Novel Hybrid Microbial Electrochemical System for Efficient Hydrogen Generation from Biomass

Project ID: PD129

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Overview

Timeline

- Project Start Date: 02/01/16
- Project End Date: 01/31/19*

* Project continuation and direction determined annually by DOE

Barriers

- Low hydrogen molar yield (AX)
- High electrode (cathode) cost (AAA)
- Low hydrogen production rate (AAB)

Budget

- Total Project Budget: $1,670K
  - Total Recipient Share: $167K
  - Total Federal Share: $1,500K

Partners

- **Oregon State University**: project lead; cost-share funding
- **PNNL**: co-project lead
- **Oregon Nanoscience & Microtechnologies Institute**: cost-share funding

Relevance

Project Objective:

Develop a microbial electrochemical system for H_2 production from low-cost feedstock (lignocellulosic biomass and wastewater) at a cost less than \$2/kg H_2.

Approach/Strategy to Achieving DOE's target:

Characteristics	Units	Current Status	Project Target	Commercial Target
Feedstock		glucose	hydrolysate/wastewater	hydrolysate/wastewater
Feedstock cost contribution	\$/kg H_2	8.2	2.0/0	1.2/0
Capital cost contribution	\$/kg H_2	3.0	0.4/0.7	0.3/0.6
Electricity cost contribution	\$/kg H_2	0.4	0.2	0.2
Other operational cost	\$/kg H_2	0.3	0.3/0.6	0.3/0.6
Total cost	**\$/kg H_2**	**11.9**	**2.9/1.6**	**2.0/1.5**
Credits	\$/kg H_2	0	0/-10	0/-10
Final cost	**\$/kg H_2**	**11.9**	**2.9/-8.4**	**2.0/-8.5**

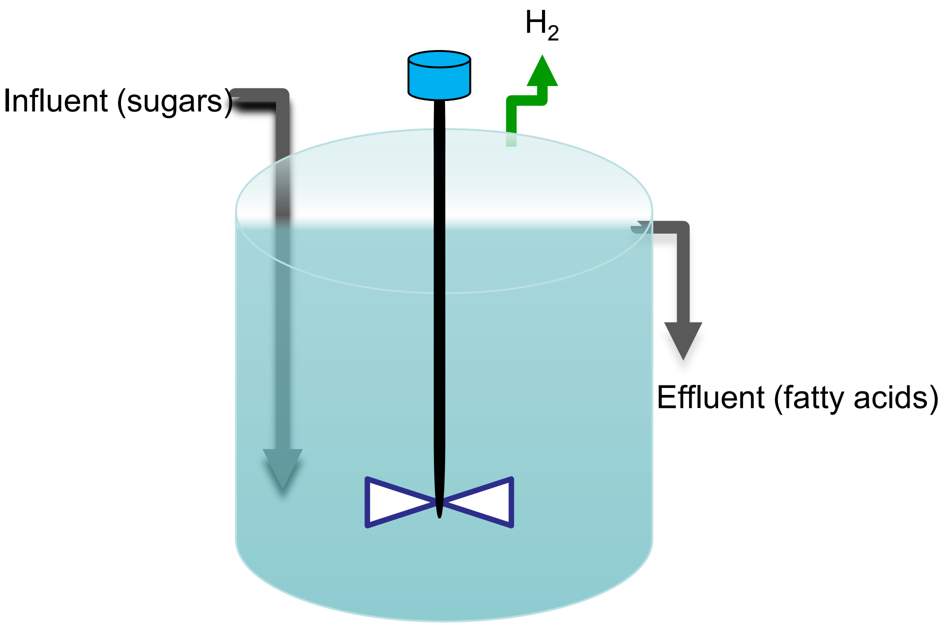
*** Using wastewater as feedstock can generate a credit as much as -\$1/kg glucose equivalent, or -\$10/kg H_2.**

Approach

Dark fermentative H_2 production

- Advantages
  - High hydrogen rate
  - Low energy input

- Challenge
  - low hydrogen yield (Fermentation Barrier):
    - Maximum 4 mol H_2/mol glucose
    - Most H_2 stored in liquid fermentation end products

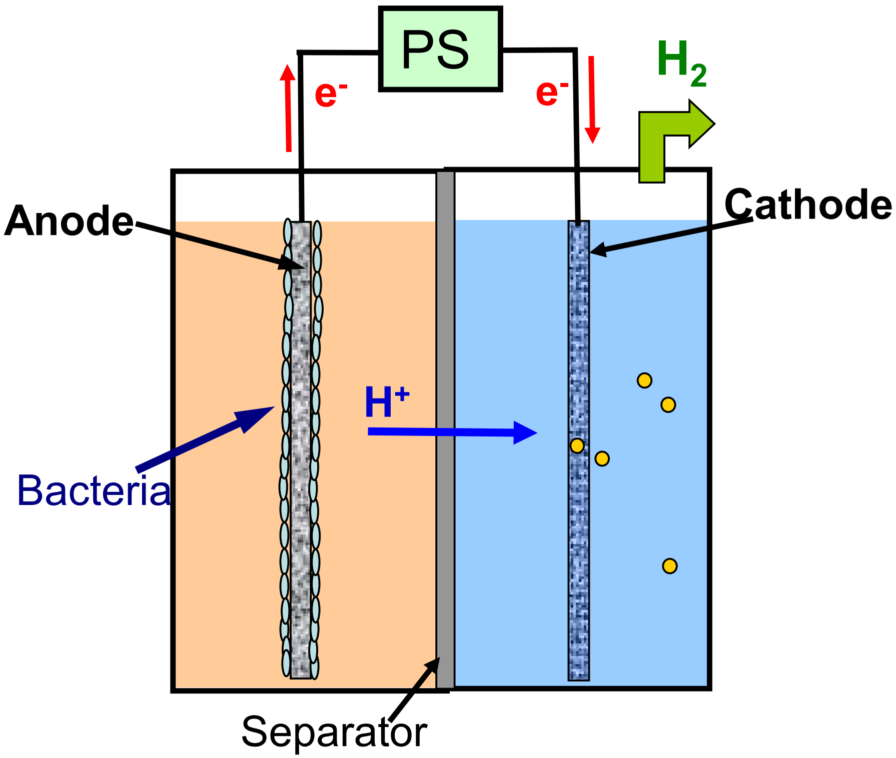


$$C_6H_{12}O_6 + 2H_2O \rightarrow 4\ H_2 + 2\ CO_2 + 2\ C_2H_4O_2$$

Approach

Microbial electrolytic H_2 production

- **Advantages:**
  - Overcoming the "Fermentation Barrier"
  - High H_2 yield
- **Challenges**
  - Incapable/inefficient in directly utilizing biomass or biomass components
  - Low H_2 production rate/high energy input
  - High costs for electrode and separator materials



Anode: $C_2H_4O_2 + 2\ H_2O \rightarrow 2\ CO_2 + 8\ e^- + 8\ H^+$

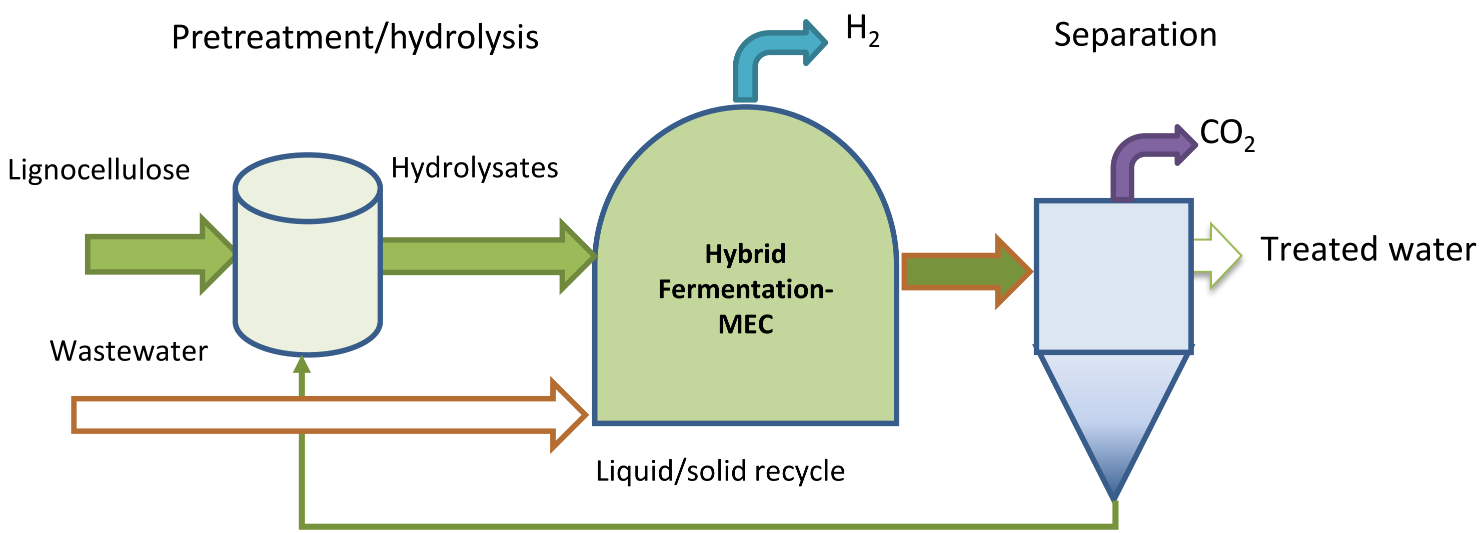
Cathode: $8\ H^+ + 8\ e^- \rightarrow 4\ H_2$

Overall: $C_2H_4O_2 + 2\ H_2O \rightarrow 2\ CO_2 + 4\ H_2$

Approach

Overall approach of this project:

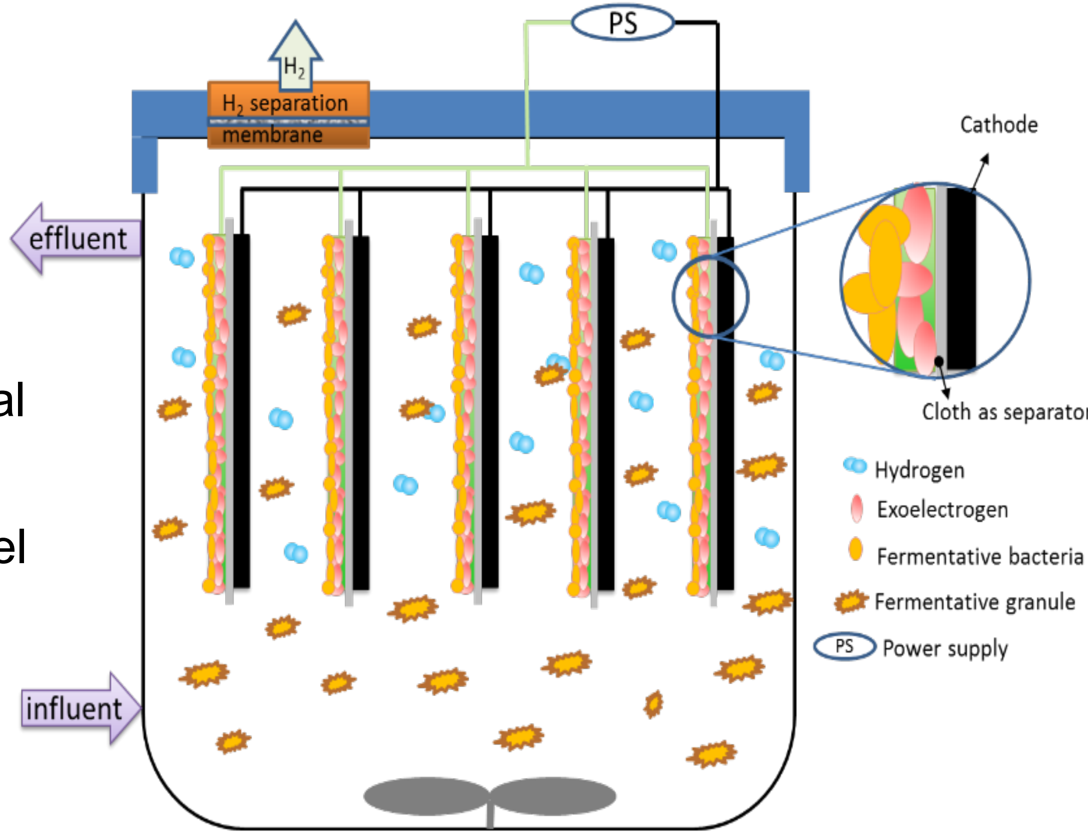
Develop a hybrid fermentation and microbial electrolysis cell (F-MEC) system that can be integrated with lignocellulose pretreatment/hydrolysis or wastewater treatment processes for H_2 production.



Approach

Uniqueness of the approach:

- Use low-cost feedstock
- Combine strengths of dark fermentation and MEC processes
- Reduce capital/operational costs with low-cost and low-overpotential cathode
- Reduce operational cost with novel reactor design and operational conditions
- Apply cost performance model throughout the project to prioritize development



Fermentation: $C_6H_{12}O_6 + 2H_2O \rightarrow 4\ H_2 + 2\ CO_2 + 2\ C_2H_4O_2$

MEC Anode: $2C_2H_4O_2 + 4H_2O \rightarrow 4CO_2 + 16e^- + 16H^+$

MEC Cathode: $16H^+ + 16e^- \rightarrow 8H_2$

Approach

Budget period 1 (FY 2016-2017)

•Fermentation optimization
•MEC cathode development

Budget period 2 (FY 2017-2018)

•MEC process optimization
•Hybrid system design/fabrication

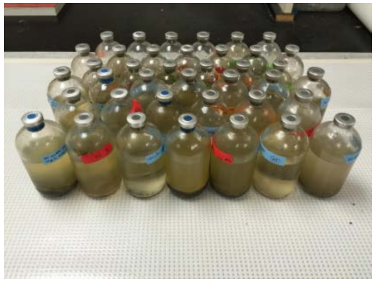
Budget period 3. (FY 2018-2019)

•Hybrid system evaluation
•Cost performance model

Approach

<u>This reporting period (Feb 2016 – April 2016)</u>

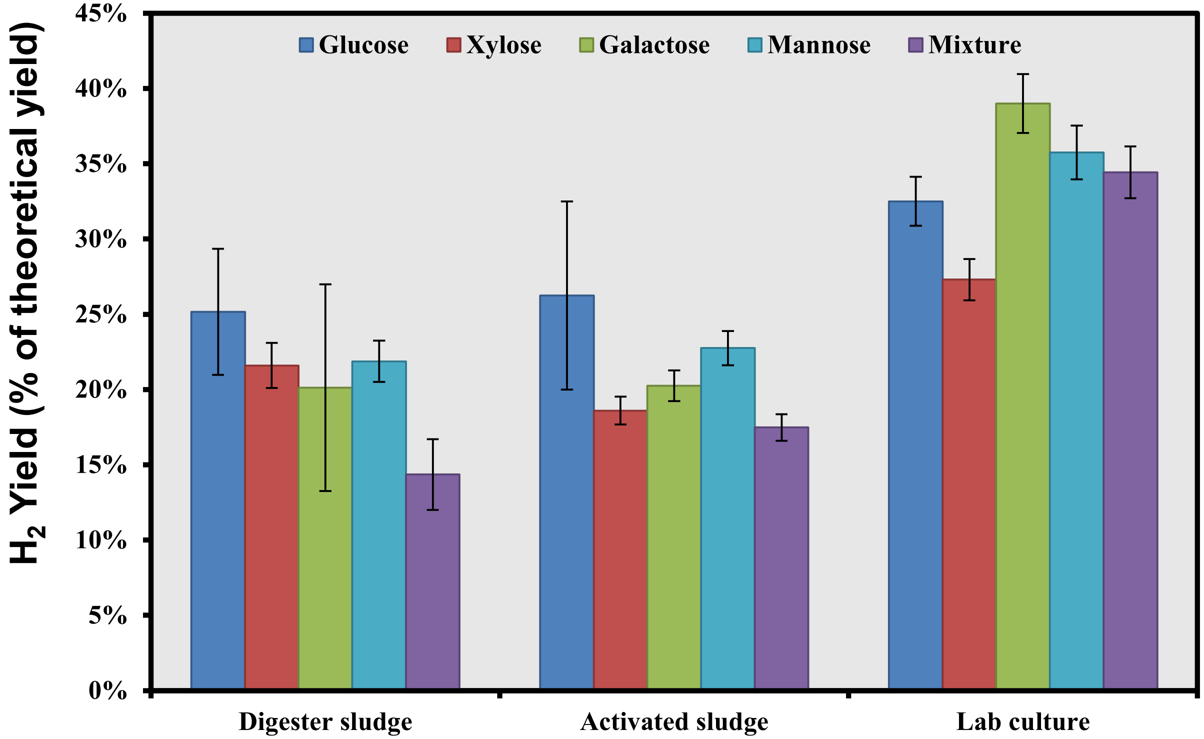
- **Identify a fermentative bacterial culture capable of producing H_2 from all major sugars in lignocellulose hydrolysates and wastewater**
  - ***Mixed culture***
    - Higher robustness and adaptability
    - Easier to grow at large scales
    - More economical to build and operate
    - Relatively simple to manage
    - Suited for using wastewater and complex biomass hydrolysates
  - ***Batch reactors***
    - Types of bacterial culture
    - Types of sugars
    - Biogas
    - Liquid products



- **Developing MEC cathode catalysts**
- **Cost performance modeling**

Accomplishments and Progress

Identification of a bacterial culture capable of producing hydrogen from all major sugars



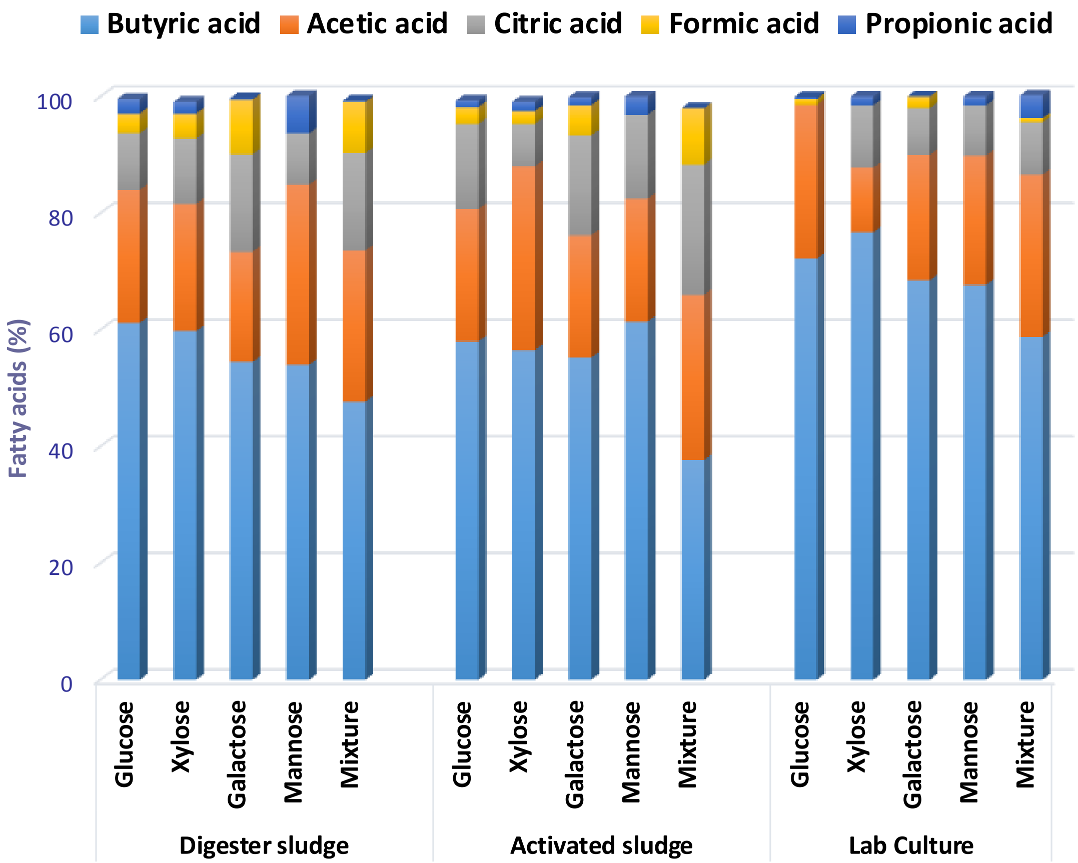
*n= 3, error bars represent standard deviation
Theoretical yield: maximum for known metabolic pathways

Summary: All three tested cultures are capable of producing hydrogen from all tested sugars. The lab culture enriched with glucose demonstrated the highest hydrogen yield.

Accomplishments and Progress

Liquid fermentation products

- **Provide information for MEC process design**
  - Types of carbon source for exoelectrogens
  - Relative production rate



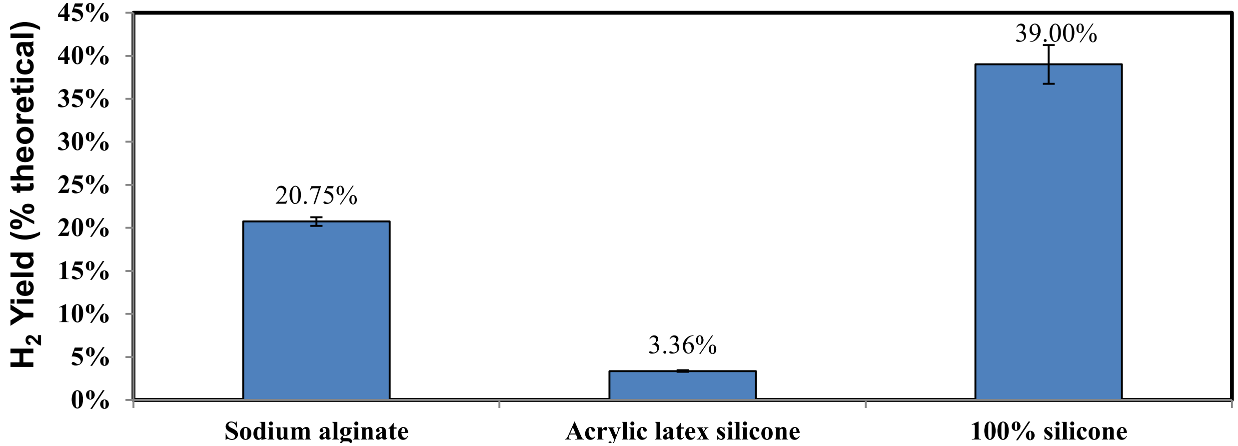
Summary:

Butyrate and acetate are the dominant fermentation liquid products for all sugars and all three cultures.

Accomplishments and Progress

Immobilization of hydrogen-producing culture

- To increase bacterial cell density in continuous-flow reactors
- To increase volumetric hydrogen production rate



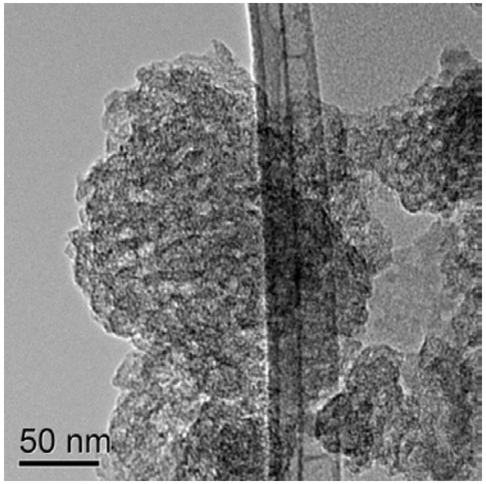
*n= 3, error bars represent standard deviation; Theoretical yield: maximum for known metabolic pathways

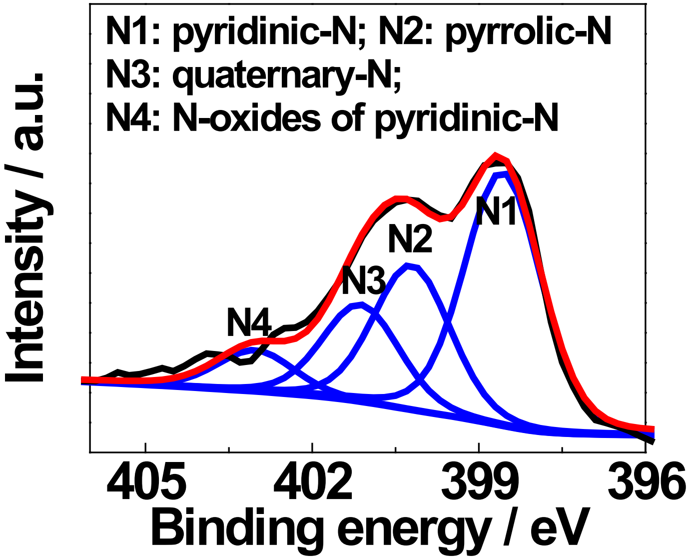
Summary: Immobilization of the lab culture using silicone demonstrates the highest hydrogen yield.

Accomplishments and Progress

Cathode catalysts

- **Synthesized nitrogen doped porous carbon (N-C), surface area tunable between 1000-2500 m^2/g. Metal catalysts will be applied onto N-C.**
- **Identified metal catalyst candidates (NiMo, NiCo, NiCoMo) from literature research.**





*Black line: original data; Red line: fitted data

Accomplishments and Progress

Cost performance modeling

- Test driving DOE H2A model for hydrogen production
- Successfully ran the model with mock input values
  - Received suggestions from NREL experts
  - Conducted preliminary cost estimation of feedstock, yield and required reactor size
- Working on implementing the model for this work

Responses to Previous Year Reviewers' Comments

- This project just started this year.

Collaborations

- **Oregon State University (OSU)**
  - Liu group (Lead): biohydrogen production
  - Murthy group: feedstock treatment
  - Center for Genome Research and Biocomputing (CGRB): microbial community characterization
- **Pacific Northwest National Lab (PNNL)**
  - Shao group: cathode development
  - Viswanathan group: cost performance modeling
- **Oregon Nanoscience and Microtechnologies Institute (ONAMI)**
  - Supplemental funding to support a graduate student to work on this project

Remaining Challenges and Barriers

- **Butyrate utilization rate by exoelectrogens may be slower than that of acetate in MEC**
  - Enrich butyrate-utilizing exoelectrogens
  - Addition of butyrate-utilizing pure cultures
- **Methane production may occur during long term operation**
  - Apply low-cost methane inhibitors to inhibit methanogens
- **Cathode performance may deteriorate over time**
  - Evaluate/modify the cathode catalyst to enhance stability

Proposed Future Work

Remainder of the year:

- Characterize the microbial community
- Optimization of fermentative H_2 production in continuous-flow reactors
- Develop hybrid nonprecious metal electrocatalysts for MEC cathode
- Evaluate MEC H_2 production rate from fermentation liquid products
- Cost performance modeling

FY 2017-2018:

- MEC development
  - Integrate the cathode materials developed
- Hybrid system design/fabrication
- Evaluation of the hybrid system with glucose
- Cost performance modeling

Technology Transfer Activities

- **Technology-to-market or technology transfer plans or strategies**
  - IP related to reactor design and operation
  - IP related to cathode catalyst/material
  - Scale up the system
  - Identify industry partners for commercialization

- **Plans for future funding**
  - Responding to NSF PFI opportunities
  - Seeking support from industry partners

Summary

Objective: Demonstrate a novel microbial system for efficient H_2 production from low-cost biomass

Relevance: Provide a green and renewable approach for H_2 production at a cost less than $2/kg

Approach: Develop a hybrid fermentation and microbial electrolysis cell (F-MEC) system that can be integrated with lignocellulose pretreatment/hydrolysis or wastewater treatment processes for H2 production.

Accomplishment: Identified a microbial community that is capable of producing hydrogen from all major sugars in lignocellulosic biomass hydrolysates; Synthesized nitrogen doped porous carbon for loading the non-precious metal catalyst

Collaborations: A team comprised of a university (OSU), a national lab (PNNL), and a state signature center (ONAMI).