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# Analysis of Advanced $H_2$ Production & Delivery Pathways


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Project ID: PD102


# Overview

## Timeline

- Project start date: 10/1/2016
- Project end date: 9/30/2020
- Percent complete: 17%

## Budget

- Total Funding Spent
  - $125k (through March 2017, including subs)
- Total DOE Project Value
  - ~$1.2M (over 4 years, including Lab funding)
- Cost Share Percentage: 0%
  (not required for analysis projects)

## Barriers

- **Wire-Wrapping of Steel Vessels for $H_2$ Forecourt Storage**
  - A: System Weight and Volume
  - B: System Cost
- **Reformer-Electrolyzer-Purifier**
  - F: Capital Cost
  - K: Manufacturing
  - G: System Efficiency and Electrical Cost
- **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 (unpaid)

- WireTough Cylinders, LLC

# Relevance and Impact

- Investigates production and delivery pathways selected/suggested by DOE that are relevant, timely, and of value to FCTO.
- Supports selection of portfolio priorities through evaluations of technical progress and hydrogen cost status.
- Provides complete pathway definition, performance, and economic analysis not elsewhere available.
- Provides analysis that is transparent, detailed, and made publicly available to the technical community.
- Results of analysis:
  - Identifies cost drivers
  - Assesses technology status
  - Provides information to DOE that may be used to help guide R&D direction

# Selection of $H_2$ Production & Delivery Cases

- DOE selects cases that support the FCTO development mission
  - Advanced Water Splitting
  - Biomass based processes
  - Waste recovery to $H_2$ processes
- Cases selected based on:
  - Highest priority cases with direct application to FCTO mission
  - Data availability
  - Ability to assist studies in providing relevant cost estimates
    - Beneficial for cases without cost estimates
    - Provide assistance for proper development of H2A cases

- <u>Recently Completed Cases</u>
  - Fermentation
    - Waste-to-$H_2$ process
    - Academically/research review
  - Reformer-Electrolyzer-Purifier
    - $H_2$ production from Natural Gas
    - Private company
- <u>Cases under Current Analysis</u>
  - WireTough
    - High-pressure $H_2$ Storage at forecourt
- More cases will be analyzed as assigned

# Cost Analysis Process



## (Uses H2A but additional modeling is also required)

### Technology Transfer to Strategic Analysis
- Description of system as currently envisioned
- Target and Goals
- Process Conditions
- Function & Concept

### H2A Cost Analysis
- Addition of further business related expenses
- Projection of system sales price
- Discounted Cash Flow Analysis

### DFMA® Cost Summary
- Combine costs to get cost of product
- Allows for easy identification of key process steps

## Internal Modeling

### Engineering Design
- Investigate system
- Performance modeling
- Design/configuration optimization
- Develop full-scale system parameters

### Conceptual Design
- Bill of Materials, dimensions, functional concept, sufficient info to make drawings, fabrication and assembly concept

### Process Flow Diagram

### Process Train Analysis
- Identify Machinery
- Identify Process Feeds

### Cost Estimates of Fabrication Machinery
- Estimate/quote machinery costs
- Estimate/quote raw materials costs
- Utilize SA's database of previous cost estimates and quotes

### Develop Process Models
- Broken up by Process Step
- Plan for high automation in process
- Calculates Machine Rate
- Determines cost of each step
- Simultaneously estimate costs for a variety of production rates

# The team gathers data for two cases for each technology

## Projected Current Case ("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.

## Projected Future Case ("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 $H_2$ production efficiency, longer plant lifetime, and improved replacement cost schedule.
- Case assumes greater reductions in capital cost.

**Case parameters for a central $H_2$ production facility**

| Public Cases | Plant Start Date | Production of $H_2$ (kilograms (kg)/day) | Plant Life (years) |
|---|---|---|---|
| Current Central | 2015 | 50,000 | 40 |
| Future Central | 2025 | 50,000 | 40 |

**Case parameters for a forecourt $H_2$ production facility**

| Public Cases | Plant Start Date | Production of $H_2$ (kilograms (kg)/day) | Plant Life (years) |
|---|---|---|---|
| Current Forecourt | 2015 | 1,500 | 20 |
| Future Forecourt | 2025 | 1,500 | 20 |

# TRL Descriptions

| TRL | Description |
|---|---|
| 1 | Basic Concepts Conceived and Reported |
| 2 | Technology Concept and Application Formation |
| 3 | Analytical and Experimental Critical or Proof of Concept |
| 4 | Component or System Validation in Laboratory Environment |
| 5 | Bench Scale or Similar System Validation in Relevant Environment |
| 6 | Engineering Scale, system validation in a Relevant Environment |
| 7 | Full-scale, similar system demonstrated in Relevant Environment |
| 8 | Actual System Completed and Qualified |
| 9 | Actual System Operation |

**Low TRL**

**High TRL**

TRL = Technology Readiness Level

# Previously Validated High-TRL Methodology

**Step 1: Gather Information**

- DOE Kickoff Meeting
- **Questionnaire sent to experts**
- **Information Review by Team**
- **Isolate Proprietary Data**
- **Meld data into performance parameters for design**
- TRL assessment

**Step 2: Design System**

- Determine if a single or multi-system design is required
- Develop system designs for Existing, Current, and/or Future case
- Team review of system design

**Step 3: Develop H2A Case**

- Develop H2A inputs from system design
- Create H2A cases
- Complete single parameter sensitivity study
- Conduct stochastic analysis
- Review H2A results with outside experts

**Step 4: Finalize Cases**

- Document case study and results
- Send to case study experts for final review
- Adjust cases as needed based on final review
- Publish Cases

- Currently utilized methodology parallels previous approach slide
- This methodology was validated through detailed study of PEM Fuel Cells

# Previously Validated High-TRL Methodology

Accomplishments and Progress

| Step 1: Gather Information | Step 2: Design System | Step 3: Develop H2A Case | Step 4: Finalize Cases |
|---|---|---|---|
| • DOE Kickoff Meeting<br>• **Questionnaire sent to experts**<br>• **Information Review by Team**<br>• **Isolate Proprietary Data**<br>• **Meld data into performance parameters for design**<br>• TRL assessment | • Determine if a single or multi-system design is required<br>• Develop system designs for Existing, Current, and/or Future case<br>• Team review of system design | • Develop H2A inputs from system design<br>• Create H2A cases<br>• Complete single parameter sensitivity study<br>• Conduct stochastic analysis<br>• Review H2A results with outside experts | • Document case study and results<br>• Send to case study experts for final review<br>• Adjust cases as needed based on final review<br>• Publish Cases |

Some steps of this process do not work well for low-TRL cases

- Currently utilized methodology parallels previous approach slide
- This methodology was validated through detailed study of PEM Fuel Cells

# New Methodology for Low-TRL cases

Accomplishments and Progress

Steps added to process to improve the confidence of low-TRL analysis

| Step 1: Gather Information | Step 2: Design System | Step 3: Develop H2A Case | Step 4: Finalize Cases |
|---|---|---|---|
| • DOE Kickoff Meeting<br>• **Collect data from technology experts**<br>• **Literature review**<br>• **Sample similar technologies for usable data**<br>• TRL assessment | • Determine if a single or multi-system design is required<br>• **Develop performance parameters for design**<br>• Develop system designs for Existing, Current, and/or Future case<br>• Team review of system design<br>• **Expert design review** | • Develop H2A inputs from system design<br>• Create H2A cases<br>• Complete single parameter sensitivity study<br>• Conduct stochastic analysis<br>• Review H2A results with outside experts | • Document case study and results<br>• Send to case study experts for final review<br>• Adjust cases as needed based on final review<br>• Publish Cases |

- High-TRL methodology modified for Low-TRL cases
- Difficult to validate low-TRL emerging technologies
  - Usually, no commercial product
  - Limited industrial support
- Increased the number of reviews with technology experts

# Dark Fermentation

## (Corn Stover biomass to $H_2$)

- **Preliminary analysis reported in 2016**
- **Updated analysis in 2017**

All cost/price results for Dark Fermentation in 2007$

# Recent Changes in Fermentation Case

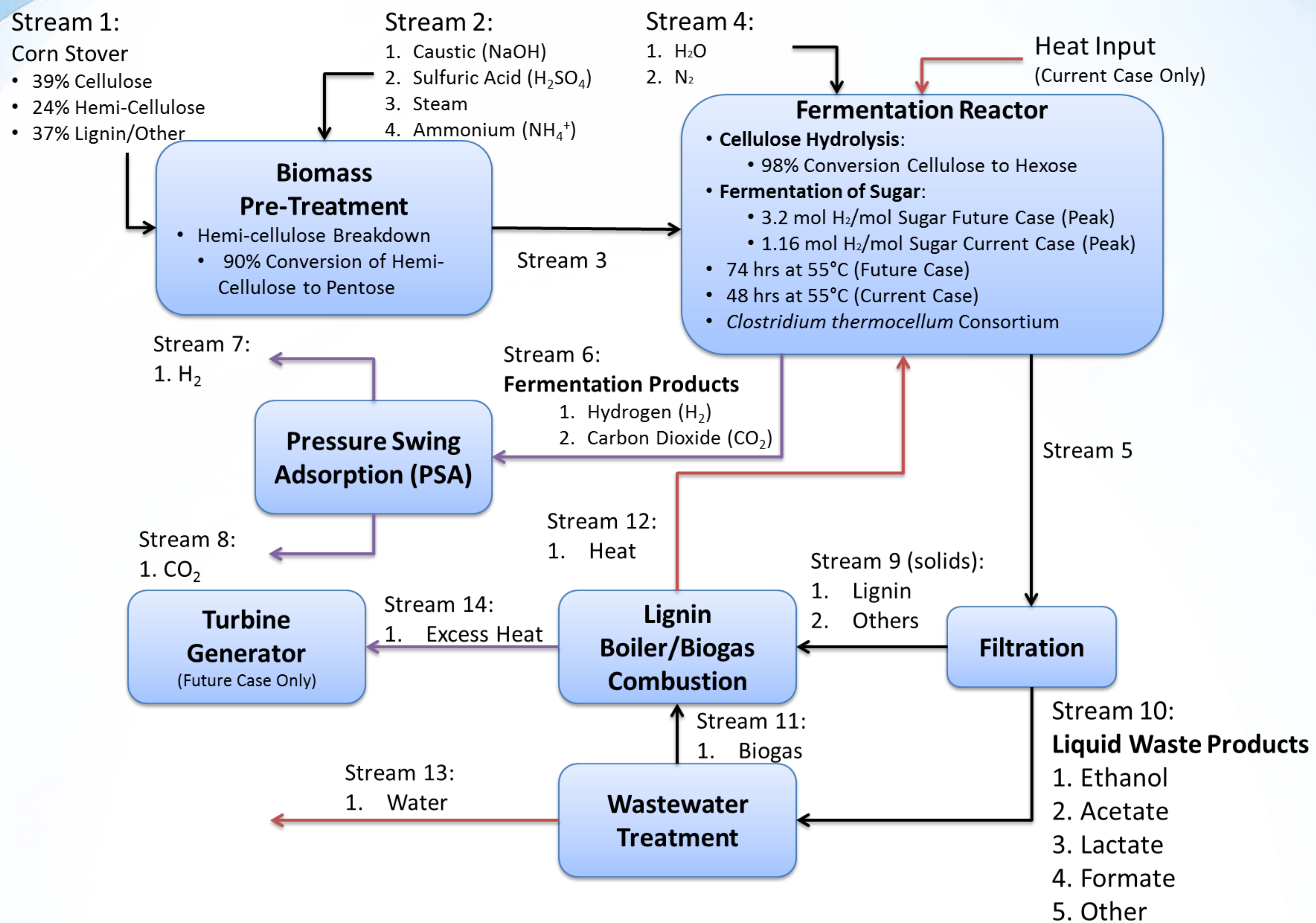
- Results changed for the Current case between 2016 and 2017
  - Future case analysis has remained the same

| | 2016 AMR Prelim. Results | 2017 AMR Final Results |
|---|---|---|
| Projected Current Prod. Cost | \$58.53/kg $H_2$ | \$51.02/kg $H_2$ |
| Future Prod. Cost | \$5.65/kg $H_2$ | \$5.65/kg $H_2$ |

- Re-evaluated Current case based on advise from technical experts
  - Formerly, both Current and Future case were considered to use a consortium of microbes to break down pentose and hexose sugars
  - Deemed inappropriate for a true Current case, though has been recently demonstrated in some studies
  - Current case now only breaks down hexose sugars
  - New steam turbine bottoming-cycle added (to generate by-product electricity) to lower net $H_2$ cost

# Dark Fermentation Process

Accomplishments and Progress



# Fermentation Results

| Component | Projected Current Central 50,000 kg/day | Projected Future Central 50,000 kg/day |
|---|---|---|
| *Installed Capital Cost* | $36.07 | $7.86 |
| *Decommissioning* | $0.05 | $0.01 |
| *Fixed operations and maintenance (O&M)* | $5.67 | $1.49 |
| *Feedstock Costs* | $18.01 | $3.82 |
| *Byproduct Credits* | -$11.93 | -$8.19 |
| *Variable O&M (including electrical utilities)* | $3.15 | $0.65 |
| **Total $H_2$ Production Cost (2007$/kg $H_2$) with byproduct credits** | **$51.02** | **$5.65** |
| **Total $H_2$ Production Cost (2007$/kg) $H_2$ w/o steam generator or energy byproduct** | **$67.71** | **$8.56** |

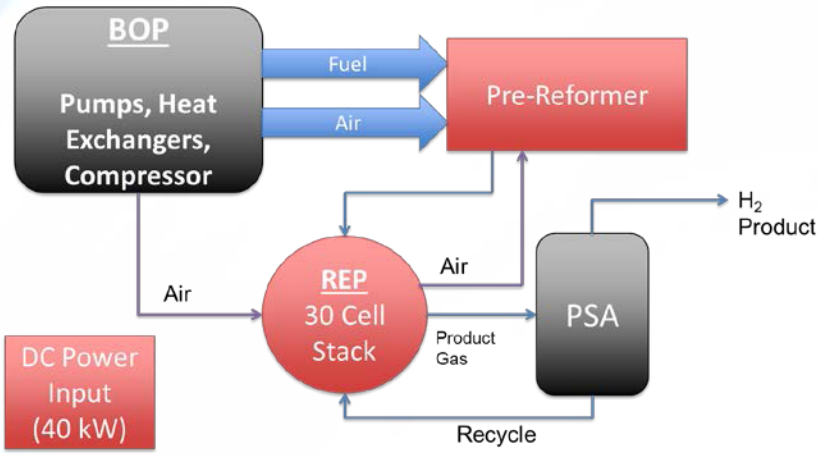
- The Current case is not feasible for large-scale production
  - But is useful as a status assessment and comparison to the Future case
- Largest cost drivers are capital cost and thermal energy cost: therefore broth concentration and thermal management are of paramount importance
  - Current case cost is largely driven by low broth concentration, which creates many large reactors (driving up capital cost) and requiring large quantities of thermal energy to heat
  - Recovered thermal energy converted to steam reduces this cost but only goes to highlight the importance of thermal energy to the system

# Fuel Cell Energy's Inc. Reformer-Electrolyzer-Purifier (REP)

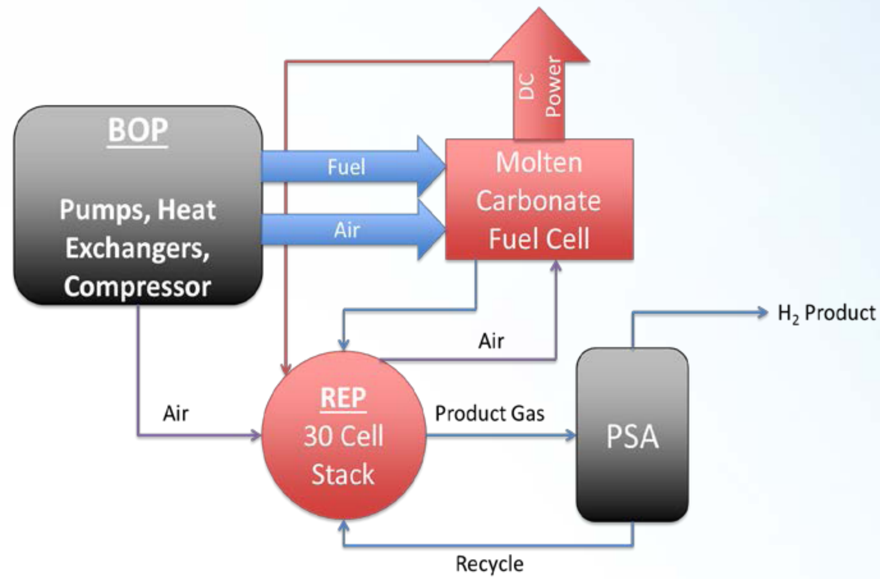
All cost/price results for REP in 2007$

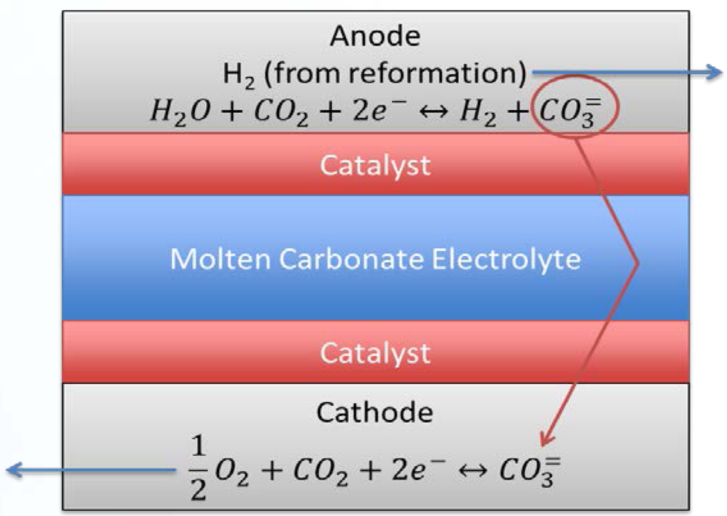
# Reformer-Electrolyzer-Purifier (REP)

REP's Standalone Process Flow Diagram




REP's Integrated Process Flow Diagram



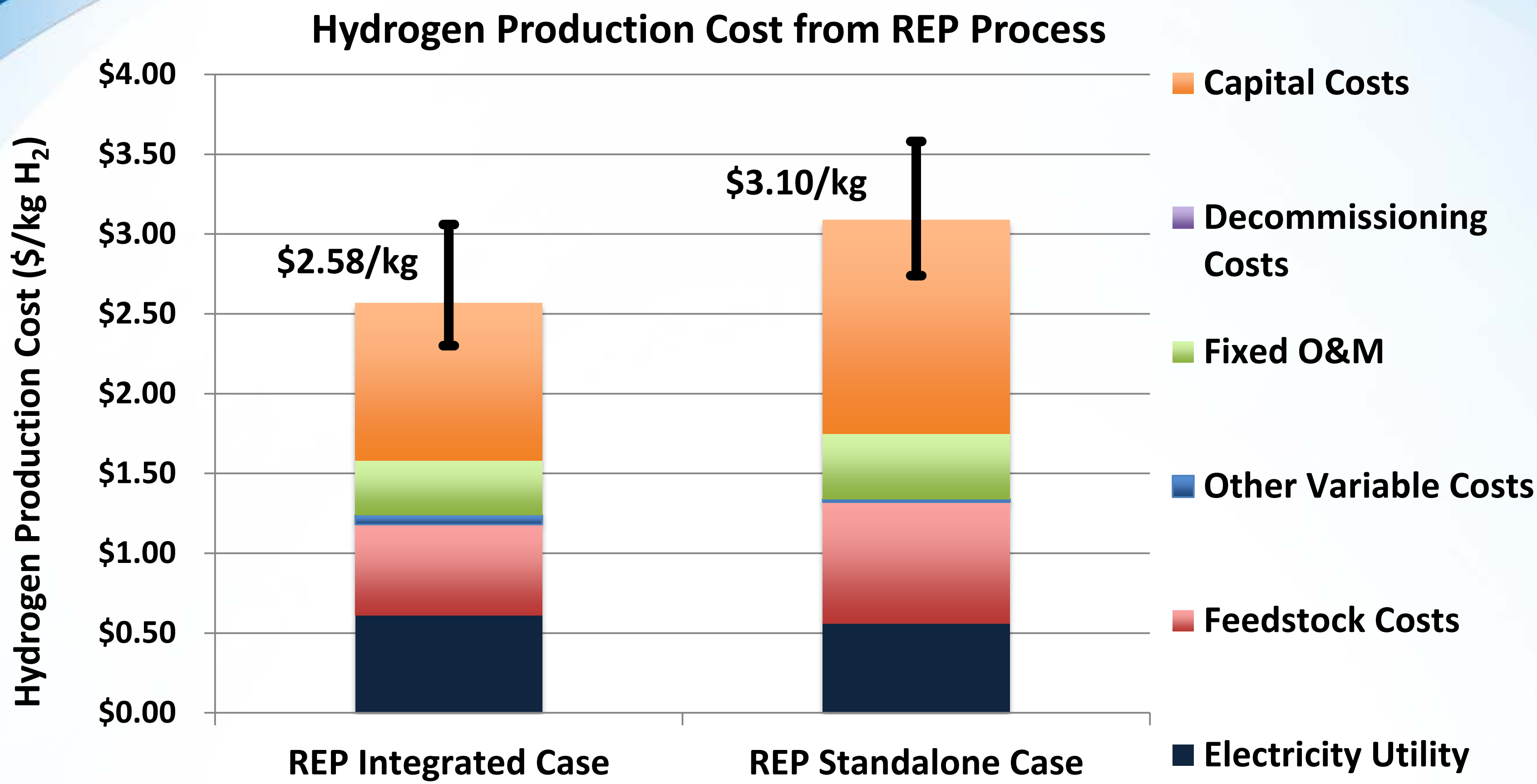




Molten Carbonate Fuel Cell Operation Diagram

1. Technology is based off of existing DFC® fuel cell
2. Reformer product is purified by passing through a REP stack
3. $CO_2$ is essentially passed across the electrolyte and removed from the product stream
4. Requires power input

# REP Proj. Current Case Results

Accomplishments and Progress



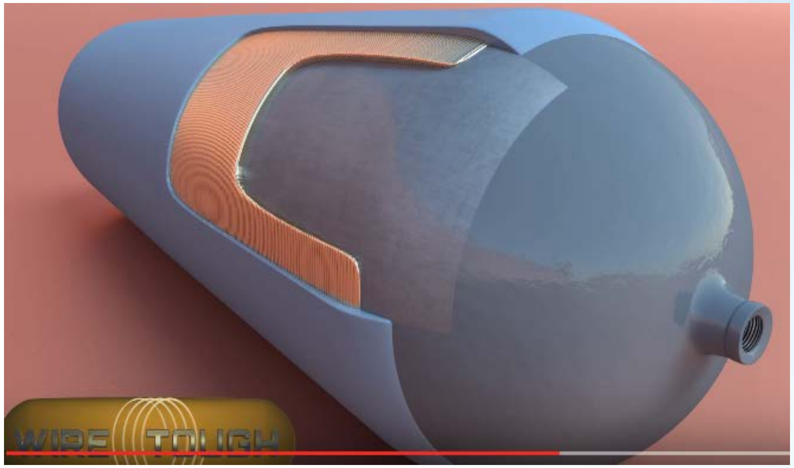

- Costs for the integrated and standalone cases are less than $4/kg
- Primary cost driver is capital cost for the system
- Error bars based on Monte Carlo analysis with a 90% confidence interval

# WireTough's Wire-Wound $H_2$ Storage Pressure Vessel

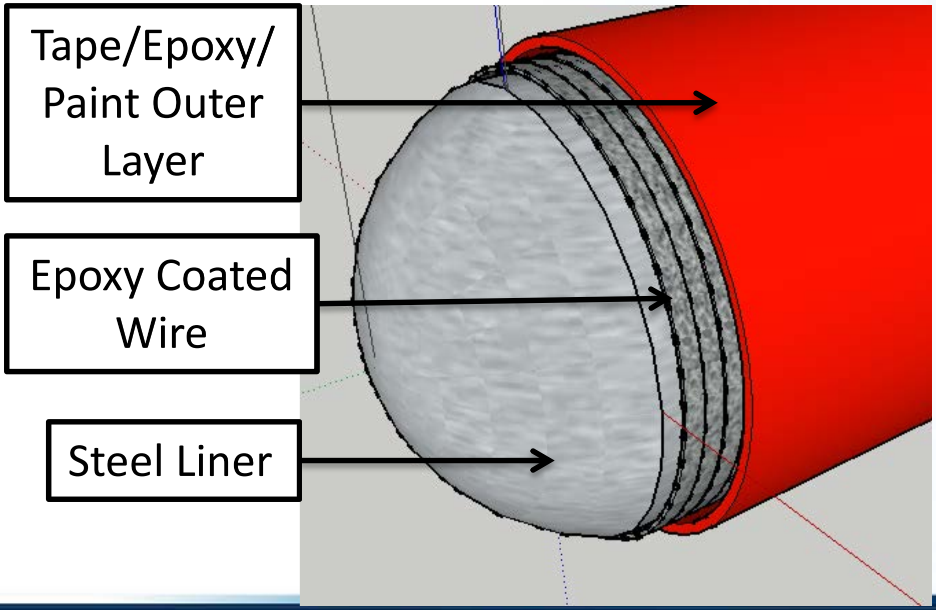
All cost/price results for WireTough Pressure Vessels in 2016$

# WireTough LLC $H_2$ Storage System

- 13kpsi-rated $H_2$ storage vessel for use at forecourt facilities
  - Steel liner wrapped with steel wire
  - 6,600 psi pressure vessel acts as Liner
  - Steel wire is layered around cylindrical section of liner, coated in epoxy, and taped to hold in place
    - After wire wrapping, vessel is rated for greater than 13,000 psi
- Vessel fabrication modeled by SA
  - DFMA® analysis methodology
  - Sensitivity analysis identifies the most cost impactful parameters
  - Monte Carlo (uncertainty) analysis projects the range of vessel costs for 90% confidence



Courtesy of WireTough Cylinders, LLC
http://wiretough.com/innovative/



# Cascade Storage for 13,000 psi $H_2$ Dispensing


- High-pressure storage vessels are required to hold $H_2$ or NG at forecourt dispensing stations
- Focus on vessel cost reduction
- System consists of:
  - 6 vessels (3 banks of 2 vessels)
  - Each vessel:
    - 457mm OD X 9.1 m, ~34kg $H_2$, 765 L
  - Balance of System
    - Pressure regulation, automatic solenoid valves, fittings, tubing, pressure relief devices, rack
- Both cascade storage (high-pressure) and low-pressure storage are used at Forecourt sites
  - Low-Pressure Storage (4,000 psi)
    - 18 low-pressure storage vessels on-site

# Process Flow Schematic

Accomplishments and Progress

30' length, 765L, 13kpsi Vessel
Manufacturing Rate: 180 – 3,000 tanks per year

**Liner**
*Cost:*
*$10k – $16k*

Crane Transfer
*10 min*

**Epoxy Resin (Cyply®1002)**
*Cost: $18.5/L*
*Epoxy to Wire Vol. Ratio : 0.61*

**Fiberglass Mesh Tape**
*Cost: $5/roll*
*Roll: 1" x ~250ft*
*Usage: 20 rolls per vessel*

**Epoxy Resin**
(Cyply®1002)
*Cost: $18.50/L*

**Wire Winding**
*Total Cost: $341k*
*Wire Laydown: 105 m/min*
*Eff. Cycle Time: 10 hrs*
*Laborers/Line: 1-2*

**Tape Winding**
*Machine Cost: incl. in wire winding*
*Tape Laydown: 26 m/min*
*Cycle Time: 0.3 hrs*
*Laborers/Line: 1*

Crane Transfer
*10 min*

**Epoxy Curing**
*Oven Cost: $66k*
*Eff. Cycle Time: 12 hrs*
*Temp: 120°F*
*Laborers/Line: 0.25*

Crane Transfer
*10 min*

**Wire**
*Cost: $2.25/kg*
*Usage: ~1,000kg per vessel*

**UV-Resistant Polymer Paint**
*Cost: $29/L*
*Usage: 0.75 gal/vessel*

**Room Temperature Final Curing**
*Eff. Cycle Time: 12 hrs*
*Temp: Ambient*
*Laborers/Line: 0.125*

Crane Transfer
*10 min*

**Autofrettage**
*Cost/Line: $76k*
*Cycle Time: 120 min*
*Laborers/Line: 2*

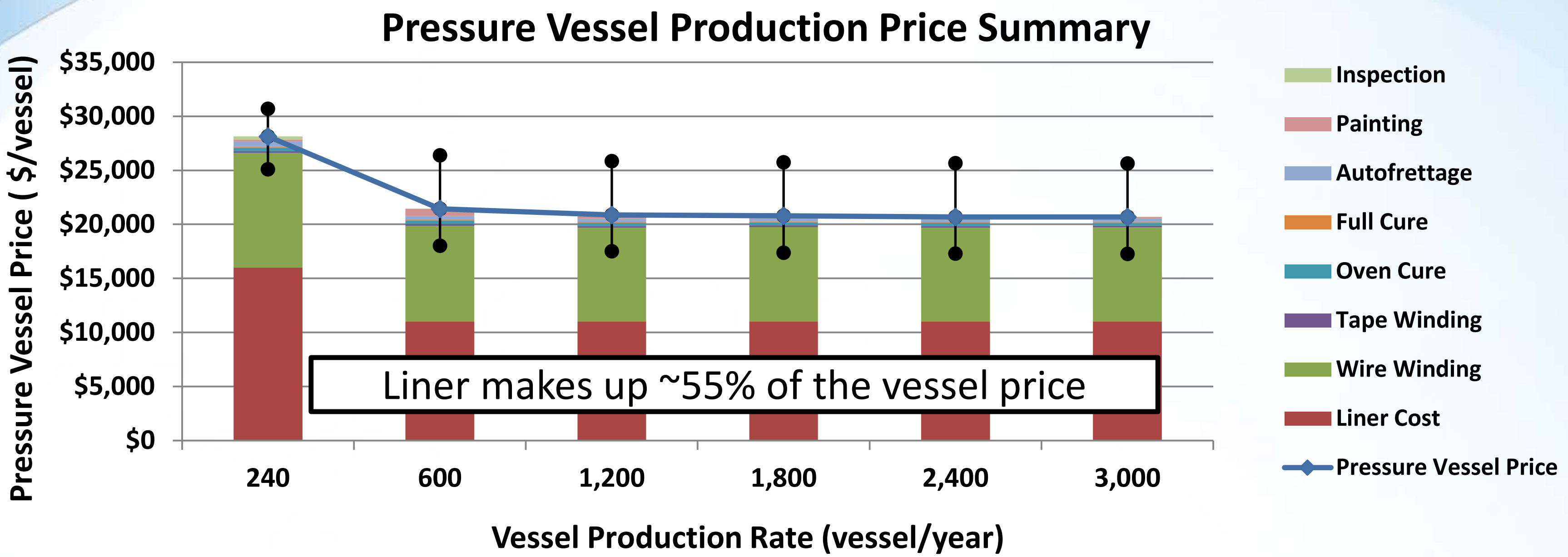
Crane Transfer
*10 min*

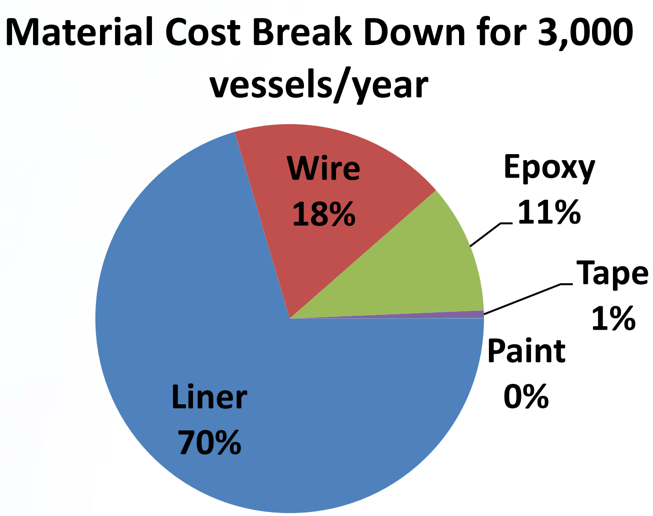
**Painting**
*Booth Cost: $587k*
*Cycle Time: 40 min*
*Application Time*
*Laborers/Line: 0.2*

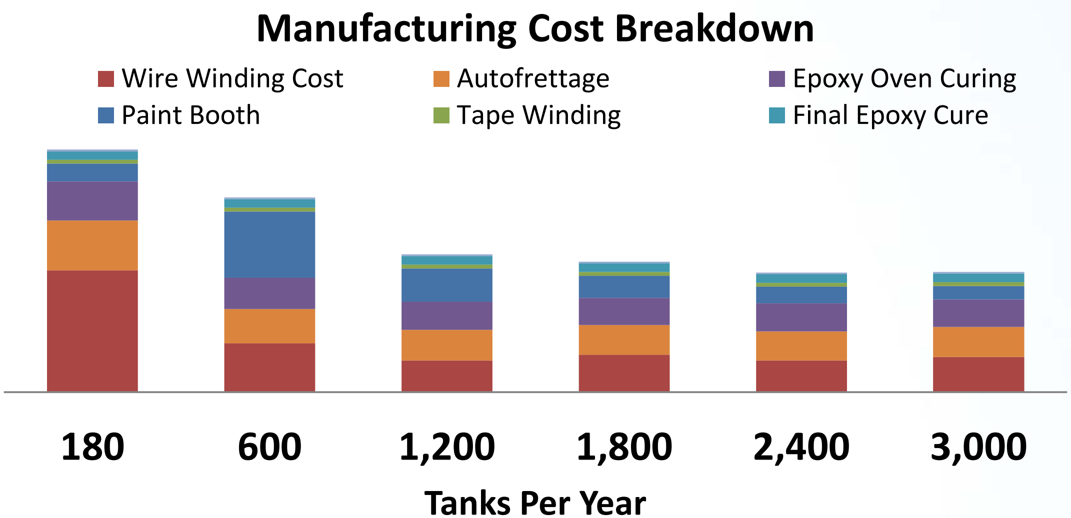
**Inspection**

To Shipping

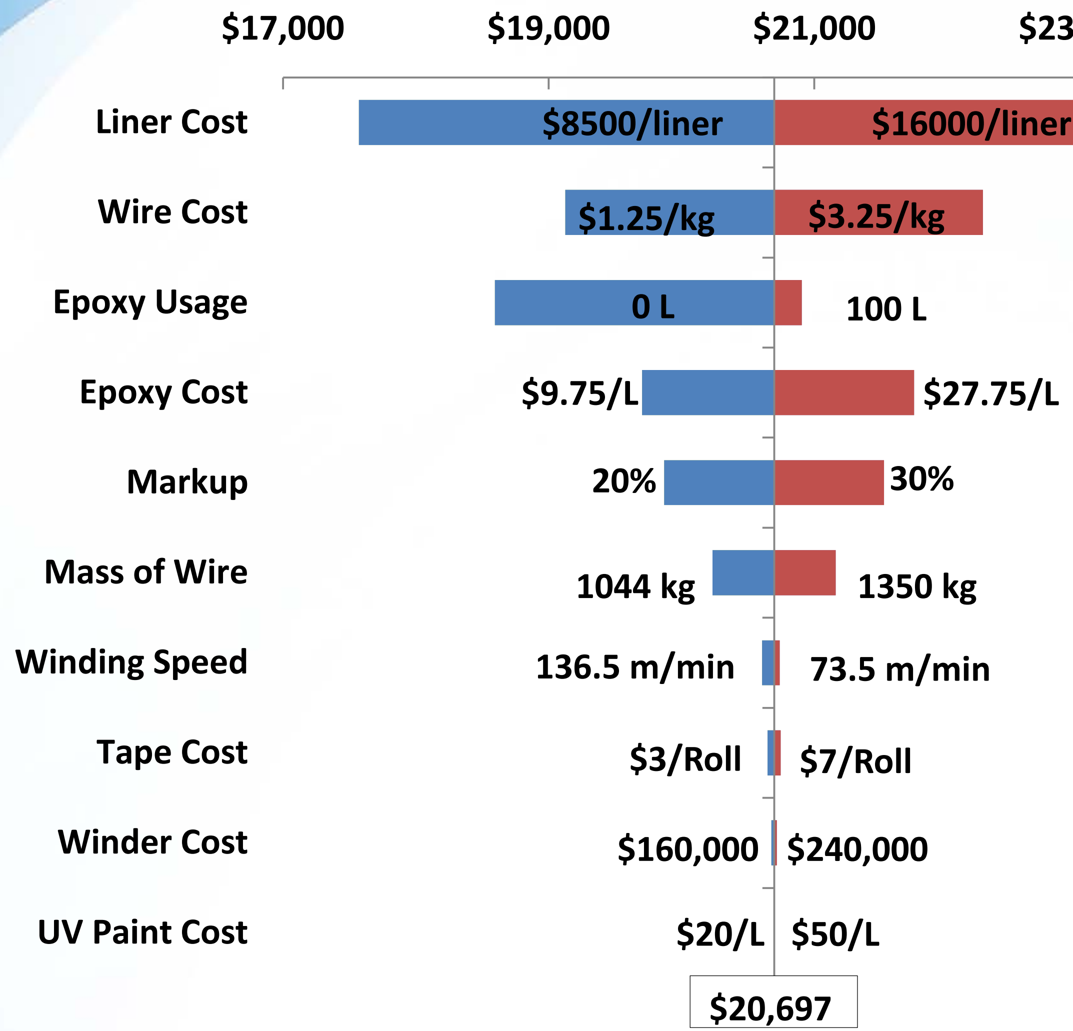
# Pressure Vessel Analysis Results



# Single Parameter Sensitivity Study for 3,000 vessels per year




**Liner is most uncertain cost element. DFMA analysis was conducted to explore cost drivers. Price quotes obtained to validate analysis. Chinese vs. US production has meaningful impact.**

Conducted a sensitivity study using generous percentages for each variable. The liner cost, wire cost, and epoxy usage are the largest cost drivers.

# Proposed Future Work

- Complete WireTough cost analysis
  - Finalize Balance of System cost analysis
  - Develop installation cost analysis for Forecourt site
  - Complete written documentation of analysis
- Production and Delivery analysis of new pathways
  - Photoelectrochemical (PEC) Production of $H_2$
  - Update analyses to reflect recent advances in Carbon Capture and Sequestration (CCS)
- Other P&D cost analysis as directed by DOE

Any proposed future work is subject to change based on future funding levels.

# Response to Reviewer Comments

| FY16 Reviewer Comments | FY16 Response to Comment |
|---|---|
| **The main sources for technical information have been research organizations rather than industry; the reasons for this are unclear.** | Actually, we often reach out to industry and have had extensive input from industry, especially for the PEM, SOEC, REP, and WireTough projects. For other projects (fermentation), industry has opted not to provide information or review for a project. For still other projects, the technology is being investigated solely by research organizations. |
| **A project weakness is lack of experimental data for emerging systems.** | When possible, experimental data is gathered from research groups or from journals. However, some research groups do not have complete research data. |
| **The project should ensure that assumptions are harmonized with Argonne National Laboratory's (ANL's) analysis work since ANL is working on the same cases to assess the lifecycle footprint of the technologies.** | ANL is a member of the project team. SA has provided data from our work to ANL's LCA analysis team for use in their studies, specifically the report and PFD developed for our fermentation analysis. Coordination was increased this past year. |
| **It is not clear whether any other pathways are planned or how the analyzed pathways are selected.** | Other pathways are planned (PEC, CCS update). The selection process and criteria were added to this year's presentation (Slide 4). |

# Collaborators

| Institution | Relationship | Activities and Contributions |
| --- | --- | --- |
| **National Renewable Energy Laboratory (NREL)**<br>• Genevieve Saur<br>• Pin-Ching Maness | Subcontractor | • Participated in weekly project calls.<br>• Assisted with H2A Production Model runs & sensitivity analyses<br>• Provided laboratory data results for dark fermentation<br>• Drafted reporting materials<br>• Reviewed reporting materials |
| **Argonne National Lab (ANL)**<br>• Rajesh Ahluwalia<br>• Dennis Papadias | Subcontractor | • Participated in select project calls.<br>• Vetted process work<br>• Sized PSA systems |
| **Department of Energy (DOE)**<br>• Sarah Studer<br>• Eric Miller<br>• Katie Randolph<br>• David Peterson | Sponsor | • Participated in some weekly project calls.<br>• Assisted with H2A Model and sensitivity parameters<br>• Reviewed reporting materials |

# Summary

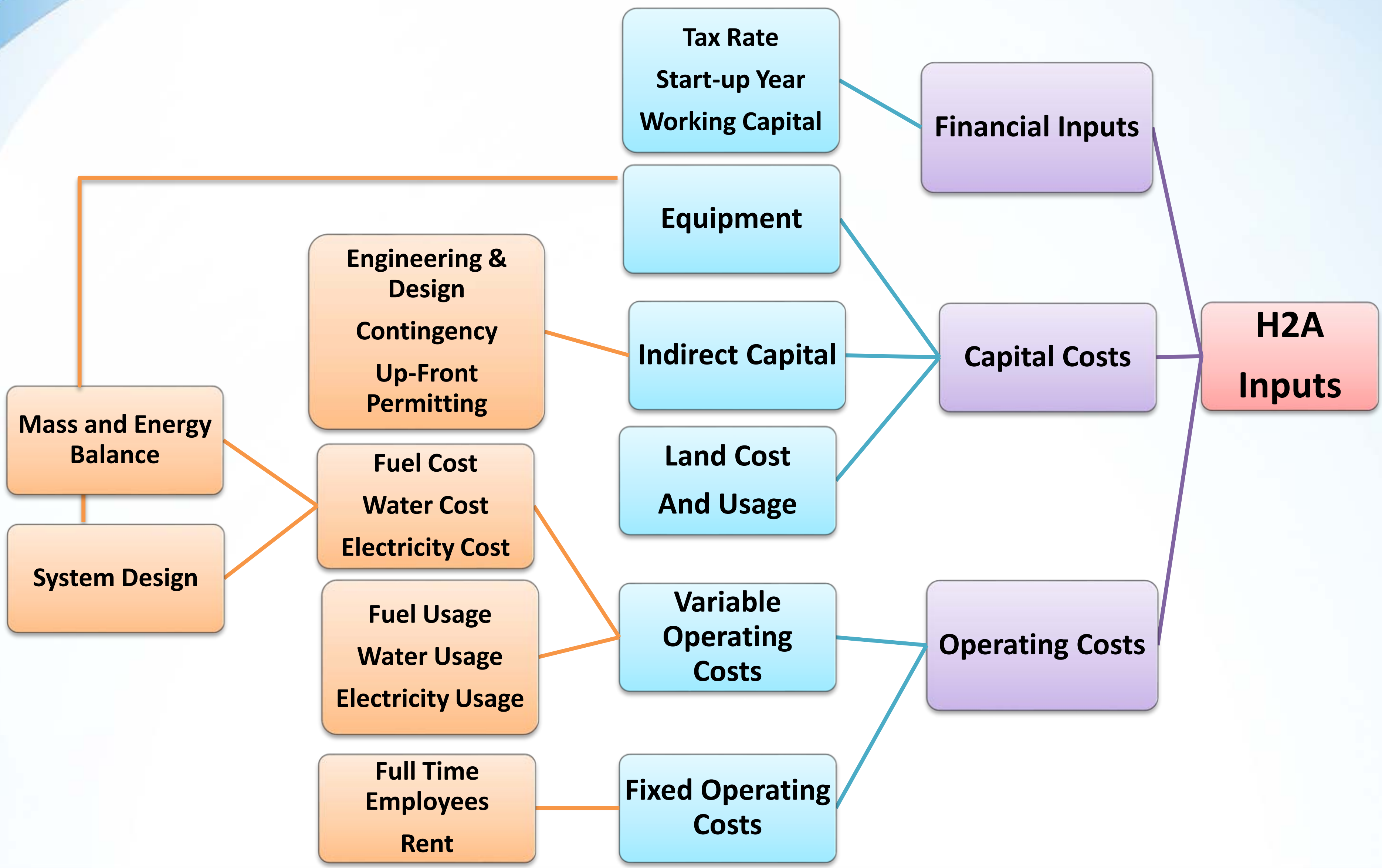
- **Overview**
  - Conducted P&D pathways cost analysis for fermentation, REP, and WireTough storage.
- **Relevance**
  - Cost analysis is a useful tool because it:
    - Provides a complete pathway definition
    - Identifies key cost drivers and helps focus research topics to lower cost
    - Creates transparent documentation available to the community with relevant data for improved collaboration
- **Approach**
    - Utilize various cost analysis methods for determining system cost: DFMA® and H2A
- **Accomplishments**
  - Updated and completed analysis of $H_2$ production via dark fermentation of corn stover
  - Completed analysis of Fuel Cell Energy's Reformer-Electrolyzer-Purifier (REP) technology
    - Two different systems analyzed: Integrated and Standalone
  - Preliminary analysis of WireTough's wire-wrapped 13kpsi $H_2$ storage
    - Further analysis regarding the Balance of System and Installation is forthcoming
  - Expanded analysis methodology to address challenges of low-TRL systems

# Thank you


- This work funded by the Fuel Cell Technologies Office at DOE/EERE under DOE contract number: DE-EE0006231.
- Special thanks to:
  - Dr. Eric Miller (DOE)
  - Dr. Katie Randolph (DOE)
  - Dr. David Peterson (DOE)

# Backup Slides

# H2A Inputs


Tax Rate
Start-up Year
Working Capital
Financial Inputs
Equipment
Engineering & Design
Contingency
Up-Front Permitting
Indirect Capital
Capital Costs
H2A Inputs
Mass and Energy Balance
System Design
Fuel Cost
Water Cost
Electricity Cost
Land Cost And Usage
Fuel Usage
Water Usage
Electricity Usage
Variable Operating Costs
Operating Costs
Full Time Employees
Rent
Fixed Operating Costs

# Fermentation Parameters and Results

Accomplishments and Progress

| Parameter | *Projected Current* Central | *Projected Future* Central |
|---|---|---|
| **Plant Capacity (kg/day)** | 50,000 | 50,000 |
| **Fermentation Broth Concentration[1] (g/L)** | 12.8 | 175 |
| **Broth volume per batch (L)** | 2.7 billion | 43.5 million |
| **Number of reactors required** | 728 | 12 |
| **Total Uninstalled Capital (2010$)** | $1,773M | $386M |
| **Total Feedstock Required (kg/kg $H_2$)** | 229.2 | 49.47 |
| **Hemi-Cellulose to Pentose Conversion (%)** **(in pretreatment reactors)** | 90 | 90 |
| **Pentose Conversion (%)** **(in fermentation reactor)** | 0 | 100 |
| **Cellulose to Hexose Conversion (%)**Error! Bookmark not defined.,2 **(in fermentation reactor)** | 98 | 98 |
| **Hexose Conversion (%)** **(in fermentation)** | 100 | 100 |
| **Molar Conversion (mol $H_2$/mol Sugar)** **(in fermentation reactor)** | 1.16 mol$H_2$/mol Hexose 74h batch time | 3.2 mol$H_2$/mol (Pentose & Hexose) for 74h batch time |
| **Energy Byproduct Recovery** | Energy Excess | Energy Excess |
| **Electrical Energy Purchased (kWh/kg $H_2$)** | 5.4 | 2.6 |
| **Electrical Energy Byproduct (kWh/kg $H_2$)[3,4]** | 179 | 116 |
| **Repair And Maintenance Costs** **(% of capital cost/year)** | 0.5 | 0.5 |

[1] Broth concentration is not an actual input to the H2A model but is listed here because it is a defining parameter in determining capital cost and energy use.
[2] Varanasi, S., Rao, K., Relu, P. A. & Yuan, D. Methods for Fermentation of Xylose and Hexose Sugars. (2013).
[3] Electrical purchases and byproducts are reported separately for clarity but in practice only a net electrical transaction would occur.
[4] Energy purchase and byproduct are book-kept separately to ensure clarity of energy distribution. In reality, most facilities would likely use the generated energy onsite to run the plant equipment.

| Component | *Projected Current* Central *50,000 kg/day* | *Projected Future* Central *50,000 kg/day* |
|---|---|---|
| *Installed Capital Cost* | $36.08 | $7.86 |
| *Decommissioning* | $0.05 | $0.01 |
| *Fixed operations and maintenance (O&M)* | $5.80 | $1.49 |
| *Feedstock Costs[1]* | $18.01 | $3.82 |
| *Byproduct Credits* | -$11.93 | -$8.19 |
| *Variable O&M (including electrical utilities)* | $3.15 | $0.65 |
| **Total $H_2$ Production Cost (2007$/kg $H_2$) with byproduct credits** | **$51.17** | **$5.65[2]** |
| **Total $H_2$ Production Cost (2007$/kg $H_2$ without steam generator or energy byproduct[3]** | **$63.41** | **$8.56** |

[1] 2009 AEO Projections for Corn Stover Feedstock.
[2] While the sum of the *projected Future* Case subcategory costs in **Table 3** is $5.64/kg $H_2$, this is due to rounding of the subcategory costs and the actual H2A projected total cost is $5.65/kg $H_2$
[3] Removal of the byproduct energy credit also considers removing the associated steam-turbine generator from the system, reducing the total capital cost. As such, the price adjustment is not a simple subtraction of the byproduct credit.

Current case for fermentation requires excessive heat due to the low broth concentration and the resulting large volumes. This heat requirement leads to the high price.

# REP Tornado Charts