DOE Bioenergy Technologies Office (BETO) 2023 Project Peer Review

Integrated biochemical and electrochemical technologies (IBET) to convert organic waste to biopower via North American research and educational partnerships

April 6th , 2023
Technology Area Session

Lutgarde Raskin
University of Michigan

Project Overview

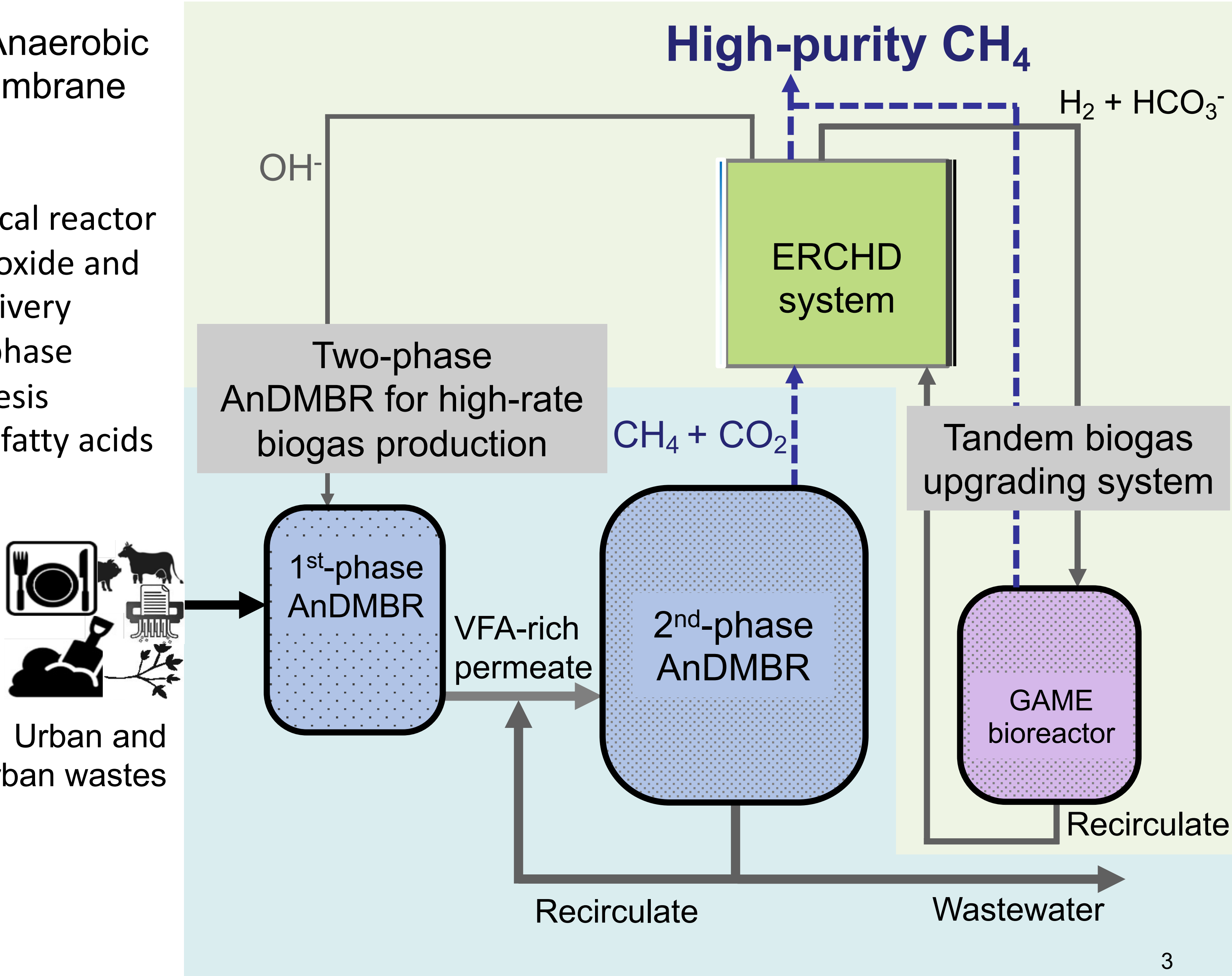
We identified the technical requirements needed to produce market-competitive renewable CH_4 production:

- Improve hydrolysis of recalcitrant, lignocellulosic components in organic waste streams (e.g., fractions of fruits and vegetables, napkins, etc. in food waste)
- Produce biogas efficiently at low capital and operating costs
- Develop affordable biogas purification and upgrade technologies that are versatile and scalable

We are addressing these requirements by developing novel biochemical and electrochemical technologies and integrating them into one pilot-scale process train.

Integrated Biochemical and Electrochemical Technologies (IBET)

AnDMBR: Anaerobic dynamic membrane bioreactor
ERCHD: Electrochemical reactor for carbon dioxide and hydrogen delivery
GAME: Gas-phase methanogenesis
VFA: Volatile fatty acids



Our project goals align with BETO goals

- The project goal is to produce pipeline-ready methane with purity >98% at a production rate of 9 m^3/m^3 reactor/day with an integrated pilot-scale system to be operated at the Great Lakes Water Authority water resource recovery facility in Detroit, MI.

- Demonstrating high yields and production rates at a technology readiness level (TRL) of 5 will provide confidence that renewable methane production cost can be reduced by >25% and that the use of organic waste for renewable energy production is feasible.

Our research aims to answer the following question

What are the key innovation points that can help to reduce the cost of renewable energy production from organic waste, and thus facilitate deployment at the full-scale level?

The main research partners are developing the various technologies at the lab-scale level before integration

Univ. of Michigan: development and operation of two-phase biogas production system treating real organic waste streams

Challenge: understand how operating conditions and substrate characteristics affect the filtration performance of dynamic membranes

Argonne National Lab (ANL): development and operation of electrochemical biogas upgrade system treating real biogas

Challenge: establish economic benefits of the ERCHD system

Northwestern Univ. and inCTRL: design and construction of biological biogas upgrade system

Challenge: determine the operating conditions for the GAME bioreactors

Lab-scale integration at ANL (M25-M36), followed by pilot-scale integration at the Great Lakes Water Authority (GLWA) (M37 – M60)

Risk analysis and mitigation

Primary risk: the diverse knowledge and expertise required for the different technology components can make system integration challenging

Mitigation:

- Knowledge transfer is facilitated by monthly meetings and student visiting and exchange programs
- Process models and control strategies for system integration are developed with InCTRL Inc., an industry leader in biological process models and control
- Lab-scale integration will be accomplished prior to pilot-scale integration
- Techno-economic analysis and life-cycle assessment are guiding system integration

Communication and collaboration

- Monthly team meetings include all researchers on the technology development teams to share technical updates and discuss integration strategies
- Industry leaders and potential users are important contributors to the project team
- Cross-institution student mentorship and student exchanges to ensure communication and facilitate knowledge transfer
- In-person meetings in June 2022 (IWA Anaerobic Digestion Conference) and May 2023 (Annual Team Meeting and Waste-to-Energy Student Symposium)

This project has made substantial efforts in promoting diversity, equity, and inclusion

We have strong education components that focus on student careers and workforce development, including through engagement with minority-serving institutions

- This focus on education is supported by a diverse group of researchers, education, industry, and utility partners
- We have created and promoted internships for undergraduate and Master's students with research, industry, and utility partners
- We have developed Ph.D. student exchange opportunities between North American universities
- We are organizing a Waste-to-Energy Student Symposium with research sessions, networking opportunities, and career panels
- We are developing three Bioenergy online courses with support from the Center for Socially Engaged Design at the Univ. of Michigan

Progress made in meeting project goals

	BP2 go/no-go (M15)	Status
Two-phase system	VFA yield 0.4 kg VFA/kg VS_{fed} CH_4 yield 0.4 m^3 CH_4/kg VS_{fed}	VFA yield **0.47** kg VFA/kg VS_{fed} CH_4 yield **0.74** m^3 CH_4/kg VS_{fed}
ERCHD system	90% CO_2 capture power consumption < 13.3 kWh/kgCO_2	>**94%** CO_2 capture power consumption < **12** kWh/kgCO_2
GAME system	NA	

Key technical accomplishments and status of the key milestones

- Two-phase system
  - developed an energy-efficient operating strategy while achieving high VFA and methane yields
  - a process model describing the system is under development.
- ERCHD system
  - has exceeded the target CO_2 capture rate and simultaneous H_2 production at the target ratio
  - electrode design optimization is ongoing to minimize energy requirements while testing a range of operating conditions
- GAME bioreactors
  - have been designed and constructed
  - The baseline performance will be established by treating gas and liquid substrates from the ERCHD system

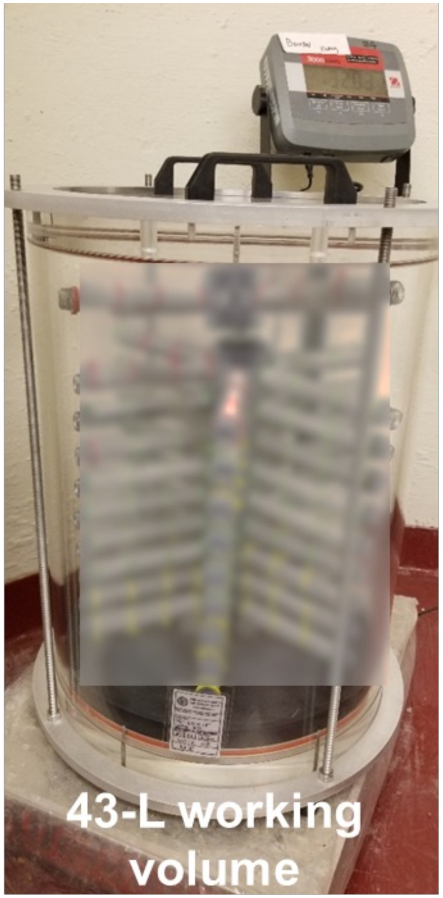
Tasks that led to technical accomplishments

Modeled, constructed, and operated lab-scale systems fed with real waste or biogas

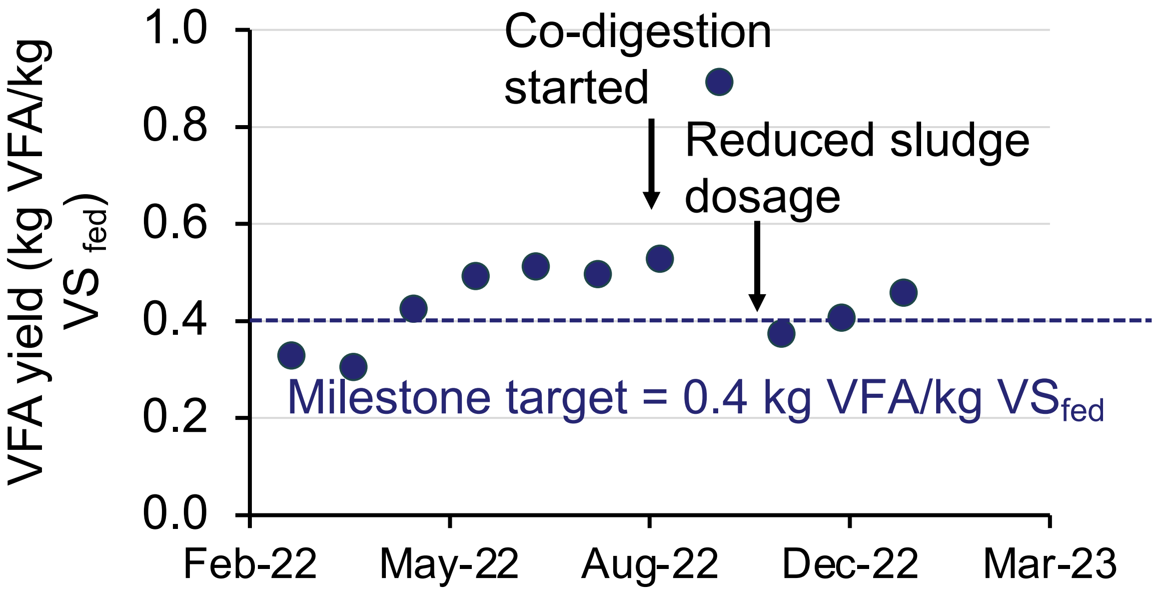
- Two-phase system – food waste and sludge co-digestion (**T2.1**)
- ERCHD system – synthetic and real biogas purification (**T2.2**)
- GAME bioreactor – process model developed, reactor designed and constructed (**T2.3**)
- Techno-economic analysis and life cycle assessment for all three components (**T2.4**)

Data and Results

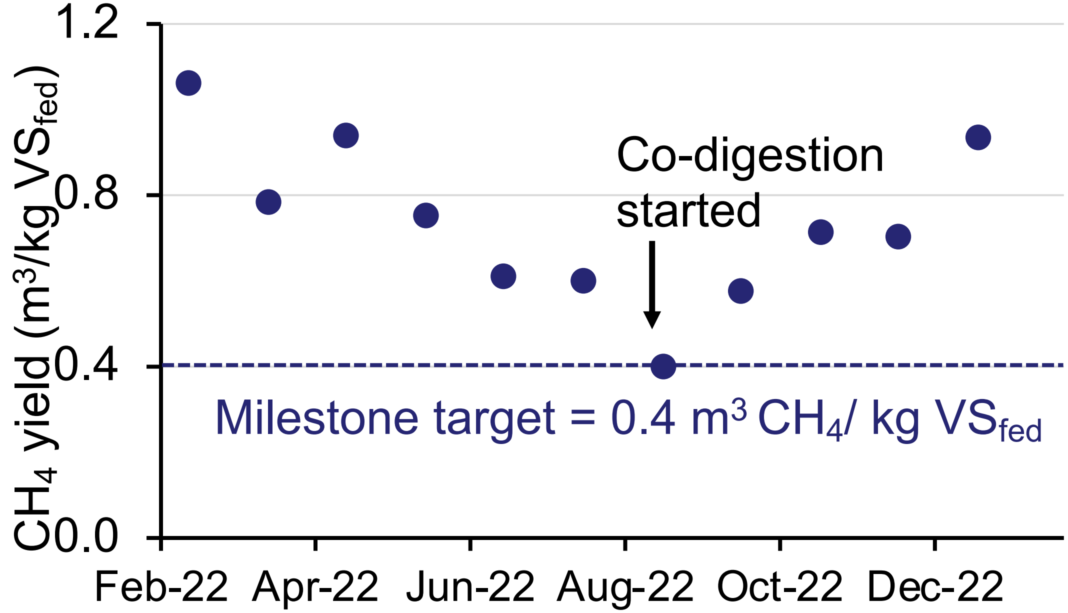
Two-phase system was constructed and has been in operation to co-digest food waste and sludge



Data and Results



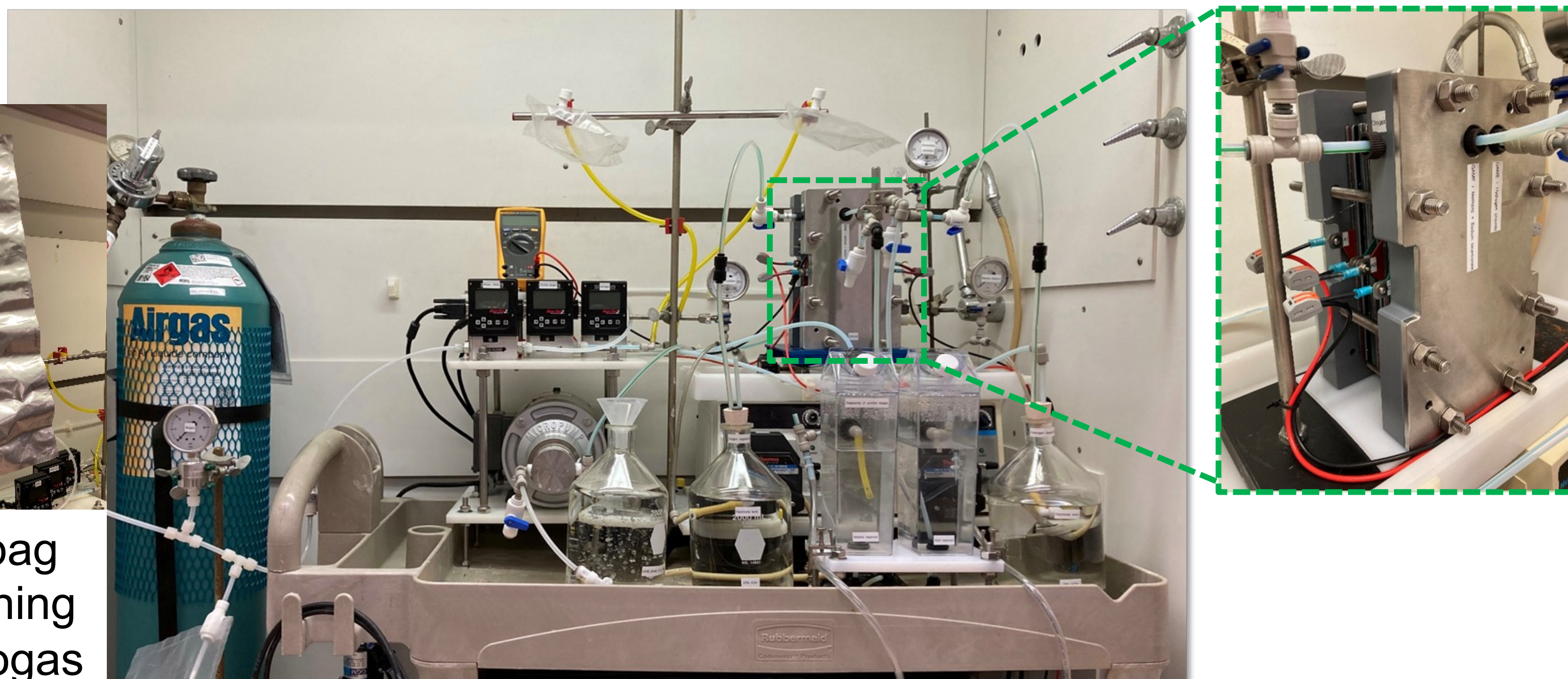
High VFA and methane yields in the two-phase system suggest high degree of substrate conversion, which is crucial to cost reduction



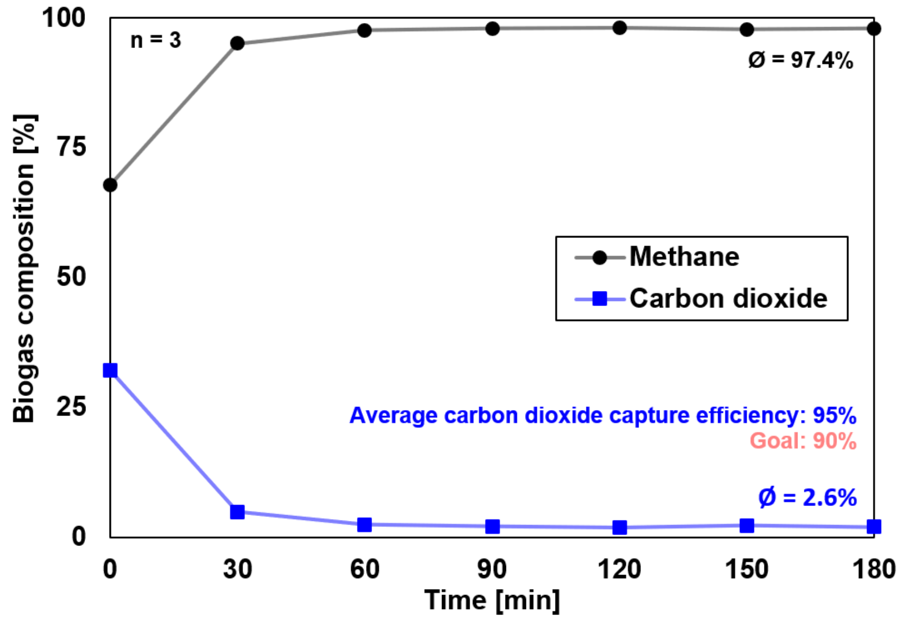
Data and Results

A lab-scale ERCHD system was constructed and is operated to purify synthetic and real biogas

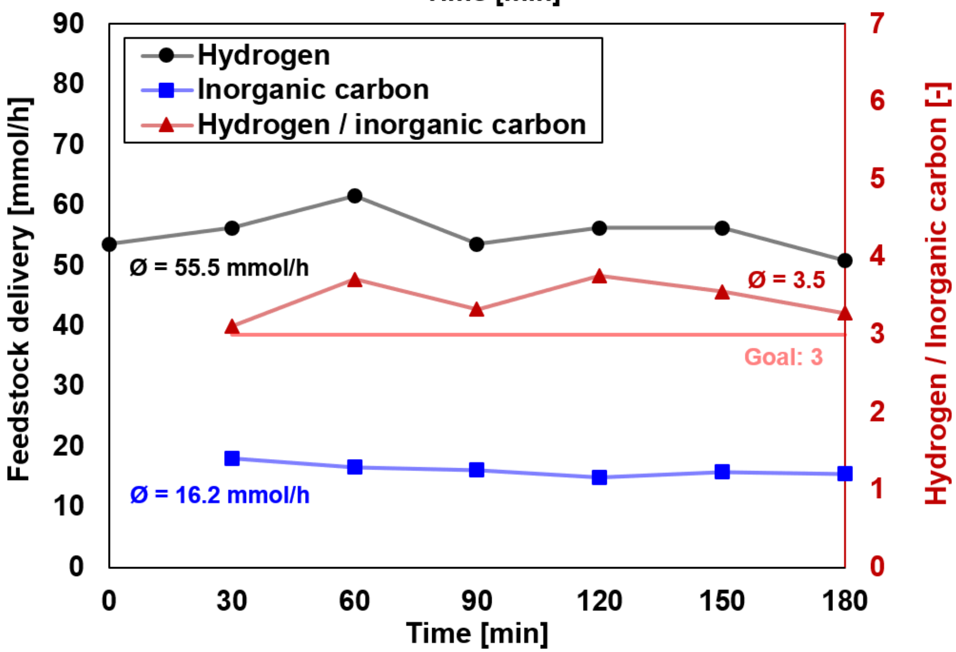
Gas bag containing real biogas

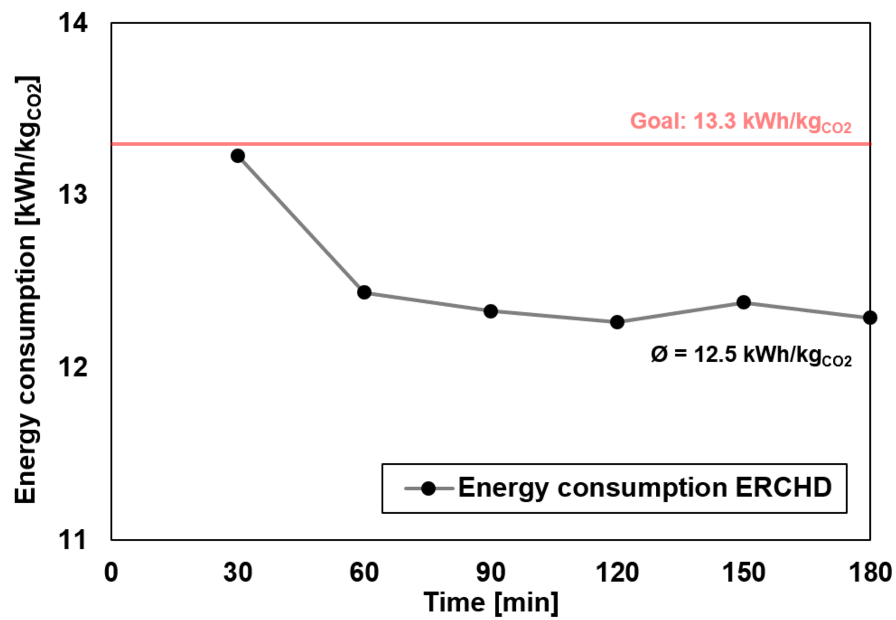


Data and Results



ERCHD system has produced highly purified CH_4 from real biogas while producing H_2 at the desired ratio with the captured CO_2 with low energy consumption





Data and Results

Lab-scale GAME bioreactors have been constructed based on model-informed design

Results Summary

Three technological components of the IBET system have been developed

- The two-phase system achieved 0.47 kg VFA/kg VS_{fed} and 0.74 m^3 CH_4/ kg VS_{fed}
- The ERCHD system captured >94% CO_2 from real biogas and produced H_2 simultaneously at a ratio of CO_2:H_2 = 1:3.5 at energy consumption of 12.5 kWh/kg_{CO2}
- Lab-scale GAME bioreactors have been designed and constructed

Impact on the state of technology and the industry

- High methane yields and low energy operation can substantially reduce the production cost of biomethane (>25%) compared to state-of-the-art anaerobic membrane bioreactors
- This cost reduction makes recovering renewable biomethane from waste more market competitive
- Electrochemical conversion of electricity to bioenergy is an efficient and easily utilizable energy storage method when electricity is produced in excess

Project output includes publications, potential patents and commercialization opportunities

- Fundamental insights in electrochemistry, microbiology, microbial ecology, sustainability, and economics gained during the technology development provide high-impact publication opportunities

- The technology readiness level (TRL) of 5 of the final product and participation of industry and utility partners offers opportunities for commercialization

- Development of novel reactor and control strategies can result in new patents

Summary

- An integrated biochemical and electrochemical technology (IBET) system is being developed to reduce the production cost of renewable biomethane by at least 25%
- The three components of the system have been built and achieved most of their performance targets
- System integration is being prepared through model and control strategy development
- Strong educational and industry partnerships are used to support student careers and develop future workforce in bioenergy

Quad Chart Overview

Timeline
- *12/1/2021*
- *11/30/2026*

	FY22 Costed	Total Award
DOE Funding	$249,711.34	$5,000,000
Project Cost Share *	$257,742.59	$1,790,983

TRL at Project Start: TRL-2
TRL at Project End: TRL-5

*Only fill out if applicable.

Project Goal

Production of pipeline-ready renewable methane (at least 98% purity) from a mixture of real organic waste streams with at least 20% reduction of production cost and 40% increase in production rate compared to state-of-the-art technologies

End of Project Milestone

*Demonstrate pilot-scale operation of IBET system with a feedback control system to generate **98% pure** pipeline-quality CH_4 at a rate of **9 m^3/m^3 reactor/day** as predicted by the process model*

Funding Mechanism

DE-FOA-0002203_FY20_BETO_Multi-Topic

Project Partners*
- Argonne National Laboratory
- Northwestern University
- inCTRL Solutions
- Great Lakes Water Authority