Scalable and Highly-Efficient Microbial Electrochemical Reactor for Hydrogen Generation from Lignocellulosic Biomass and Wastes

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Oregon State University
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Project ID P184
Overview

Timeline

• Project Start Date: 01/01/20
• Project End Date: 12/30/22

Barriers

• High electrode cost (AAA)
• Low hydrogen production rate (AAB)

Budget

• Total Project Budget: $1,277,145
  • Total Recipient Share: $277,239
  • Total Federal Share: $999,906
  • Total DOE Funds Spent*: $2,233

* As of 4/30/20

Partners

• US DOE: project sponsor and funding
• OSU: project lead; cost-share funding
• TAM: co-project lead; cost-share funding
• PNNL: co-project lead
## Relevance

**Overall objective:** develop a scalable hybrid microbial electrochemical reactor for hydrogen recovery from lignocellulosic biomass and wastewater at a cost close to or less than $2/kg \( \text{H}_2 \).

**Specific objective** of this budget period: develop and evaluate low-cost and scalable electrode materials.

### Strategy to Achieving DOE’s target:

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Units</th>
<th>Current Status</th>
<th>Project Target</th>
<th>Commercial Target</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feedstock</td>
<td></td>
<td>Hydrolysate/wastewater</td>
<td>hydrolysate/wastewater</td>
<td>hydrolysate/wastewater</td>
</tr>
<tr>
<td>( \text{H}_2 ) production rate</td>
<td>( \text{L}_{\text{H}_2}/\text{L-d} )</td>
<td>20/20</td>
<td>35/25</td>
<td>35/25</td>
</tr>
<tr>
<td>Feedstock cost contribution</td>
<td>$/kg ( \text{H}_2 )</td>
<td>1.3/0</td>
<td>1.0/0</td>
<td>1.0/0</td>
</tr>
<tr>
<td>Separator electrode assembly</td>
<td>$/m(^2)</td>
<td>$80#</td>
<td>$40</td>
<td>$20</td>
</tr>
<tr>
<td>Capital cost contribution</td>
<td>$/kg ( \text{H}_2 )</td>
<td>1.6#/#1.8#</td>
<td>0.8/1.1</td>
<td>0.4/0.5</td>
</tr>
<tr>
<td>Electricity cost contribution</td>
<td>$/kg ( \text{H}_2 )</td>
<td>0.8</td>
<td>0.6</td>
<td>0.5</td>
</tr>
<tr>
<td>Other O&amp;M cost</td>
<td>$/kg ( \text{H}_2 )</td>
<td>0.4*/0.4*</td>
<td>0.2/0.3</td>
<td>0.1/0.2</td>
</tr>
<tr>
<td>Total cost</td>
<td>$/kg ( \text{H}_2 )</td>
<td>4.1/3.0</td>
<td>2.6/2.0</td>
<td>2.0/1.2</td>
</tr>
<tr>
<td>Credits</td>
<td>$/kg ( \text{H}_2 )</td>
<td>0/-10</td>
<td>0/-10</td>
<td>0/-10</td>
</tr>
<tr>
<td>Final cost</td>
<td>$/kg ( \text{H}_2 )</td>
<td>4.1/-7.0</td>
<td>2.6/-8.0</td>
<td>2.0/-8.8</td>
</tr>
</tbody>
</table>

*H\(_2\) separation/purification cost not included; #Estimated current collector cost included
Approach

- Develop low-cost CNT sponge electrodes
- Develop high-performing platinum group metal (PGM)–free cathodic catalyst
- Fabricate separator electrode assemblies (SEAs) with new electrode and catalyst materials
- Evaluate small reactors for hydrogen production from waste.

Uniqueness of the approach and impact:

- Use low-cost feedstock
- Reduce capital/operational costs with low-cost electrode materials
- Reduce operational cost with novel reactor design and operational conditions
- Apply cost performance model throughout the project to prioritize development
- Formulate new designs and processing parameters for generating H\(_2\) from other biomass feedstocks
- Increase environmental sustainability through simultaneous waste treatment during H\(_2\) production process
### Phase I  Electrode material development and evaluation (FY 20-21)

<table>
<thead>
<tr>
<th>Milestone 1.1:</th>
<th>Synthesize low-cost CNT electrodes capable of producing an anodic current density &gt; 20 A/m² in MECs and fabricate roll-to-roll setup</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>100%</td>
</tr>
<tr>
<td>Milestone 1.2:</td>
<td>Optimize the synthesis conditions and fabricate low-cost CNT sponge electrodes capable of producing an anodic current density &gt; 30 A/m² in MECs</td>
</tr>
<tr>
<td></td>
<td>70%</td>
</tr>
<tr>
<td>Milestone 1.3:</td>
<td>Fabricate functionalized CNT sponge electrodes capable of producing an anodic current density of 40 A/m² in MECs feedstock</td>
</tr>
<tr>
<td></td>
<td>Started</td>
</tr>
<tr>
<td>Milestone 2.1:</td>
<td>Synthesize HER catalyst that can deliver &gt; 40 A/m² in MECs</td>
</tr>
<tr>
<td></td>
<td>Started</td>
</tr>
<tr>
<td>Milestone 3.1:</td>
<td>Fabricate small MECs (~0.5L) using the developed electrodes and HER catalyst with an electrode area with reactor volume ratio ranging from 20-100.</td>
</tr>
<tr>
<td>Go/NoGo:</td>
<td>Demonstration of continuous production of 30 L-H₂/L/day for 48 hours either using wastewater or biomass hydrolysate in ~0.5 L reactors.</td>
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<tr>
<td></td>
<td>Not started</td>
</tr>
</tbody>
</table>

### Phase II  Scaled-up reactor fabrication and evaluation (FY 21-22)

<table>
<thead>
<tr>
<th>Milestone 1.4:</th>
<th>Fabricate 2 m² optimized CNT sponge electrode for the large reactor</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Not started</td>
</tr>
<tr>
<td>Milestone 2.2:</td>
<td>Synthesize HER catalyst enough for 1 m² CNT-supported cathode for the large reactor</td>
</tr>
<tr>
<td></td>
<td>Not started</td>
</tr>
<tr>
<td>Milestone 4.1:</td>
<td>Fabricate a 10-L large reactor with the total anode and cathode areas of at least 1 m² and the liquid volume of at least 6 liters.</td>
</tr>
<tr>
<td></td>
<td>Not started</td>
</tr>
<tr>
<td>Milestone 6.1:</td>
<td>Develop cost performance model</td>
</tr>
<tr>
<td>Milestone 5.1:</td>
<td>Demonstrate the large reactor is capable of 35 L H₂/L/day continuous production for 72 hours with lignocellulose hydrolysates or wastewater.</td>
</tr>
<tr>
<td></td>
<td>Not started</td>
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</tbody>
</table>

**Final deliverable:** Demonstrate the techno-economic feasibility of the proposed system based on the cost performance modeling, and define a pathway for this system to achieve the FCTO cost goal of <$2/gge.
The cylindrical CNT was synthesized using a chemical vapor deposition (CVD) method (a) and composed of inter-connected multi-walled CNTs whose diameters range from 50 nm to 200 nm (b). The surface of CNT was further modified by partially unzipping the multi-walls and grafting the functional groups on the surface (c), showing spiral trenches on CNT (d).
Successfully grew CNTs on the carbon veil (commercially available and inexpensive) with a thickness of ~1 mm. The thickness can be readily increased or decreased depending on the reaction time.
An MEC reactor was designed and fabricated to evaluate multiple (16) electrodes simultaneously. The anodic current density of all three CNT materials (TW-CNT, A-CNT, Pristine CNT) surpassed that of the carbon cloth. These observations indicate a significant advantage of the CNT material over standard carbon cloth material as an MEC anode.
This project just started this year.
<table>
<thead>
<tr>
<th>Partner</th>
<th>Project Roles</th>
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<tbody>
<tr>
<td>Oregon State University</td>
<td>Project lead, management and coordination</td>
</tr>
<tr>
<td>Prof. Liu’s Lab</td>
<td>Bioreactor design and operation</td>
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<tr>
<td>Prof. Murthy’s Lab</td>
<td>Lignocellulosic feedstock treatment</td>
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<tr>
<td>Texas A&amp;M University</td>
<td>Carbon nanotube electrode material fabrication and</td>
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<tr>
<td>Prof. Yu’s lab</td>
<td>characterization</td>
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<tr>
<td>Pacific Northwest National</td>
<td>Cathode catalyst development</td>
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<tr>
<td>Laboratory</td>
<td>Cost performance modeling</td>
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<tr>
<td>Dr. Shao’s group</td>
<td></td>
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<tr>
<td>Dr. Viswanathan group</td>
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</table>
Remaining Challenges and Barriers

• Increase the repeatability of the electrode evaluation results
  – Standardize the testing procedure

• Increase productivity in synthesizing CNT electrodes
  – Optimize synthesis conditions in a larger scale furnace
Proposed Future Work

**Remainder of the current budget period:**

- Optimize the synthesis conditions and fabricate low-cost CNT sponge electrodes
- Fabricate functionalized CNT sponge electrodes
- Synthesize HER catalyst
- Fabricate small MECs (0.5 L) using the developed electrodes and HER catalyst
- Evaluate the small MECs using wastewater

**FY 2021-2022:**

- Fabricate 2 m² CNT electrode material
- Synthesize HER catalyst for 1 m² CNT-supported cathode
- Design and fabricate 10-L reactor
- Evaluate the 10-L reactor
- 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 carbon nanotube electrode material development
  – IP related to scalable HER catalyst development
  – Identify industry partners for commercialization

• Plans for future funding
  – Responding to DOE STTR opportunities
  – Seeking support from industry partners
**Summary**

**Objective:** Develop a scalable hybrid microbial electrochemical reactor for hydrogen recovery from lignocellulosic biomass and wastewater.

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

**Approach:** Reduce the capital and operating costs by: 1) developing low cost and highly-conductive CNT electrode; 2) synthesizing high performing PGM–free cathodic catalyst; 3) Designing novel bioreactors with developed electrode and catalyst materials; 4) Producing $H_2$ from low-cost and negative value feedstocks.

**Accomplishment:** Synthesized and characterized cylindrical porous CNT; Modified CNT surface by grafting functional groups on the surface; Evaluated three CNT materials and the anodic current density of all three surpassed that of the carbon cloth.

**Collaborations:** A team comprised of two universities (OSU, TAM) and a national lab (PNNL).