Analysis of Advanced H₂ Production Pathways


Brian D. James (SA)
Jennie M. Moton (SA)
Daniel A. DeSantis (SA)
Genevieve Saur (NREL)

Project ID: PD102
11 June 2015
Overview

Timeline
• Project start date: 3/15/2013
• Project end date: 3/14/2016
• Percent complete: 66%

Budget
- Total Funding Spent*
  • $389k thru 3/15 (SA portion)
- Total DOE Project Value
  • $609k for all 3 years (SA portion)
- Cost Share Percentage: 0%
  (not required for analysis projects)

Barriers
- High Temperature Electrolysis using Solid Oxide Electrolysis Cell (SOEC)
  • Hydrogen ($H_2$) Generation by Water Electrolysis
    - F: Capital Cost
    - G: System Efficiency and Electricity Cost
    - K: Manufacturing
- Bio-fermentation Using Corn Stover
  • Dark Fermentative Hydrogen Production
    - AX: Hydrogen Molar Yield
    - AY: Feedstock Cost
    - AZ: Systems Engineering

Partners
- National Renewable Energy Laboratory (NREL)*
- Argonne National Laboratory (ANL)*

Collaborators
- Six SOEC developers
- Bio-fermentation specialists

* National Lab work subcontracted through DOE internal funding and not included in totals.
Relevance and Impact

- Investigating production pathways selected/suggested by DOE as relevant, timely, and of value to FCTO.
- Provide complete pathway definition, performance and economic analysis not elsewhere available.
- Analysis is transparent, detailed, and made publicly available to the technical community.
- Results of analysis:
  - Identify cost drivers
  - Assess technology status
  - Provides information to DOE that may be used to help guide R&D direction
Objectives

The objectives of this project include:

1) **Analyze H₂ Production & Delivery (P&D) pathways** to determine economical, environmentally-benign, and societally-feasible paths for the P&D of H₂ fuel for fuel cell vehicles (FCEVs).

2) **Identify key “bottlenecks”** to the success of these pathways, primary cost drivers, and remaining R&D challenges.

3) **Assess technical progress, benefits and limitations, levelized H₂ costs**, and potential to meet U.S. DOE P&D cost goals of <$4 per gasoline gallon equivalent (gge) (dispensed, untaxed) by 2020.

4) Provide analyses that **assist DOE in setting research priorities**.

5) **Apply the H2A Production Model** as the primary analysis tool for projection of levelized H₂ costs ($/kgH₂) and cost sensitivities.

In 2014-2015, these project objectives were applied to develop two cases:

- **Solid Oxide Electrolysis**
- **Bio-fermentation**
- (These cases are in addition to the PEM electrolysis case analyzed last year)

Validation Case Study Excel documents, final reports, and presentations available for download: http://www.hydrogen.energy.gov/h2aProdStudies.html
The team gathered technical & economic data from industry/researchers and synthesized data into generalized H2A cases

- Developed a detailed, *quantitative questionnaire* soliciting engineering and economic performance data.
- **Asked Research Organizations** to independently respond to the questionnaire.
- Requested relevant *detailed information* on:
  - Current and Future cases for Central production.
- Analyzed questionnaire data, and synthesized and amalgamated data *into generalized cases/input parameters*.
- Developed accurate *process and cost models*
  - Modeled system performance in Excel® and Hysys® (SOEC Cases only).
  - Populated H2A Production Models v3.1.
  - Predicted levelized H$_2$ cost and identified key cost drivers and sensitivities.
- **Vetted the public cases** with the Research Organizations.
The team gathered data for two cases for each technology

**Current Case (“if you were fabricating today at production volume”)**
- Case assumes high volume production that incorporates economies of scale.
- Demonstrated advances in technology are implemented.
- Potential reduction in capital cost from existing values.
- Plant lifetimes consistent with measured or reported data.

**Future Case (“if you were fabricating in the future at production volume”)**
- Case assumes high volume production that incorporates economies of scale.
- Case assumes new materials and systems with higher \( \text{H}_2 \) production efficiency, longer plant lifetime, and improved replacement cost schedule.
- Case assumes greater reductions in capital cost.

---

**Case parameters for a central \( \text{H}_2 \) production facility**

<table>
<thead>
<tr>
<th>Public Cases</th>
<th>Plant Start Date</th>
<th>Production of ( \text{H}_2 ) (kilograms (kg)/day)</th>
<th>Plant Life (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current Central</td>
<td>2015</td>
<td>50,000</td>
<td>40</td>
</tr>
<tr>
<td>Future Central</td>
<td>2025</td>
<td>50,000</td>
<td>40</td>
</tr>
</tbody>
</table>
SOEC Cases
SOEC System: Current Case

- 66% H₂O Consumption in stack
- Natural Gas Burner at 900°C
- System Pressure = 300 psi
- Electrical Usage = 36.8 kWh/kg
- Heat Usage = 14.1 kWh/kg
- Heat Price = $10.11/GJ
SOEC System: Future Case

- 66% H₂O Consumption in stack
- Natural Gas Burner at 900°C
- System Pressure = 700 psi
- Electrical Usage = 35.1 kWh/kg
- Heat Usage = 11.5 kWh/kg
- Heat Price = $11.47/GJ*

* Heat price higher in future due to AEO projected natural gas price escalation.
The current and future SOEC cases use input values based on feedback from a six member expert panel.

<table>
<thead>
<tr>
<th>Technical Parameters</th>
<th>Current</th>
<th>Future</th>
<th>Value Basis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Production Equipment Availability Factor (%)</td>
<td>90%</td>
<td>90%</td>
<td>H2A</td>
</tr>
<tr>
<td>Plant Design Rated Hydrogen Production Capacity (kg of H2/day)</td>
<td>50,000</td>
<td>50,000</td>
<td>H2A</td>
</tr>
<tr>
<td>System Design Rated Electric Power Consumption (MWe)</td>
<td>76.7</td>
<td>73.1</td>
<td>Eng. Calc.</td>
</tr>
<tr>
<td>System H2 Output pressure (MPa)</td>
<td>2</td>
<td>5</td>
<td>Ind. Questionnaire</td>
</tr>
<tr>
<td>System O2 Output pressure (MPa)</td>
<td>2</td>
<td>5</td>
<td>Ind. Questionnaire</td>
</tr>
<tr>
<td>Stack operating temperature range (ºC)</td>
<td>600 to 1,000</td>
<td>600 to 1,000</td>
<td>Ind. Questionnaire</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Direct Capital Costs</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Basis Year for production system costs</td>
<td>2007</td>
<td>2007</td>
<td>H2A</td>
</tr>
<tr>
<td>Uninstalled Cost (2007$/kW_{elec. input}) - (w/ approx. subsys. breakdown)</td>
<td>789</td>
<td>414</td>
<td>Ind. Questionnaire</td>
</tr>
<tr>
<td>Stack</td>
<td>35%</td>
<td>23%</td>
<td>Ind. Questionnaire</td>
</tr>
<tr>
<td>BoP Total</td>
<td>65%</td>
<td>77%</td>
<td>Ind. Questionnaire</td>
</tr>
<tr>
<td>Installation factor (a multiplier on uninstalled capital cost)</td>
<td>1.12</td>
<td>1.10</td>
<td>H2A/Eng. Judg.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Indirect Capital Costs</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Project contingency ($)</td>
<td>20%</td>
<td>20%</td>
<td>H2A</td>
</tr>
<tr>
<td>Other (depreciable capital) (%) (Site Prep, Eng&amp;Design, Permitting)</td>
<td>20%</td>
<td>20%</td>
<td>H2A</td>
</tr>
<tr>
<td>Land required (acres)</td>
<td>5</td>
<td>5</td>
<td>H2A/Eng. Judg.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Replacement Schedule</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Replacement Interval of stack (yrs)</td>
<td>4</td>
<td>7</td>
<td>Ind. Questionnaire</td>
</tr>
<tr>
<td>Replacement Interval of BoP (yrs)</td>
<td>10</td>
<td>12</td>
<td>Ind. Questionnaire</td>
</tr>
<tr>
<td>Replacement cost of major components (% of installed capital)</td>
<td>15%</td>
<td>12%</td>
<td>Ind. Questionnaire</td>
</tr>
</tbody>
</table>

Parameters of particular significance are highlighted in red.
The current and future SOEC cases use input values based on feedback from a six member expert panel.

<table>
<thead>
<tr>
<th>O&amp;M Costs-Fixed</th>
<th>Current</th>
<th>Future</th>
<th>Value Basis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yearly maintenance costs ($/kg H2) (in addition to replacement schedule)</td>
<td>3%</td>
<td>3%</td>
<td>H2A/Eng. Judge.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>O&amp;M Costs - Variable</th>
<th>Current</th>
<th>Future</th>
<th>Value Basis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total plant staff (total FTE's)</td>
<td>10</td>
<td>10</td>
<td>H2A/Eng. Judge.</td>
</tr>
<tr>
<td>Total Annual Unplanned Replacement Cost (% of total direct depreciable costs/year)</td>
<td>0.50%</td>
<td>0.50%</td>
<td>H2A</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Feedstocks and Other Materials</th>
<th>Current</th>
<th>Future</th>
<th>Value Basis</th>
</tr>
</thead>
<tbody>
<tr>
<td>System Electricity Usage (kWh/kg H2)</td>
<td>36.8</td>
<td>35.1</td>
<td>Ind. Questionnaire</td>
</tr>
<tr>
<td>System Heat Usage (kWh/kg H2)</td>
<td>14.10</td>
<td>11.50</td>
<td>Ind. Questionnaire</td>
</tr>
<tr>
<td>Total Energy Usage (kWh/kg H2)</td>
<td>50.9</td>
<td>46.6</td>
<td>Ind. Questionnaire</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>By-Product Revenue or Input Streams</th>
<th>Current</th>
<th>Future</th>
<th>Value Basis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity price (2007$/kWh)</td>
<td>0.062</td>
<td>0.069</td>
<td>AEO/Eng. Calc.</td>
</tr>
<tr>
<td>Heating price (2007$/kWh)</td>
<td>0.036</td>
<td>0.041</td>
<td>DOE/Eng. Calc.</td>
</tr>
<tr>
<td>Process water price (2007$/gallon)</td>
<td>0.00181</td>
<td>0.00181</td>
<td>H2A</td>
</tr>
<tr>
<td>Sale Price of Oxygen ($/kg O2)</td>
<td>O2 not re-sold</td>
<td></td>
<td>Eng. Judgment</td>
</tr>
</tbody>
</table>

Ind. Questionnaire = values based on SOEC industry questionnaire results
H2A = parameter default values used within H2A model
Eng. Judgment/Calc. = values based on engineering judgment or calculation

Parameters of particular significance are highlighted in red.
“Other Variable Costs” consist mainly of electricity costs. “Feedstock costs” are primarily heating costs.

“Other Variable Costs” (electricity) and “Feedstock costs” (heat) are 68% to 78% of total production costs.

Between the current and the future case, the estimated H₂ production cost declines due to expected decreases in (1) SOEC system capital costs (primarily at the stack but also the BOP), (2) indirect capital costs and replacement costs, (3) fixed operations and maintenance (O&M) costs, and (4) system energy usage.

*Accomplishments and Progress*

All cases reflect a $3.6-4.2/kg cost for H₂ production.* Electricity costs are the key cost driver.

*On a 2007 dollar cost basis, per standard reporting methodology for the H2A v3.1 tool (reflecting production costs only)*
SOEC Current Case Sensitivity Analysis

Levelized H₂ cost is most greatly influenced by electricity price and capital cost.

- Electricity Price (¢/kWh) [3.12, 6.24, 9.36]
- Uninstalled Capital Cost ($/kW) [410, 820, 1230]
- Heat Price (¢/kWh) [0, 3.64, 5.46]
- Heat Usage (kWh/kg) [7, 14.1, 15]
- Capacity Factor [0.95, 0.9, 0.8]
- Electricity Usage (kWh/kg) [36.1, 36.8, 37.5]

H₂ cost if heat was "free"
SOEC Future Case Sensitivity Analysis

Levelized H₂ cost is most greatly influenced by electricity price and heat price.

Accomplishments and Progress
SOEC Cost Drivers

1) **Electricity Cost ($/GJ)**
   a. Like alkaline & PEM electrolysis, SOEC H₂ cost is primarily driven by electr. price.
   b. Electricity price based on Annual Energy Outlook (AEO) Reference

2) **Electrical Efficiency (kWh/kg H₂)**
   a. Stack efficiency based on operating voltage (which in turn is controlled by ASR)
   b. SA selected stack operating points based on Industry input (close to thermal neutral operating point)
   c. Not much change between Current and Future cases

3) **Capital Cost ($)**
   a. Values from industry feed back have been reviewed and combined to develop the capital costs
   b. Data from industry sources are considered proprietary by SA, and the numbers used in our analysis do not directly match the industry numbers
   c. Major cost reductions expected between Current and Future cases
Biofermentation Cases
Top-Level Process Flow Diagram

Feed Handling
- Wash Tank
- Feed Shredder

Stream 1: 1 kg Corn Stover

Fermentation Reactor
- Cellulose Hydrolysis:
  - 98% Conversion Cellulose to Hexose
- Fermentation of Sugar:
  - 3.2 mol H₂/mol Sugar Future Case (Peak)
  - 1.16 mol H₂/mol Sugar Current Case (Peak)
  - 74 hrs at 55°C
  - *Clostridium Thermocellum* Consortium

Hemicellulose Pre-Treatment
- Hemi-cellulose Breakdown
- 90% Conversion of Hemi-Cellulose to Pentose
- 160°C for 5 minutes

Stream 2: 39% Cellulose
  - 24% Hemi-Cellulose
  - 37% Lignin/Other (by mass)

Stream 3:
1. Caustic (NaOH)
2. Sulfuric Acid (H₂SO₄)
3. Steam
4. Ammonium (NH₄⁺)

Fermentation Products (to Pressure Swing Adsorption):
1. 0.022 kg Hydrogen (H₂)
2. 0.174 kg Carbon dioxide (CO₂)

Stream 4

Stream 5:
1. H₂O
2. N₂

Stream 6 (gaseous)

Filtration

Stream 7

Stream 8: Waste Products
1. 0.114 kg Ethanol
2. 0.195 kg Acetate
3. 0.0211 kg Lactate
4. 0.0211 kg Formate

Stream 9 (solids)
- Lignin
- Others

Stream 9 (liquids)

→ To Waste Water Treatment Process (WWT)
## Comparison of Biofermentation Current & Future Cases

<table>
<thead>
<tr>
<th></th>
<th>Current Case (5 g/L)</th>
<th>Future Case (300 g/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corn Stover Usage</td>
<td>MT/day</td>
<td>2000</td>
</tr>
<tr>
<td>Corn Stover Concentration</td>
<td>g/L</td>
<td>5</td>
</tr>
<tr>
<td>Hemi-Cellulose to Pentose Conversion</td>
<td>%</td>
<td>90%</td>
</tr>
<tr>
<td>Cellulose to Hexose Conversion</td>
<td>%</td>
<td>98%</td>
</tr>
<tr>
<td>Mol H₂/ Mol Pentose</td>
<td>mol H₂/ mol Pentose</td>
<td>1.16 (Exp. Data)</td>
</tr>
<tr>
<td>Mol H₂/ mol Hexose</td>
<td>mol H₂/ mol Hexose</td>
<td>1.16 (Exp. Data)</td>
</tr>
<tr>
<td>Energy Recovery</td>
<td></td>
<td>Energy Deficient (Heat/Energy req.)</td>
</tr>
<tr>
<td>H₂ Production Rate</td>
<td>kgH₂/day</td>
<td>12,428 At 74 hours</td>
</tr>
<tr>
<td>Total Installed Capital Cost</td>
<td>$</td>
<td>$1.26B</td>
</tr>
<tr>
<td>$/kg H₂ (prod. only)</td>
<td>$/kg H₂</td>
<td>$577.74</td>
</tr>
</tbody>
</table>
H₂A Cost Summary: Biofermentation Current

H₂A Biofermentation Current Case Cost Breakdown

- Capital Costs, $29.60
- Feedstock Costs, $10.12
- Fixed O&M, $2.85
- Decommissioning Costs, $0.02
- Utility Heat Requirement, $535.57

- Current Case cost is dominated by the heating requirements of the system
  - Dilute fermentation broth (5 g/L) requires excessive amounts of warm broth
- Future Case will use a more concentrated broth (300 g/L)
  - Heat requirement is offset by burning lignin from the system
  - Excess biogas and lignin can be converted to electricity for byproduct**

* On a 2007 dollar cost basis, per standard reporting methodology for the H2A v3 tool (reflecting production costs only)

** Byproduct credit not shown in cost breakdown
H₂A Cost Summary: Biofermentation Future

H₂A Biofermentation Future Case Cost Breakdown

- **Feedstock Costs**, $3.60
- **Capital Costs**, $4.38
- **Fixed O&M**, $1.07
- **Decommissioning Costs**, $0.01
- **Utility Heat Requirement**, $0.00

- Current Case cost is dominated by the heating requirements of the system
  - Dilute fermentation broth (5 g/L) requires excessive amounts of warm broth
- Future Case will use a more concentrated broth (300 g/L)
  - Heat requirement is off set by burning lignin from the system
  - Excess biogas and lignin can be converted to electricity for byproduct**

* On a 2007 dollar cost basis, per standard reporting methodology for the H₂A v3 tool (reflecting production costs only)

** Byproduct credit not shown in cost breakdown

Accomplishments and Progress
Biofermentation Cost Drivers

1) Feed Stock Cost ($/kg)
   a. Based on 2014 BETO MYPP values (~$75/dry metric ton)
   b. All costs taken for Corn Stover at reactor inlet

2) Fermentation Broth Concentration (g/L)
   a. Low concentration broth (Current Case) drives cost up due to liquid quantities, heat utilities, and waste water treatment required to produce 50,000 kg H₂/day.
      a. Cost of producing H₂ with a broth concentration of 5 g/L is over $500/kg H₂
   b. High concentration broth (Future Case) lead to a smaller, lower capital system. Also reduces heat demand leading to a system surplus (byproduct) energy.

3) Capital Cost ($)
   b. Scaled to account for changes in plant design and size between original report and Current vs. Future Case
Tornado Chart shows results for single variable sensitivity analysis for Biofermentation Future Case

Feed Stock Cost ($/dry metric ton) 
($56.53, $75.37, $94.21)

Total Installed Capital Cost 
(75%, 100%, 125%)

Broth Concentration (g/L) 
(500, 300, 100)

Electrical Turbine Generator Efficiency 
(55%, 50%, 45%)

Increased Reaction Rate/ Decreased Reaction Time 
(24hrs, 74hrs, 74hrs)

Levelized H₂ cost is most greatly influenced by feedstock price, capital cost, and broth concentration.
Waterfall Chart shows a progression of changes in cost in moving from the Future Case to a reduced H₂ cost

Baseline | Increase Molar Yield from 3.2 to 3.8 | Raise Broth Concentration to 500 g/L | Reduce Capital Cost by 10% | Increase Electrical Production Efficiency to 55% | Adjusted
---|---|---|---|---|---
$5.00 | ↓0.58 | ↓0.16 | ↓0.32 | ↓0.44 | $3.12

$2.00/kg Production Target for H₂ * (2020)

* Value based on MYRDD for target for Biomass Gasification by the year 2020
## Response to Previous Year Reviewers’ Comments

<table>
<thead>
<tr>
<th>FY14 Reviewer Comments</th>
<th>FY15 Response to Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>“Part of the reason for this work was to measure progress against DOE goals; however, this comparison was never presented.”</td>
<td>This year’s presentation compares results against DOE targets of $2/gge. The purpose of these studies is to provide DOE with information that assists them in status assessment, performance projection, and research direction formulation. The output of this analysis is enhanced understanding and is thus broader than just comparison to the DOE goals.</td>
</tr>
<tr>
<td>“I would like to see the variability of the results in the waterfall charts as opposed to just the &quot;most likely&quot; case and draw a horizontal line to reflect the target cost on the chart.”</td>
<td>Uncertainty/Variability is addressed in the Tornado Chart. We added a horizontal line on the Waterfall Charts to reflect the $2/kgH2 DOE Target. A fuller description/justification for the Tornados and Waterfalls appears in the backup slides.</td>
</tr>
<tr>
<td>“The basis for the predicted [PEM electrolyzer] cost reduction in going from “existing” to “current” systems and from “current” to “future” systems should be described and justified. The exclusion of the “existing” cost case detracts from the overall usefulness of the study.”</td>
<td>The exclusion of the existing cases is to maintain confidentiality of the companies’ current system costs.</td>
</tr>
</tbody>
</table>
# Collaborators

<table>
<thead>
<tr>
<th>Institution</th>
<th>Relationship</th>
<th>Activities and Contributions</th>
</tr>
</thead>
<tbody>
<tr>
<td>National Renewable Energy Laboratory (NREL)</td>
<td>Subcontractor</td>
<td>• Participated in weekly project calls.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Assisted with H2A Production Model runs &amp; sensitivity analyses</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Provided laboratory data results for biofermentation</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Drafted reporting materials</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Reviewed reporting materials</td>
</tr>
<tr>
<td>• Genevieve Saur</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Todd Ramsden</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Pin-Ching Maness</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Argonne National Lab (ANL)</td>
<td>Subcontractor</td>
<td>• Participated in select project calls.</td>
</tr>
<tr>
<td>• Rajesh Ahluwalia</td>
<td></td>
<td>• Scoping investigation: Evaluated four classes of technologies for producing hydrogen via high-temperature thermochemical water splitting cycles.</td>
</tr>
<tr>
<td>• Thanh Hua</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Industry Sources</td>
<td>Collaborator</td>
<td>• Participated in technical questionnaire</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Provided extensive company-sensitive information</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Clarified input data</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Vetted H2A Model input data, sensitivity parameters, and results</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Reviewed public documentation.</td>
</tr>
</tbody>
</table>
## Collaborators

<table>
<thead>
<tr>
<th>Institution</th>
<th>Relationship</th>
<th>Activities and Contributions</th>
</tr>
</thead>
</table>
| Idaho National Lab (INL)         | Collaborator | • Participated in select project calls  
• Provided Aspen/HYSYS® simulations for SOEC system  
• Supplied capital cost estimations for SOEC system |
| Jim O’Brien                     |              |                                                                                             |
| Department of Energy (DOE)       | Sponsor      | • Participated in (some) weekly project calls.  
• Assisted with H2A Model and sensitivity parameters  
• Reviewed reporting materials |
| Sarah Studer                     |              |                                                                                             |
| Eric Miller                      |              |                                                                                             |
| Katie Randolph                   |              |                                                                                             |
| David Peterson                   |              |                                                                                             |
Proposed Future Work

- DOE Records for SOEC and Biofermentation
- Make H2A Cases publicly available (via website)
- New Pathway Cases such as
  - Bio-derived feedstock reforming
  - Solar Thermal Chemical Hydrogen (STCH)
  - Photo-electrochemical Hydrogen (PEC)
Summary Conclusions

- Case studies were completed for SOEC and Biofermentation using H2A pathways V3.1
- Future Cases reflect $3.7 - $4.6 per kg of H₂ production
- SOEC
  - SOEC cases are driven by electricity costs
  - Future improvements are primarily realized in lower capital cost
    - Energy usage is projected to only modestly improve
  - Alternate system configurations may yield lower H₂ cost (but our analysis suggests not by much)
  - Sale of byproduct O₂ is an option (but is not considered in this analysis)
- Biofermentation
  - Current systems are uneconomical due to low broth density and low H₂ yield
  - Future systems must operate at high(er) broth density to reduce capital & energy costs
  - An example path to reduced H₂ cost (beyond the Future case) is defined
Presentation Summary

• **Overview**
  – Exploration of selected H₂ production and delivery pathways to find most feasible
  – Transparent, objective, and internally consistent comparison of alternatives
  – In year 2 of 3 year project, added SOEC & Biofermentation Cases to our Analysis

• **Relevance**
  – Identify key “bottlenecks” to the success of these pathways, primary cost drivers, and remaining R&D challenges
  – Assess technical progress, levelized H₂ costs, benefits and limitations
  – Analyses assist DOE in setting research direction & priorities

• **Approach**
  – Input based on interviews of technical experts
  – Create engineering performance models of system operation
  – Projected cost results from use of H2A Production Model Version 3.1

• **Accomplishments**
  – Analysis of PEM electrolysis H₂ Production systems (last year)
  – Analysis of SOEC H₂ Production systems
  – Analysis of Biofermentation H₂ Production systems

• **Collaborations**
  – DOE, INL, ANL and NREL provide cooperative analysis/vetting of assumptions/results
Technology Transfer Activities

This project was an analysis of different types of hydrogen production systems and technology transfer does not apply to this project.
Technical Backup Slides
### Technical Parameters

<table>
<thead>
<tr>
<th></th>
<th>SOEC Current</th>
<th>SOEC Future</th>
<th>Biofermentation Current</th>
<th>Biofermentation Future</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Production Equipment Availability Factor (%)</strong></td>
<td>97%</td>
<td>97%</td>
<td>97%</td>
<td>97%</td>
</tr>
<tr>
<td><strong>Plant Design Capacity (kg of H₂/day)</strong></td>
<td>50,000</td>
<td>50,000</td>
<td>50,000</td>
<td>50,000</td>
</tr>
<tr>
<td><strong>System Energy Cost ($/kW)</strong></td>
<td>$743.00</td>
<td>$389.00</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td><strong>Single Unit Size (kg/day)</strong></td>
<td>500</td>
<td>750</td>
<td>500</td>
<td>750</td>
</tr>
<tr>
<td><strong>System H₂ Output Pressure (psi)</strong></td>
<td>450</td>
<td>1000</td>
<td>80</td>
<td>80</td>
</tr>
<tr>
<td><strong>System O₂ Output Pressure (psi)</strong></td>
<td>14</td>
<td>14</td>
<td>14</td>
<td>14</td>
</tr>
</tbody>
</table>

### Direct Capital Costs

<table>
<thead>
<tr>
<th></th>
<th>Basis Year for production system costs</th>
<th>2007</th>
<th>2007</th>
<th>2007</th>
<th>2007</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Uninstalled costs ($/kg H₂)</strong></td>
<td>$56,959,567</td>
<td>$28,489,221</td>
<td>$757,603,978</td>
<td>$216,606,367</td>
<td></td>
</tr>
<tr>
<td><strong>Installed Cost ($/kg H₂)</strong></td>
<td>$63,794,715</td>
<td>$31,338,144</td>
<td>$1,258,448,873</td>
<td>$273,699,755</td>
<td></td>
</tr>
</tbody>
</table>
H2A calculates the levelized cost of H₂, based on these inputs. Capital cost, heat usage, & electrical usage vary, and are key cost drivers.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Current SOEC</th>
<th>Future SOEC</th>
<th>Current Biofermentation</th>
<th>Future Biofermentation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Levelized Cost of H₂ (2007$/kg H₂)</td>
<td>$4.21</td>
<td>$3.68</td>
<td>$578.16</td>
<td>$5.17</td>
</tr>
<tr>
<td>Plant Capacity (kg day)</td>
<td>50,000</td>
<td>50,000</td>
<td>50,000</td>
<td>50,000</td>
</tr>
<tr>
<td>Total Installed Capital (2007$/kg H₂)</td>
<td>$1.02</td>
<td>$0.52</td>
<td>$29.60</td>
<td>$4.38</td>
</tr>
<tr>
<td>Total Electrical Usage (kWh/kg H₂)</td>
<td>36.8</td>
<td>35.1</td>
<td>0</td>
<td>-55</td>
</tr>
<tr>
<td>Electricity Price (H₂A Start-up year)</td>
<td>$0.0574</td>
<td>$0.0659</td>
<td>0</td>
<td>$0.0659</td>
</tr>
<tr>
<td>Thermal Energy Price</td>
<td>$0.0364</td>
<td>$0.0413</td>
<td>$0.0364</td>
<td>0</td>
</tr>
<tr>
<td>Total Heat Usage (kWh/kg H₂)</td>
<td>14.1</td>
<td>11.5</td>
<td>14,372</td>
<td>0</td>
</tr>
<tr>
<td>Total Feed Stock Usage (kg/kg H₂)</td>
<td>0</td>
<td>0</td>
<td>128.69</td>
<td>46.67</td>
</tr>
<tr>
<td>Feed Stock Price (H₂A Start-up year)</td>
<td>0</td>
<td>0</td>
<td>$0.0870</td>
<td>$0.0565</td>
</tr>
</tbody>
</table>

Accomplishments and Progress
## Project milestones are up to date

<table>
<thead>
<tr>
<th>Milestone Number</th>
<th>Project Milestone</th>
<th>Progress Notes</th>
<th>Percent Complete</th>
</tr>
</thead>
<tbody>
<tr>
<td>Milestone 1</td>
<td>Delivery of Project Management Plan</td>
<td>Final version submitted to DOE</td>
<td>100%</td>
</tr>
<tr>
<td>Milestone 2</td>
<td>Delivery of Validation Case Study (on PEM Electrolysis)</td>
<td>Final versions of Excel models, final report, and slide presentation submitted to DOE</td>
<td>100%</td>
</tr>
<tr>
<td>Year 2 Milestone</td>
<td>Completed Year 2 Case Studies</td>
<td>Work nearly finished on biofermentation and solid oxide electrolysis cell (SOEC) studies.</td>
<td>90%</td>
</tr>
<tr>
<td>Year 3 Milestone</td>
<td>Completed Year 3 Case Studies</td>
<td></td>
<td>0%</td>
</tr>
</tbody>
</table>