart Overview

Timeline

Start: October 1, 2019 (CRADA executed 7/2020)
End: September 30, 2022

	FY20	Active Project
DOE Funding	(10/01/2019 – 9/30/2020) $600K	$1.7MM
Project Cost Share	SoCalGas - $602K Electrochaea - $57K	SoCalGas - $645K Electrochaea - $120K

Project Partners

- Southern California Gas Company
- Electrochaea GmbH

Project Goal

Advance the science and reduce the cost of the biomethanation process using waste CO_2 from biogas and renewable H_2 feedstocks through systems integration, and improved hydrogen mass transfer for utility-scale commercialization

End of Project Milestone

Demonstrate continuous operation of scaled-down 20L bioreactor at pressures up to 18-bar using biogas feedstock to produce a product gas composition of >97% CH_4, <3% CO_2, <0.2% O_2 and <4 ppm H_2S

Barriers

Ct-H: Gas Fermentation Development

Funding Mechanism

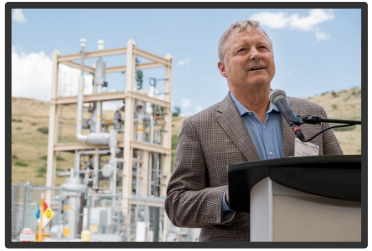
Lab Call – Biopower R&D (DE-LC-000L045)
Topic Area – Biological Biogas Clean-Up (2018)

Summary

1. **Management:** Cross-functional diverse team consisting of University, technology providers, utility partners, national labs, and multiple research disciplines
2. **Approach:** Focused on systems integration, business case studies with multiple utility partners, design, build and deploy a mobile RD&D bioreactor system to validate upgrading of different biogas feedstocks
3. **Impact:** Patent applications and licensing IP, address utilities goal to decarbonize the NG network while enabling increased renewable electricity penetration, and provide a cross-sectoral power-to-gas drop-in direct replacement for fossil NG
4. **Progress & Outcomes:**
   - Lessons learned from 700L operations informed scale-down 20L mobile bioreactor design improvements
   - Bioreactor and dosing system design complete and in build phase. System operations by end of calendar year 2021 and field trials expected in 2022
   - Demonstrated improved reliability and accuracy of scaled-down dosing needed for stable biomethanation process control
   - Multiple funds-in utility partnerships formed to develop case studies and blueprint for large-scale (5 – 50MW) Power-to-RNG deployment

Southern California Gas Company
A Sempra Energy utility®

Electrochaea



Thank you!

Ron Kent **Doris Hafenbradl** **www.nrel.gov**

Team Members

- University of Chicago
- Argonne National Laboratory
- Spectrum Automation Controls
- NREL's Analytical Development and Support
- NREL's Algae Team
- NREL's Biochemical Analysis Team

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Additional Slides

Patents and Presentations

- International PCT application corresponding to NREL Record of Invention (ROI) No's. 18-48 and 18-48A
  - Application No. PCT/US19/42861 (7/2019)
- SoCalGas entered into exclusive licensing agreement for IP developed under ROI 18-48 (5/2020)
- U.S. provisional patent application corresponding to NREL ROI No. 19-140
  - Application No. 63/063,000 (8/2020)

- *Electrolyzer/Bioreactor Integration,* DOE Hydrogen and Fuel Cell Technologies Office, Annual Merit Review Poster Presentation, April 2020
- *Storing Renewable Electricity As Molecules: The Promise of Renewable Natural Gas & Hydrogen, Colorado Renewable Energy Society Webinar, August 2020*
- *Power-to-RNG, 2020 Virtual Fourth Annual RNG Workshop – American Gas Association, September 2020*
- Presented and provided virtual tour for NREL's Camp Cleantech during the Electrons-to-Molecules session on September 2020
- *Power-to-Renewable Natural Gas: Renewable Hydrogen & Biomethanation, A long-duration energy storage solution using recycled carbon dioxide and renewable hydrogen*, Wet Waste Workshop, October 2020
- *Introduction to Power-to-Renewable Natural Gas*, NREL's Investor Advisory Board, November 2020
- *Scaling Electrolyzer and Bioreactor Systems with Utility Support,* NREL's Science & Technology Committee, February 2021

Responses to Previous Reviewers' Comments

Weakness: It is unclear what novel research is being performed here. After looking through Electrochaea's web site it appears that all of the proposed work has already been done. The robustness of the catalyst could be evaluated in a chemostat being fed various $CH_4/CO_2/H_2S$ gas mixtures. (Approach)

Weakness: No mention of key technology/IP handoff with their industry partners. (Future Work)

- NREL Response: The R&D focus of this Biopower project has many facets; First, doubling the pressure over any of Electrochaea's bioreactor vessels should essentially double the amount of H_2 dissolved in solution, thereby doubling the methane production rate - H_2 mass transfer is the limiting factor. Secondly, creating a mobile research platform capable of visiting various biogas sources will provide new insight into organism/process tolerance of trace constituents not easily synthesized for a chemostat experiment in the lab. Finally, new intellectual property developed at NREL to improve capital cost, system efficiency and systems integration has pending domestic and international patent applications and SoCalGas has licensed the IP technology already.

Project Overview & History

- **SoCalGas & SETO CRADA** – Ended in 2020 – Final CRADA report submitted to SoCalGas
  - Power systems modeling and analysis
  - Design, safety, installation and commissioning of 700L 18-bar bioreactor at NREL
- **BETO Biopower - Upgrade biogas to pipeline quality RNG -** This project WBS 5.1.3.102 CRADA Executed July 2020 for 3 years.
  - Utility case studies to estimate carbon intensity
  - Mobile scaled-down bioreactor and balance of plant system design & build
  - Analytical development for mass/energy balance
  - Field trials at biogas sites
- **Electrolyzer/bioreactor Integration -** WBS 2.3.2.700 - CRADA Executed August 2019
  - SoCalGas, BETO and HFTO partnership
  - IP development
  - Electrolyzer design & build
  - Integrate in mobile system