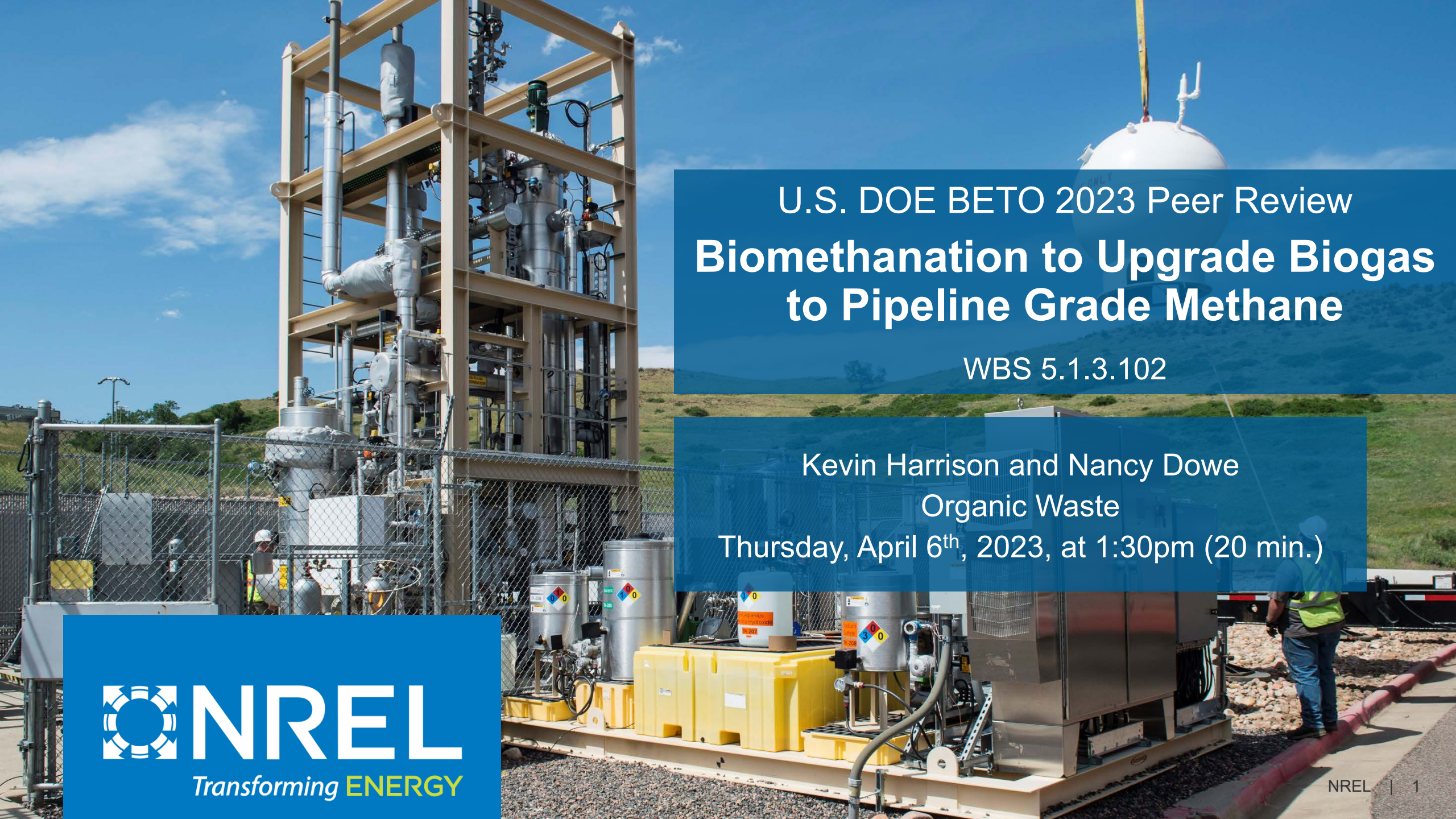


U.S. DOE BETO 2023 Peer Review

Biomethanation to Upgrade Biogas to Pipeline Grade Methane

WBS 5.1.3.102

Kevin Harrison and Nancy Dowe

Organic Waste

Thursday, April 6th, 2023, at 1:30pm (20 min.)

NREL Transforming ENERGY

Project Overview

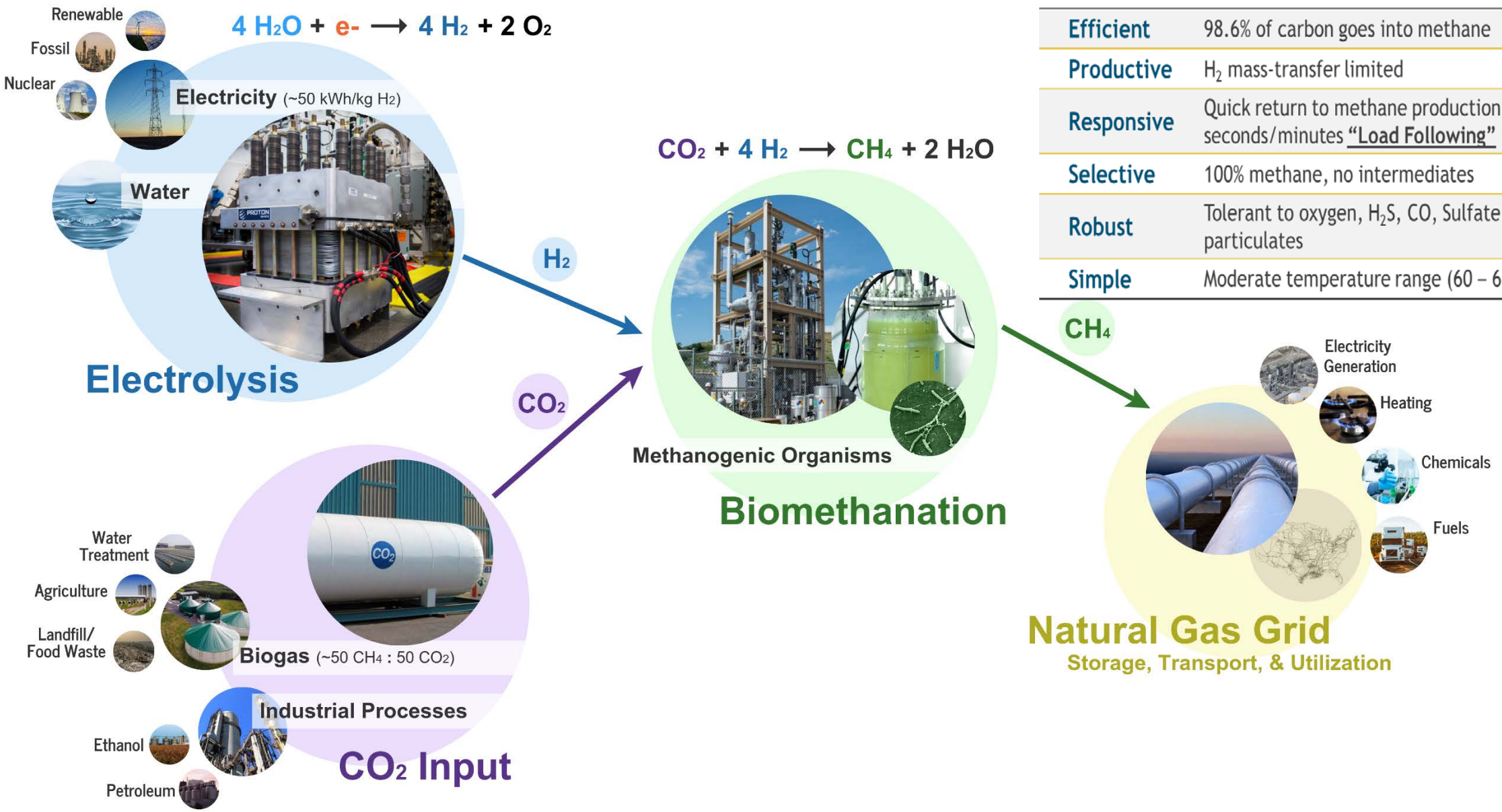
Goal: Develop, innovate, **reduce costs and de-risk the biomethanation (Power-to-Gas) process** to upgrade biogas sources to pipeline quality natural gas for long-duration energy storage and decarbonization of the transportation sector.

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

Why is it important? Upgrades CO_2 present in biogas using naturally-occurring organisms, **increasing production 60 – 70%.**

Relevance to DOE-BETO? Cross-programmatic gas fermentation (Ct-H) project with significant utility participation to advance hydrogen-at-scale, **organic waste-to-energy**, energy storage, and increases renewable electricity penetration.

Technology Description



Biomethanation Biocatalyst Is…

Efficient	98.6% of carbon goes into methane
Productive	H_2 mass-transfer limited
Responsive	Quick return to methane production within seconds/minutes **"Load Following"**
Selective	100% methane, no intermediates
Robust	Tolerant to oxygen, H_2S, CO, Sulfate, Ammonia, particulates
Simple	Moderate temperature range (60 – 65°C)

H_2 and RNG System at NREL

Electrolyzer System

- Today, 750 kW PEM stack
  - ~13 kg H_2 / hr
- 30 bar H_2 Pressure
  - Up to 70 bar max
- (4) Power Supplies
  - Current-sharing mode
  - 4000 A_{dc} at 250 V_{dc}

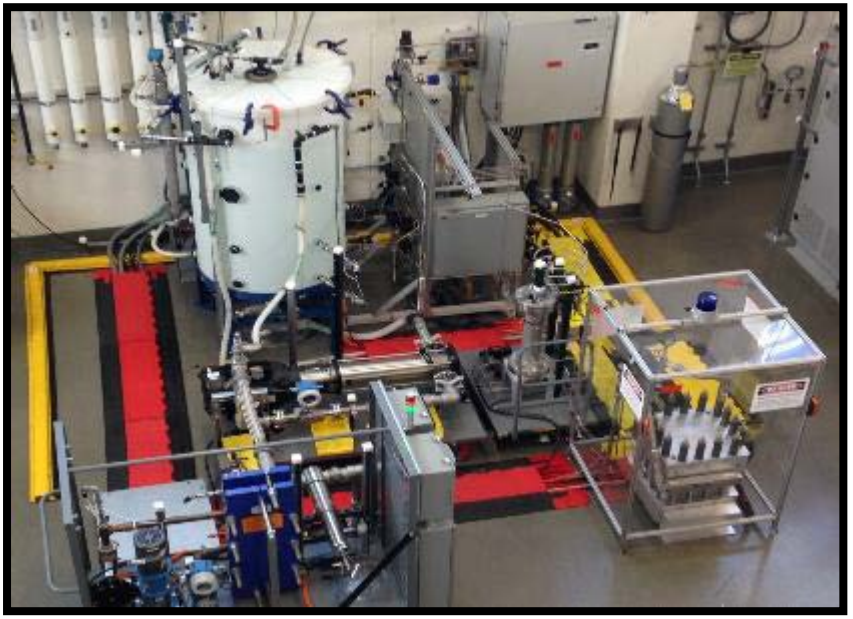
H_2 and RNG R&D Site

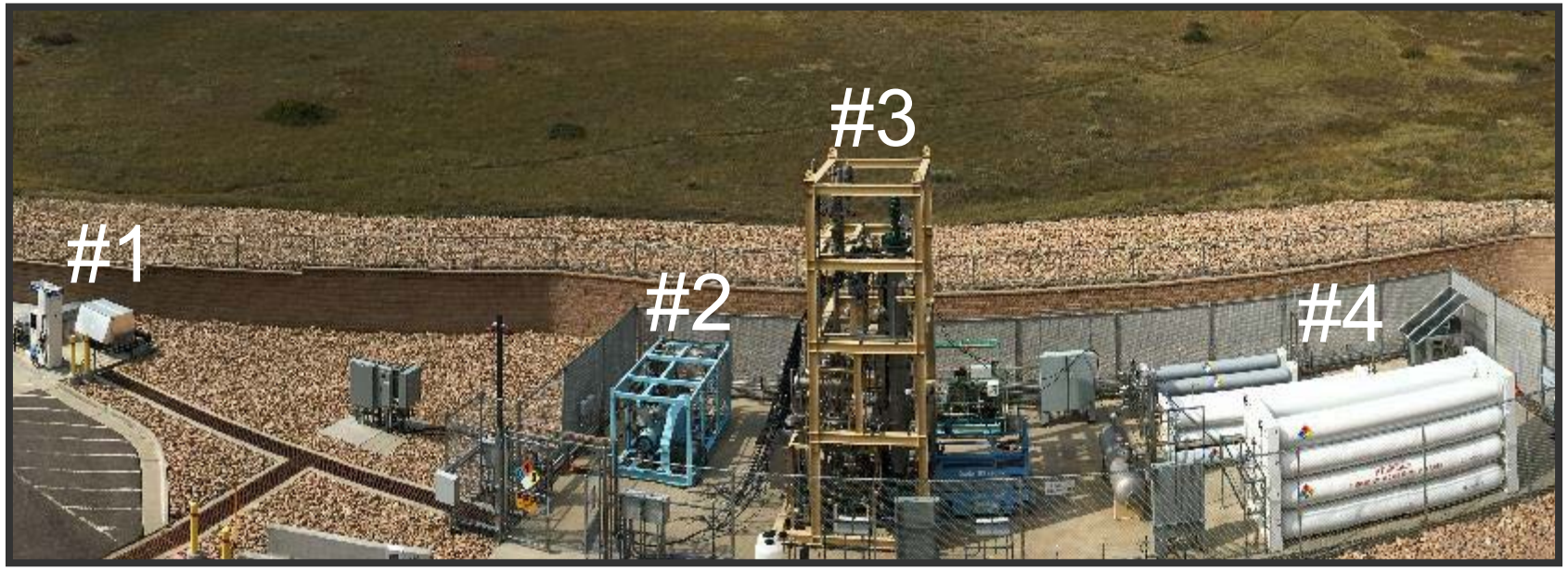
#1) 350 and 700 bar pre-cooled H_2 dispensing system

#2) Diaphragm and piston compressors

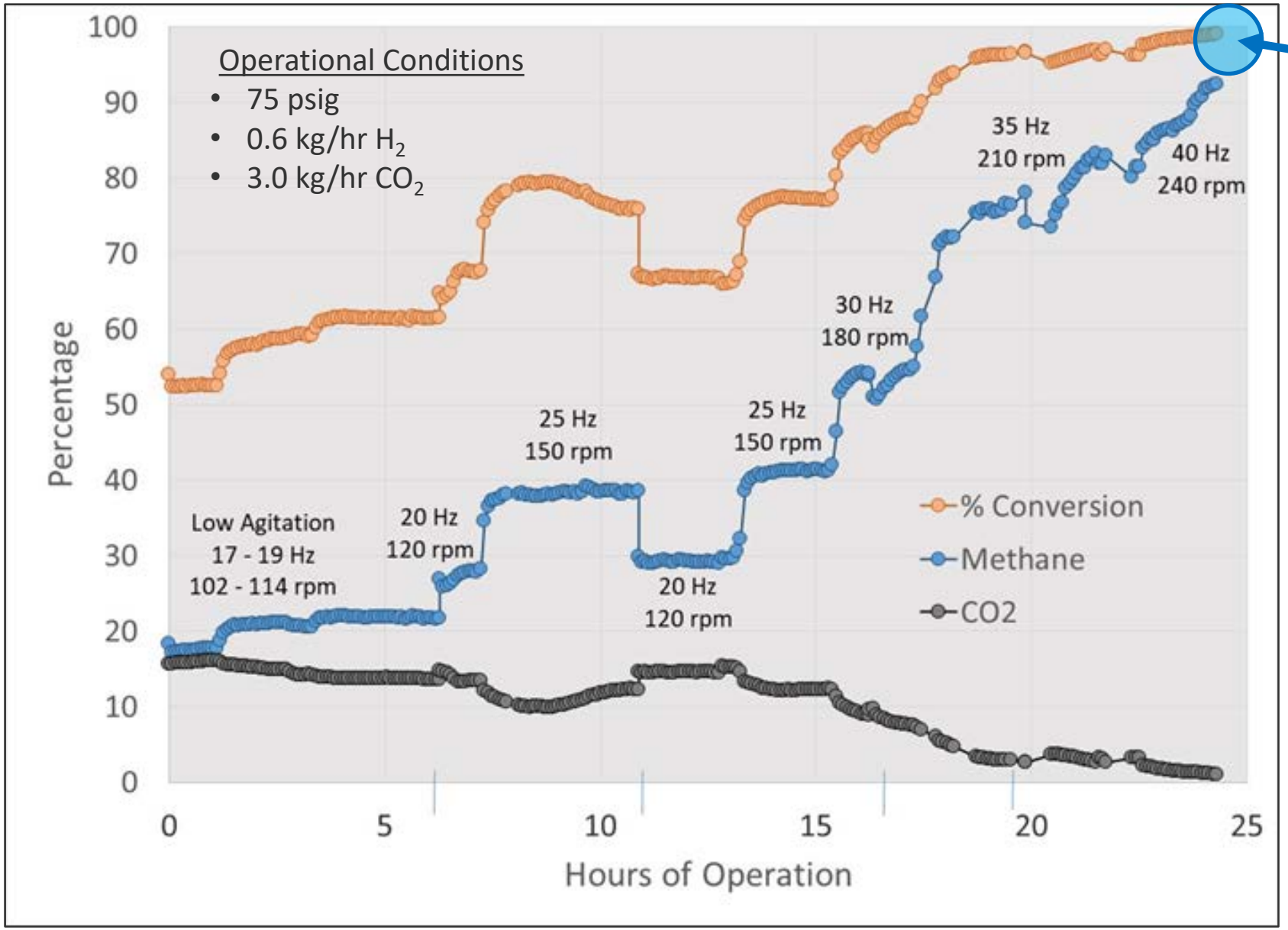
#3) 700 L bioreactor – operates at 18 bar (260 psig) and 60 - 65°C with agitation, recirculation loop and cell recycle + STORAGE at 350 bar

#4) 200, 400 & 900 bar storage - 625 kg Total





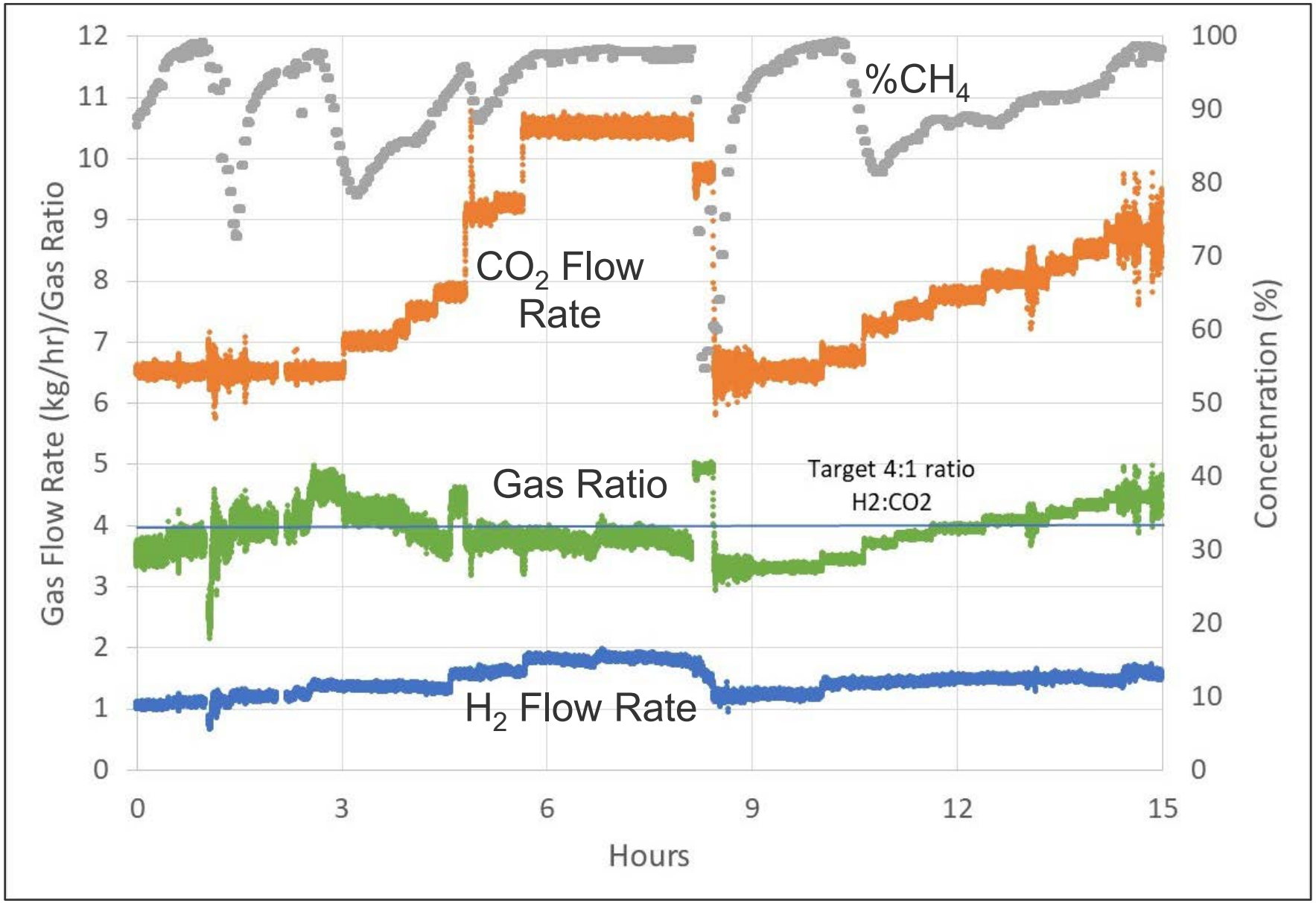
Operational Data from Commissioning 700L



Conversion reached 98%

$$\text{Conversion} = \frac{\%\ CH4}{\%\ CH4 + \%CO2}$$

Variable Gas Feeding "Load Following"

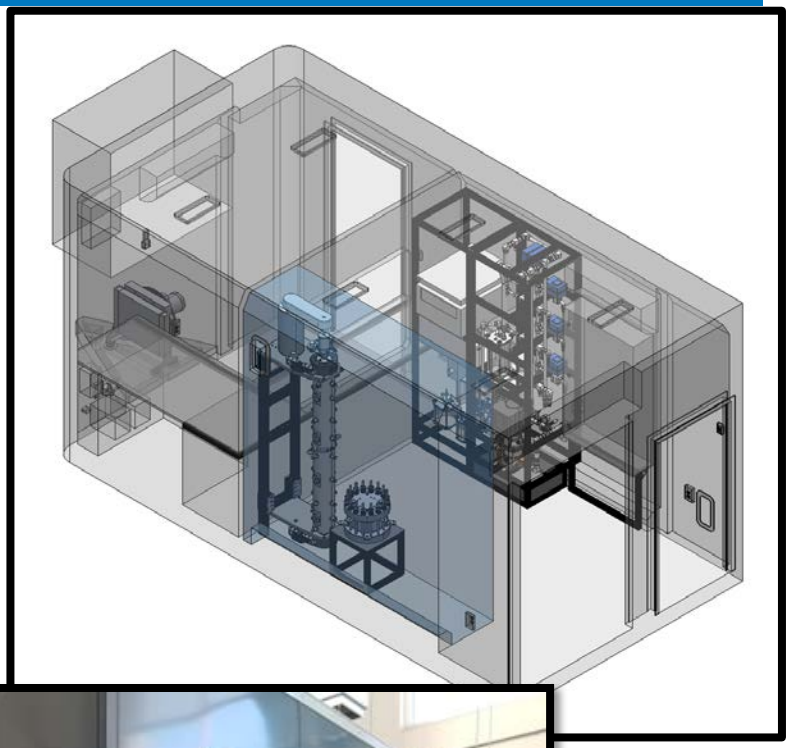


Operational Conditions

- Achieved 98% CH_4
- 130 psig, 60°C, pH 7
- Fast recovery when gas flows changed

1. Approach – Design-Build-Deploy

Research Objective to Design-Build-Deploy: Scale-down entire hydrogen-biomethanation system into **mobile RD&D platform** to enable faster research in the field, IP development & validation, and **improved gas mass transfer to reduce cost of RNG via biomethanation.**



- **Challenge:** Relocation of 700L bioreactor system is possible but costly while a mobile RD&D system opens new opportunities to conduct fast & flexible 'research in the field' on actual biogas (or other CO_2) sources.
- **Risk Mitigation:** Gas clean up requirements at biogas sites will vary. Smaller (20L) system will be easier to adapt and innovate to different gas clean up requirements and recover.
- **FY22 Q3 Milestone:** 3kW PEM electrolyzer system operation.
- **End of Project Goal:** Achieve at least 10 g CH_4 / L-hr productivity (20x improvement over baseline) and demonstrate a product **gas composition of > 95% CH_4, < 4% H_2, < 1% CO_2 < 0.2% O_2 and < 4 ppm H_2S** using the mobile bioreactor at a biogas source.

1. Approach – LCA

Research Objective: Determine carbon intensity of biomethanation produced RNG using dairy biogas and H_2 from electrolysis using a variable mix of renewable electricity from the CA grid

LCA: Worked with ANL to complete a **technical feasibility study** of RNG production using GREET and CA's LCFS assumptions to show **utility-scale deployment** opportunities for biomethanation.

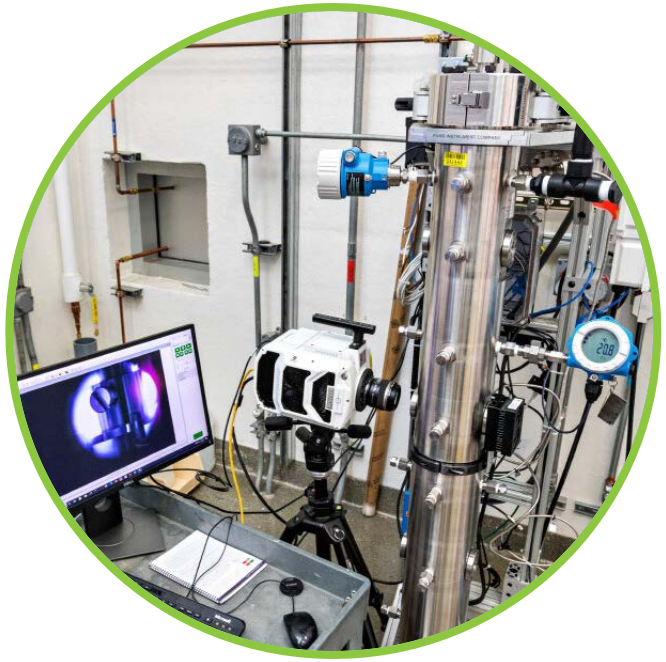
- **Challenges:** Biogenic CO_2 not credited under LCFS, distance from CA impacts carbon intensity, cost and CI of electricity for hydrogen production is the primary driver.
- **Metrics:** Cost and carbon intensity of RNG for transportation
  - A) Business as Usual, B) Gas Separations, and C) Biomethanation
- **Opportunity:** Inform **regional business cases for RNG production via biomethanation** versus gas separation.

Task Management

- **NREL –** Framed the analysis, assumptions, and provided TEA
- **ANL –** Using GREET model to perform LCA

https://www.bluesource.com/services/procure-renewable-energy/

1. Approach – Related Projects & Collaboration

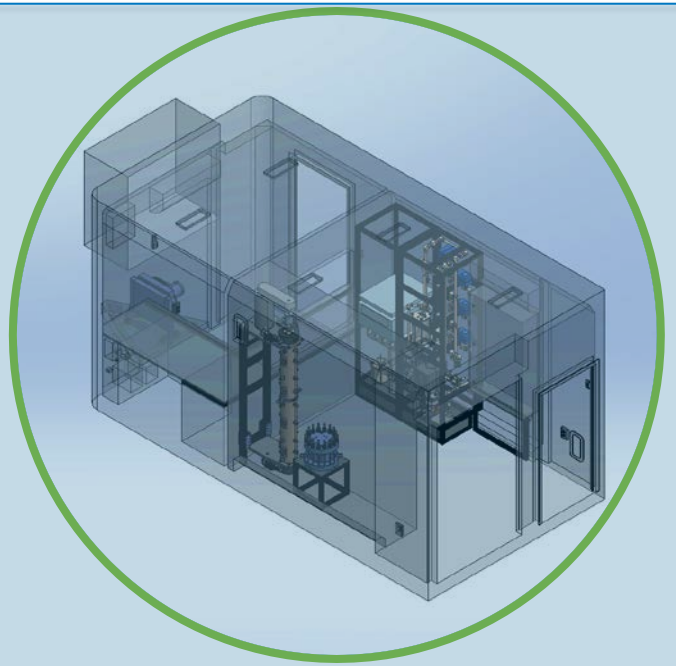


ELX/Bioreactor Integration

SoCalGas, BETO, HFTO, & University of Chicago

Close-coupling of electrolyzer and bioreactor to advance IP, advancing water management techniques, and improving hydrogen mass transfer with advanced gas mixing

WBS 2.3.2.700



Biopower

BETO, Electrochaea, & SoCalGas

Producing pipeline quality RNG from Biomethanation via 20L bioreactor on a mobile RD&D platform and collaborating with ANL to investigate CI from dairies with TEA/LCA

WBS: 5.1.3.102

Peaks Renewables

BETO, SoCalGas, Electrochaea, Plug, & CDM Smith

Supporting Summit Utilities/Peaks Renewables with successful deployment of CO_2 utilization, integration with renewable electricity & hydrogen, and biologically-derived high-value products

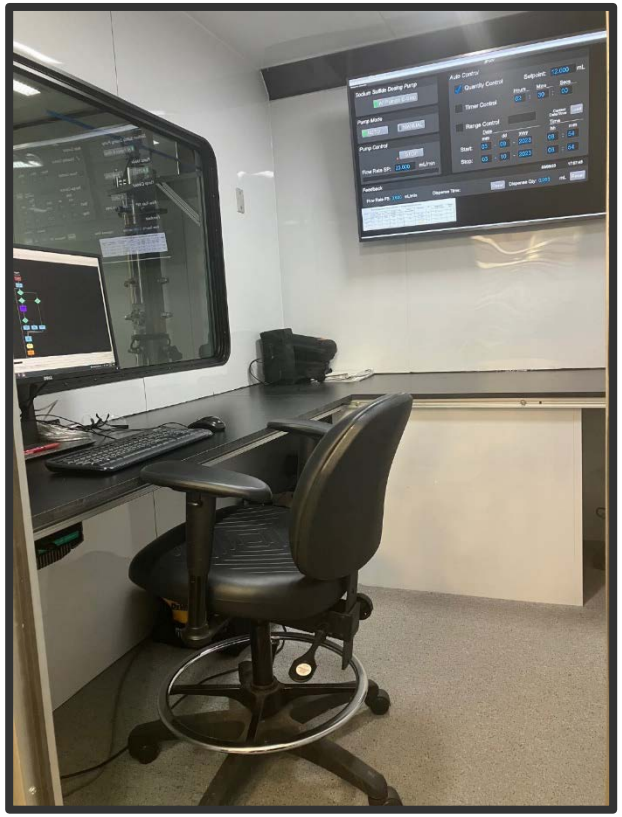
2021 Scale-Up Award

2. Progress and Outcomes – Mobile RD&D

Trailer and Control Room

16' Mobile RD&D

- 10' Test Bay, 6' Control Rm
- 100 cu. ft Class 1, Div. 2, Grp B & D
- Heat Pump for heating/AC



Control Room

- 55” monitor
- PC - data archiving and display
- 2kW/2kWh Back-up Power

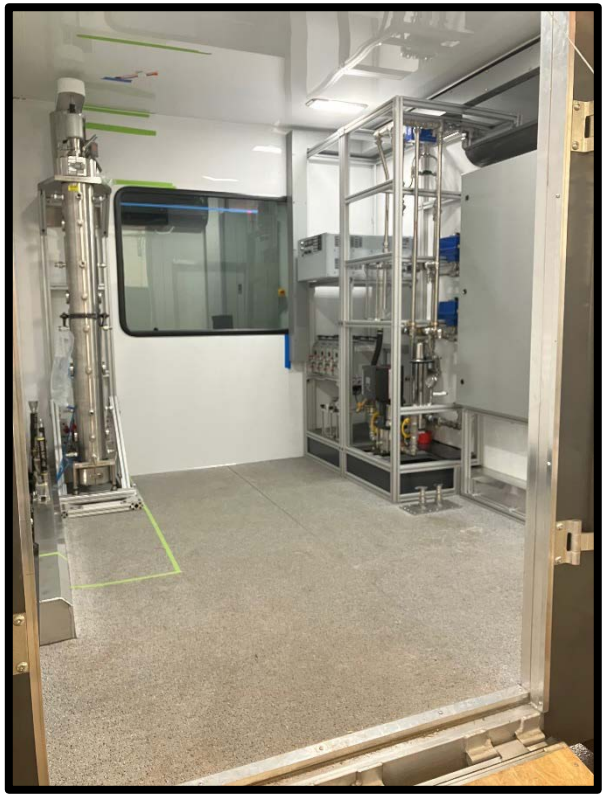
Power Center

- 208V, 3ph., 100A
- EPO x3
- Passed electrical inspection

2. Progress and Outcomes – Mobile RD&D

Research Bay with Installed Equipment

* Planned FY23



Research Bay

- Temperature Controlled
- Gas detection (H_2, H_2S, O_2)*
- Gas cleanup & chromatography*

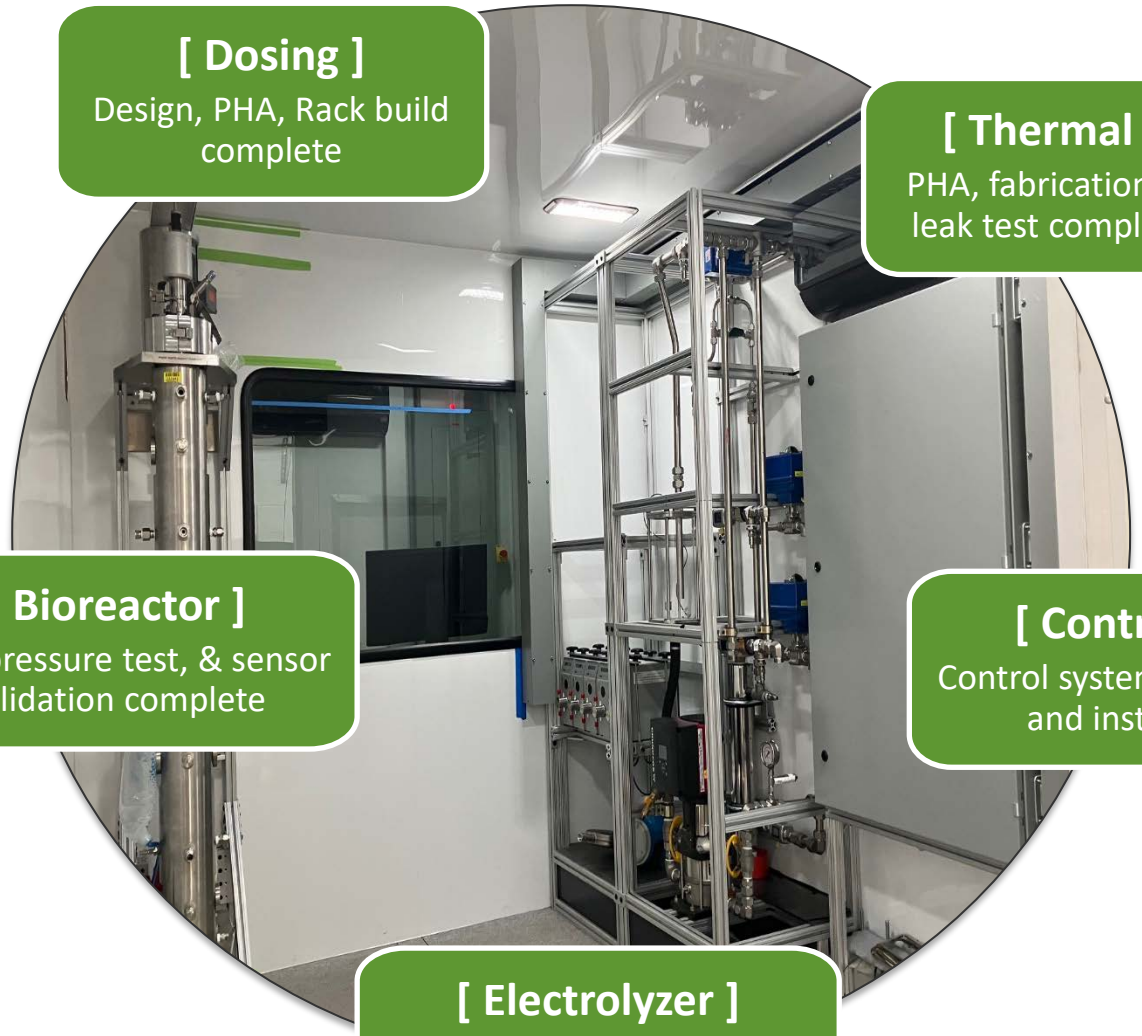
Bioreactor & Electrolyzer

- 20L, 18-bar, 1000 RPM agitator bioreactor
- 100 cu. ft. C1, D2, Grp BD enclosure*
- 3 – 25kW PEM electrolyzer (NREL IP)

Sub-Systems

- Dosing Rack, 5 PD pumps, Electrolyzer Power supply*
- Thermal (heating/cooling) rack

2. Progress and Outcomes – Mobile RD&D



[Dosing]
Design, PHA, Rack build complete

[Thermal]
PHA, fabrication, & leak test complete

[Bioreactor]
PHA, pressure test, & sensor validation complete

[Controls]
Control system procured and installed

[Electrolyzer]
Design Complete, PHA in Process, Q3 milestone

2021 Patent Applications

Application No. 17/261,473

Improving capital and operating costs of the electrolyzer

- 5 - 10% EL capital cost reduction
- 3 - 5% EL system efficiency improvement
- Advancement of operational safety via elimination of dissolved H_2 at EL anode

Application No. 17/397,665

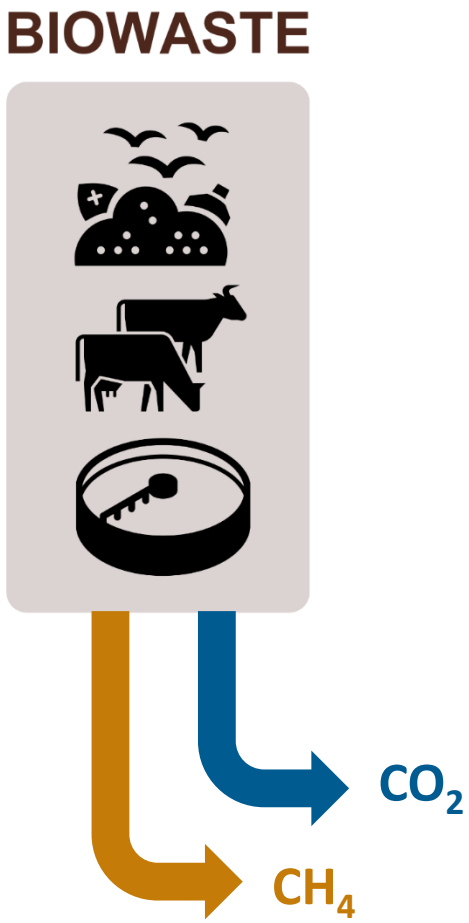
Using stack current for H_2 mass flow and gas ratio control

- Enhancement of mixed gas ratio control
- Improvement of H_2 mass transfer
- Elimination of H_2 mass flowmeter and flow control valve

2. Progress and Outcomes – LCA with ANL

CASE A: Business As Usual

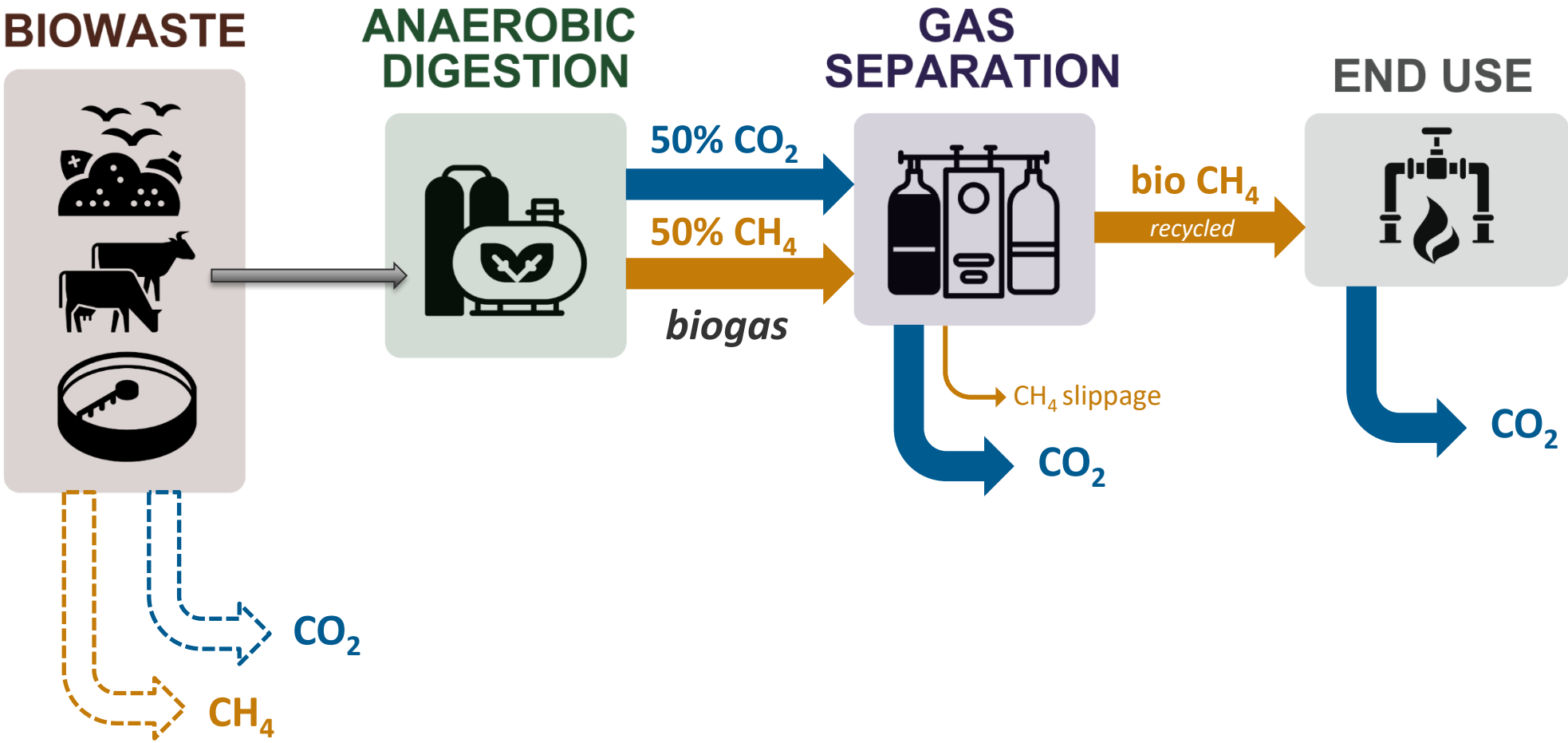
Waste streams produce CH_4 and CO_2 which are released into the atmosphere



2. Progress and Outcomes – LCA with ANL

CASE B: Conventional Biogas Separation

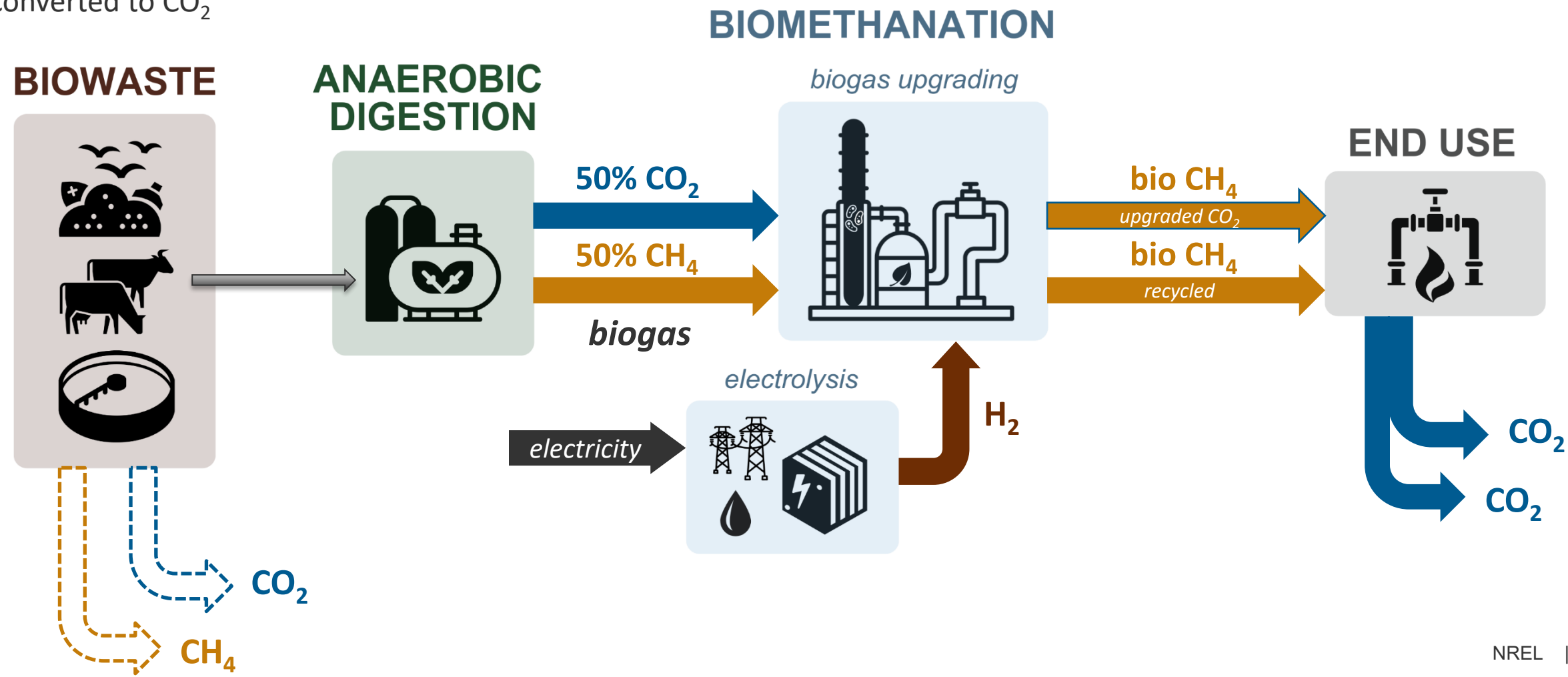
Initial CH_4 and CO_2 emissions are avoided: waste streams feed an anaerobic digester that produces biogas and conventional gas separation technologies separate the CH_4 and CO_2 . The CH_4 is captured and the and CO_2 is released into the atmosphere. At the end use, CH_4 is converted to CO_2



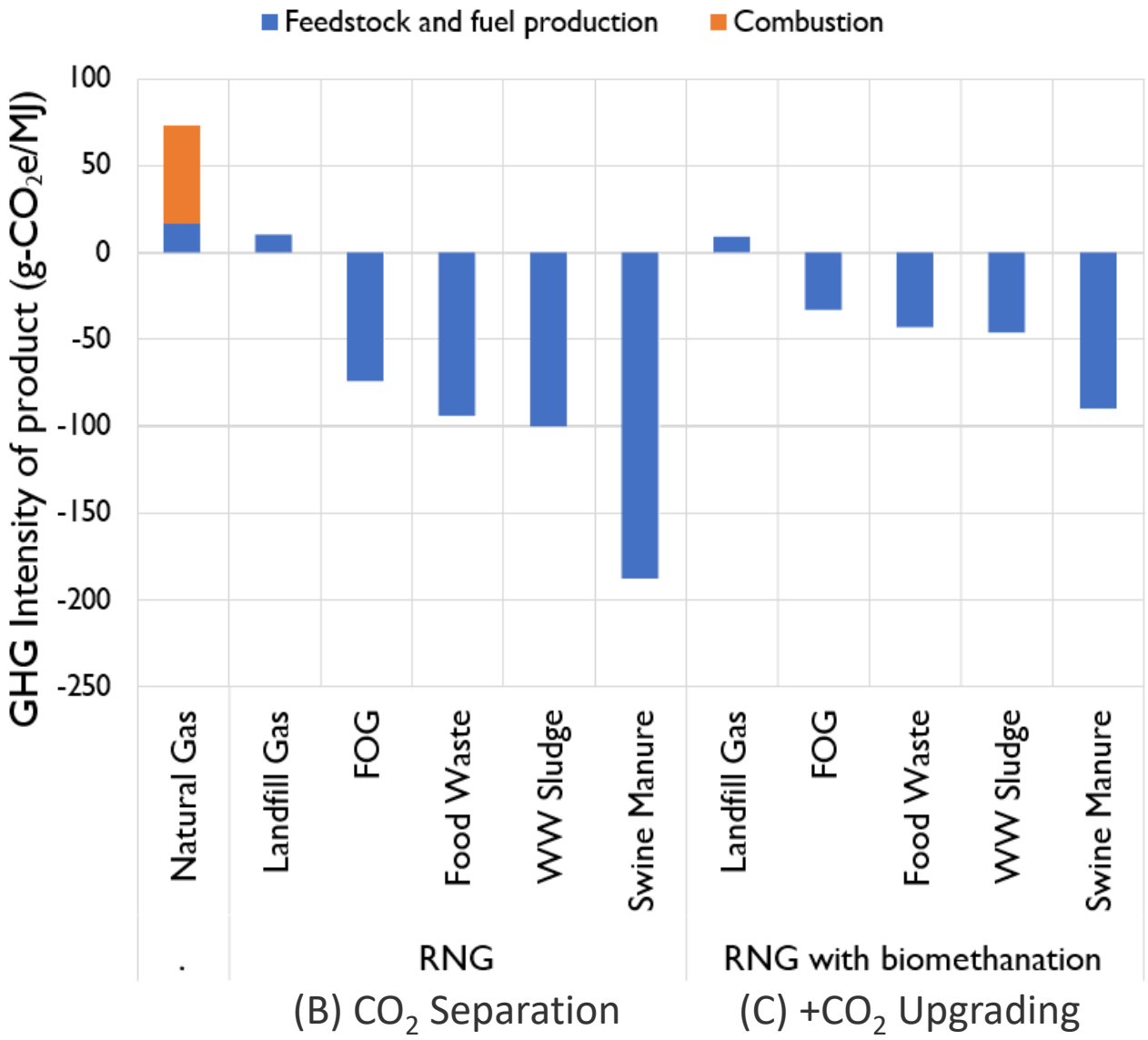
2. Progress and Outcomes – LCA with ANL

CASE C: Biogas Upgrading via Biomethanation

Initial CH_4 and CO_2 emissions are avoided: waste streams feed an anaerobic digester that produces biogas. With electro-chemical production of H_2 , biomethanation upgrades the CO_2 to CH_4 . All the CH_4 is captured and at the end use, CH_4 is converted to CO_2



2. Progress and Outcomes – LCA with ANL



- CI under RNG w/ Biomethanation is roughly cut in half due to 2x energy output.
  - Upgrading biogenic CO_2 to RNG does not count towards CI score under LCFS but may qualify for the Federal 45Q carbon tax program.
- RNG commodity sales with biomethanation would be twice that of gas separation technology.
- **Hydrogen production alone is not carbon negative but coupled with waste-to-energy can enable a negative CI.**

3. Impact

The Wall Street Journal predicted that RNG may make up nearly 30% of the total natural gas supply by 2040 compared to less than 1% today

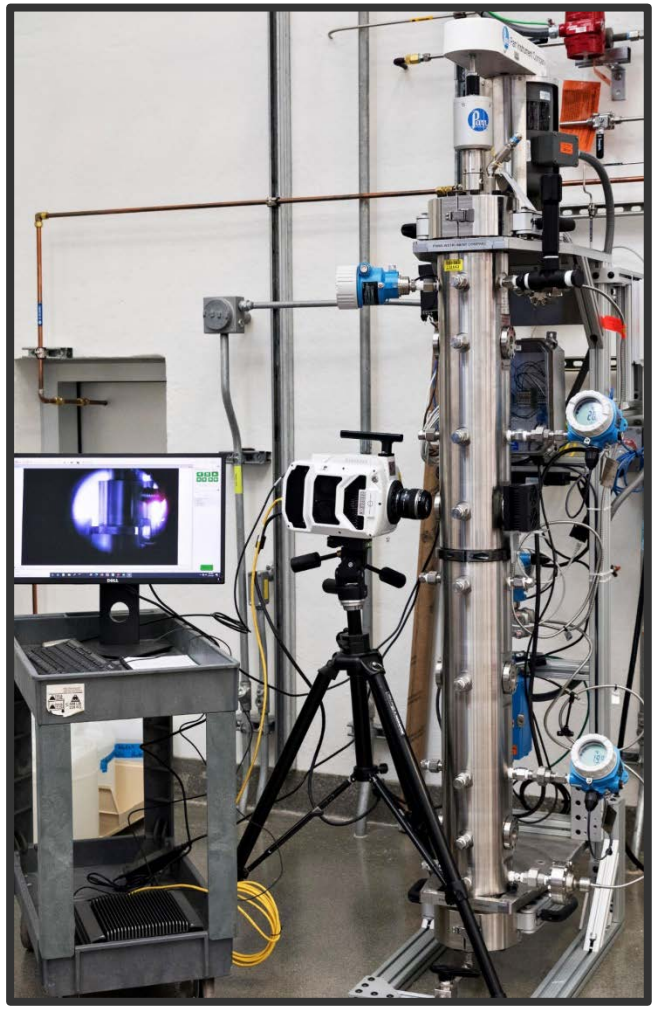
https://www.projectfinance.law/publications/2021/december/lcfs-credit-for-renewable-natural-gas/

Communication, Outreach, and DEIA

- Mobile RD&D system will bring the technology to the public (DEIA), stakeholders, develop partnerships, and serve as mobile laboratory (capability) for future electrons-to-molecules (C2+)
- 8 Industrial partnerships being developed, HFTO, FECM, 10+ invited presentations in 2022, 1 book chapter, and 2 filed patents

Innovation & Integration

- Deployment of mobile RD&D system and applying NREL IP will inform next-generation biomethanation system and drive down costs.
- Mobile system could become a platform to qualify various biogas sources under existing and future carbon markets.

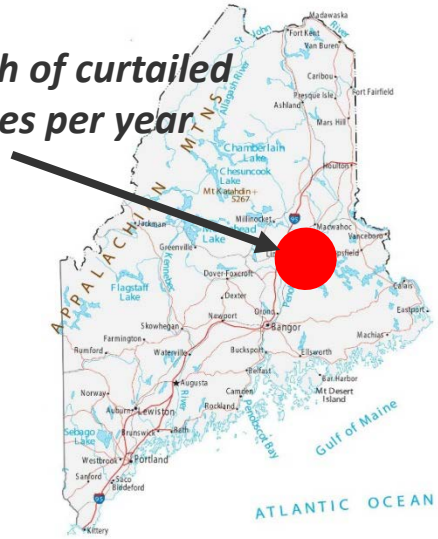


3. Impact – Commercialization

Maine Wants to Store, Not Waste, Excess Renewable Energy

https://www.governing.com/news/headlines/maine-store-not-waste-excess-renewable-energy.html

75,000 MWh of curtailed renewables per year



Partners

- SoCalGas
- Electrochaea
- Plug Power
- CDM Smith

Summit Utilities/Peaks Renewables

$10M - 2021 BETO Scale-Up Award

How is this project enabling success?

- Relocating 700L SoCalGas/NREL bioreactor system to diary digester in Clinton, ME accelerates timeline
- NREL IP data using mobile RD&D system to justify design improvements of pilot system

Existing Utility/Industry Partners

- SoCalGas (CA)
  - IP Licensed
- Electrochaea (DE)
- Summit Utilities (ME)
- Queen's University Belfast (UK)
  - IP License - pending

New Business Development

- Jonah Energy (WY)
- Endress + Hauser (CH)
- Carbon Creek (WY)
- Shell USA
- HACH and DuPont

3. Impact

1

Low-cost, Low-carbon Electricity

Utility scale solar PV and wind are cost-competitive with conventional fossil generation technologies when considering unsubsidized levelized cost of electricity (LCOE)

2

Waste-to-Energy

Biomethanation via the 13,500+ potential RNG facilities can increase RNG production by 60% to 70% for the NG transportation industry today (the US currently has 175,000+ NG vehicles on the road)

3

Carbon Markets

	Federal RFS	CA LCFS
Manure	**D3** $19.93/mmbtu	-250 CI $61.98/mmbtu
Food Waste	- -	0 CI $15.54/mmbtu -25 CI $20.18/mmbtu
Wastewater	**D3** $19.93/mmbtu	
Landfill	**D3** $19.93/mmbtu	45 CI $7.18/mmbtu

Federal and state carbon markets support RNG production

4

Long-duration Energy Storage

In addition to its high energy density, methane has the highest storage capacity (up to 100's of TWh) for long duration storage (years)

The existing NG Network has Terawatt-hour-scale energy storage capacity (>130 billion cubic feet of storage space in Southern CA alone)

Summary

1. **Approach:** Supported by TEA/LCA the NREL team will design, build, and deploy a mobile RD&D electrolyzer-bioreactor system to validate upgrading of different biogas feedstocks to RNG. Focus on systems innovation and systems integration with the H_2 producing electrolyzer to reduce cost and improve efficiency (NREL IP).
2. **Progress & Outcomes:**
   - Mobile RD&D Design-Build-Deploy Status
     - Trailer infrastructure nearly complete
     - Bioreactor, Dosing, and thermal rack designed, built, and installed
   - LCA case study completed with ANL comparing gas separations and biomethanation to upgrade biogas CO_2 to RNG under CA LCFS
     - Hydrogen production coupled with waste-to-energy can enable a negative CI.
     - Upgrading biogenic CO_2 to RNG does not count towards CI score under LCFS but may qualify for the Federal 45Q carbon tax program.
3. **Impact: Patent applications and licensing IP to decarbonize the NG, industrial processes, and transportation sectors.**
   - Mobile system capable of qualifying various biogas sources for carbon markets.
   - **Multiple industry partnerships** formed to advance the state of technology

Quad Chart Overview

Timeline DEIA plan not required in 2019

- Project start date: October 1, 2019
- Project end date: September 30, 2024*

	FY22 Costed	Total Award
DOE Funding	$580K (10/01/2021–9/30/2022)	$1.7MM (Negotiated total federal share)
Project Cost Share	$195K (10/01/2021–9/30/2022)	SoCalGas - $645K Electrochaea - $120K DOE HFTO - $100K

TRL at Project Start: 4

TRL at Project End: 6

* CRADA No-cost time extension needed with partners

Project Goal:

Project is supporting on-site renewable energy production from animal waste, landfills, and wastewater treatment by using the CO_2 typically released by these facilities to nearly double pipeline quality renewable natural gas production compared with gas separations systems. Reduce cost and de-risk an integrated two-step conversion process using the mobile bioreactor system to demonstrate CO_2 conversion at biogas sites using real gas feedstock.

End of Project Milestone

Operate the mobile bioreactor system at pressure using real biogas from up to 2 field locations and achieve pipeline quality renewable natural gas. Achieve at least 10 g/L-hr CH_4 productivity and demonstrate a product gas composition of > 95% CH_4, < 4% H_2, < 1% CO_2, < 0.2% O_2 and < 4 ppm H_2S.

Funding Mechanism

2018 Bioenergy Technologies Office – Lab Call for Biopower R&D (DE-LC-000L045) Topic Area 3: Biological Biogas Cleanup

Project Partners

- Southern California Gas Company
- Electrochaea GmbH
- Argonne National Laboratory
- Spectrum Automation Control

NREL Team Members

- Claire Victor
- Dave Sievers
- Brian Alexander
- Nate Mitchel
- ESIF Operations staff

Thank You!

Partners

- Southern California Gas Company
- Electrochaea GmbH
- University of Chicago
- Argonne National Laboratory
- Spectrum Automation Controls

www.nrel.gov

NREL/PR-5B00-85588

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Transforming ENERGY

Additional Slides

Responses to Previous Reviewers' Comments

Reviewer Comment: A couple reviewers were unclear as to **why we are scaling down** into the mobile RD&D platform with a 20L bioreactor vessel while also pursuing scale-up demonstrations.

Background: The 700-L bioreactor provided by SoCalGas was designed for pilot-scale operations with an electrolyzer having an electrical capacity in the range of 125 kW (2.5 kg H_2/hr), which was the electrolyzer capacity that NREL was operating in 2014 (today it's 750 kW, with capability to 1 MW). 250 gallons of culture (total) in the bioreactor vessel and balance of plant (e.g., pump, heat exchanger, piping) **does not provide staff the flexibility to easily make modifications needed for research aimed at improving reactor design, reducing capital and operating cost, and execute gas mixing trials needed to increase hydrogen mass transfer.**

Response: The scaled-down 20L 18-bar system provides a flexible mobile research platform that is more manageable for the types of trials needed to conduct advanced R&D in this two-step process: electrolysis plus biomethanation of waste biogas to produce RNG. The end-of-project goal for this biopower project is upgrade actual biogas in the field to pipeline-quality RNG. The team considered bringing large quantities of compressed biogas from different sources to NREL, but decided a smaller, flexible research platform was the more effective solution. The complementary Electrolyzer/Bioreactor Integration (EBI) project (WBS 2.3.2.700, CRD-19-00809) will also use this scaled-down platform to reduce to practice intellectual property developed at NREL and being licensed by SoCalGas. The ability to modify the smaller (3 - 25kW) electrolyzer and 20L bioreactor will provide a manageable platform for this ongoing and future work. The EBI project is co-funded between BETO, SoCalGas, and the Hydrogen and Fuel Cell Technologies Office.

Patents and Selected Pubs & Presentations

Patents

- 17/261,473 – Renewable Power to Renewable Natural Gas Using Biological Methane Production
- 17/397,665 – Hydrogen Flow and Ratio Control Using Electrolyzer Stack Current

} **Southern California Gas Company License and AgriAD (UK) License Pending**

Publications

- New Industry Partnerships: Solar Energy Technologies Office Support for Early Projects in the Energy Systems Integration Facility - An Agreement Closeout Summary Report; Palmintier, Bryan; Hoke, Andy; Baggu, Murali; Lundstrom, Blake; Chakraborty, Sudipta; Harrison, Kevin; Dowe, Nancy; Lewis, John; Stark, Greg; Ruth, Mark; Greco, Tessa; Symko-Davies, Martha, NREL/TP-5C00-81106, 2022
- Book chapter: Chapter 3: Power Conversion Technologies: The Advent of Power-to-Gas, Power-to-Liquid, and Power-to-Heat; Schaidle, Joshua A.; Grim, R. Gary; Tao, Ling; Ruth, Mark; Harrison, Kevin; Dowe, Nancy; McMillan, Colin; Pless, Shanti; Arent, Douglas J., NREL/CH-5100-80504, 2022

Select Presentations

- Presentation, Computational Fluid Dynamics Simulation of Biomethanation in a Large-Scale Gas Bioreactor; Rahimi, Mohammad; Sitaraman, Hariswaran; Stickel, Jonathan; Harrison, Kevin; Dowe, Nancy, NREL/PR-2C00-81528, 2021
- Invited Presentation, Power-to-Renewable Natural Gas - Recycling CO2 Waste Stream Using H2 and Biology, Air & Waste Management Association (A&WMA) Annual Conference, October 28, 2021
- Invited presentation, Energy Storage: Converting Waste CO2 and Renewable H2 to Renewable Natural Gas, Alaska Sustainable Energy Conference, Kevin Harrison, May 25, 2022
- Required Presentation, Electrolyzer/Bioreactor Integration, DOE Hydrogen Program 2022 Annual Merit Review and Peer Evaluation Meeting, Kevin Harrison and Nancy Dowe, June 3-6, 2022
- Invited presentation, Electrons-to-Molecules - Electrolytic H2 as a Pathway for Renewable Fuel Production, Energy Storage, & Waste-to-Energy Applications, Nancy Dowe, Kevin Harrison, and Claire Victor, Bioenergy Energy Science & Technologies Directorate, Presentation to the Science & Technology Advisory Board, September 29, 2022
- Invited presentation, A Biological Solution Utilizing Waste Carbon Dioxide and Renewable Hydrogen for Long-Duration Energy Storage and De-Carbonizing the Natural Gas Grid, Water Environment Federation's Technical Exhibition and Conference (WEFTEC), Nancy Dowe, Kevin Harrison, and Claire Victor, New Orleans, Louisiana, October 12, 2022
- Invited presentation, Electrons-to-Molecules, Electrolytic H2 as a Pathway for Renewable Fuel Production, Energy Storage, and Waste-to-Energy Applications, National Association of Regulatory Utility Commissioners, Long-Duration Energy Storage Webinar, October 13, 2022
- Invited presentation, Biological Solutions Utilizing Waste Streams and Renewable Hydrogen for Long-Duration Energy Storage and Decarbonizing our Economy, Nancy Dowe, Kevin Harrison, and Claire Victor, USTDA Workshop, Green Hydrogen, Cape Town, South Africa, Barriers Toward Implementation & Paths Forward, November 1, 2022
- Invited presentation, Green Hydrogen Production to Turn Waste Streams into Energy for Long-Duration Energy Storage and Decarbonization, Nancy Dowe, Kevin Harrison, and Claire Victor, III Workshop on Offshore Wind & Ocean Renewable Energy in Brazil, Panel IV - Cutting-Edge Technologies for Floating Wind Turbines, Decarbonization, and Green Hydrogen Production, November 17, 2022
- Invited presentation, Turning Waste Streams into Energy for Long-Duration Energy Storage and Decarbonization with Hydrogen, Nancy Dowe, Kevin Harrison, and Claire Victor, Agricultural Utilization Research Institute's Minnesota Renewable Energy Roundtable , Future Biogas Uses and Upgrades, FarmAmerica Waseca, Minnesota, December 1, 2022