Overview

• Overview of H2A

• Past H2A techno-economic analyses of water splitting technologies
  – High Temperature Solid Oxide Electrolysis Cell (SOEC)
  – Photoelectrochemical (PEC)
  – Solar Thermochemical Hydrogen (STCH)

• System and Component Metrics
  – Tiered technology metrics
    • Common metrics for technologies
    • Local metrics for developmental technologies
Overview of H2A

• H2A is a discounted cash flow analysis that computes the required pump price of H$_2$ for a desired after-tax internal rate of return (IRR)
• SA uses the H2A tool along with a blend of TEA approaches
• Uses custom macros within Microsoft Excel
• NREL developed H2A
  – https://www.hydrogen.energy.gov/h2a_analysis.html
• Objective:
  – Establish a standard format for reporting the price of H$_2$ to compare technologies and case studies
  – Analyze H$_2$ cost from new technologies in transparent manner
  – Apply a consistent approach to analysis
H2A Inputs

- Tax Rate
- Start-up Year
- Working Capital

Financial Inputs

- Equipment

Capital Costs

Indirect Capital

- Land Cost
- And Usage

Operating Costs

Variable Operating Costs

Fixed Operating Costs

Total Operating Costs

- Full Time Employees
- Rent

System Design

- Mass and Energy Balance

- Fuel Cost
- Water Cost
- Electricity Cost

Engineering & Design

- Contingency
- Up-Front Permitting

Fuel Usage

- Water Usage
- Electricity Usage
Technology Readiness Level (TRL)

- Technology Readiness Level
  - A.K.A. Technology Readiness Assessment
  - Measure of development status of a given technology

- Various TRL definitions
  - NASA
  - DOD
  - DOE
  - European Space Agency
  - Oil and Gas Industry
  - And More!

- Use in H2A
  - Future case TRL is generically assumed to be higher than the Current case
    - May estimate parameters that raise the TRL for Future case
  - If the Current case TRL is low enough, only Future case analysis might be conducted
TRL Descriptions

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
## DOE TRL Descriptions

### Table 1 Technology Readiness Levels

<table>
<thead>
<tr>
<th>Relative Level of Technology Development</th>
<th>TRL Level</th>
<th>TRL Definition</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>System Operations</td>
<td>TRL 9</td>
<td>Actual system operated over the full range of expected conditions.</td>
<td>Actual operation of the technology in its final form, under the full range of operating conditions. Examples include using the actual system with the full range of real wastes.</td>
</tr>
<tr>
<td>System Commissioning</td>
<td>TRL 8</td>
<td>Actual system completed and qualified through test and demonstration.</td>
<td>Technology has been proven to work in its final form and under expected conditions. In almost all cases, this TRL represents the end of true system development. Examples include developmental testing and evaluation of the system with real waste in hot commissioning.</td>
</tr>
<tr>
<td></td>
<td>TRL 7</td>
<td>Full-scale, similar (prototypical) system demonstrated in a relevant environment</td>
<td>Prototype full scale system. Represents a major step up from TRL 6, requiring demonstration of a system prototype in a relevant environment. Examples include testing the prototype in the field with a range of simulants and/or real waste and cold commissioning.</td>
</tr>
<tr>
<td>Technology Demonstration</td>
<td>TRL 6</td>
<td>Engineering scale, similar (prototypical) system validation in a relevant environment</td>
<td>Representative engineering scale system, which is well beyond the scale tested for TRL 5, is tested in a relevant environment. Represents a major step up in a technology’s demonstrated readiness and system integration. Examples include testing a prototype with real waste and a range of simulants.</td>
</tr>
<tr>
<td>Technology Development</td>
<td>TRL 5</td>
<td>Laboratory/bench scale, similar system validation in relevant environment</td>
<td>The basic technological components are integrated so that the system configuration is similar to (matches) the final application in almost all respects. Examples include testing a high-fidelity system in a simulated environment and/or with a range of real wastes and simulants.</td>
</tr>
<tr>
<td></td>
<td>TRL 4</td>
<td>Component and/or system validation in laboratory environment</td>
<td>Basic technological components are integrated to establish that the pieces will work together. This is relatively “low-fidelity” compared with the eventual system. Examples include integration of “ad hoc” hardware in a laboratory and testing with a range of simulants. Laboratory/bench scale testing may not be appropriate for all systems. For example, mechanical systems, such as robotic retrieval technologies, may require full scale prototype testing to meet TRL 4.</td>
</tr>
<tr>
<td>Research to Prove Feasibility</td>
<td>TRL 3</td>
<td>Analytical and experimental critical function and/or characteristic proof of concept</td>
<td>Active research and development is initiated. This includes analytical studies and laboratory/bench scale studies to physically validate the analytical predictions of separate elements of the technology. Examples include components that are not yet integrated or representative. Components may be tested with simulants. For example, mechanical systems, this may include computer and/or physical modeling to demonstrate functionality.</td>
</tr>
<tr>
<td>Basic Technology Research</td>
<td>TRL 2</td>
<td>Technology concept and/or application formulated</td>
<td>Invention begins. Once basic principles are observed, practical applications can be invented. Applications are speculative, and there may be no proof or detailed analysis to support the assumptions. Examples are still limited to analytic studies.</td>
</tr>
<tr>
<td></td>
<td>TRL 1</td>
<td>Basic principles observed and reported</td>
<td>Lowest level of technology readiness. Scientific research begins to be translated into applied research and development (R&amp;D). Examples might include paper studies of a technology’s basic properties.</td>
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</tbody>
</table>

High Temperature Solid Oxide Electrolysis Cells
SOEC Technology

SOEC water electrolysis uses electricity to split water ($\text{H}_2\text{O}$) into oxygen ($\text{O}_2$) and hydrogen ($\text{H}_2$).

- Overall endothermic reaction: $\text{Energy} + \text{H}_2\text{O} \rightarrow \text{H}_2 + \frac{1}{2}\text{O}_2$
- Power: An external power supply delivers direct current (DC) electricity such that electrons ($e^-$) flow through an external electric current.

- Cathode (negative terminal): Steam ($\text{H}_2\text{O}$) reacts with electrons ($e^-$) in the presence of catalyst to form negatively charged oxygen ions ($\text{O}_2^-$) (or anions) and hydrogen gas ($\text{H}_2$).
- Electrolyte: Oxygen ions ($\text{O}_2^-$) traverse the electrolyte.
- Anode (positive terminal): In the presence of catalyst, oxygen ions ($\text{O}_2^-$) release their electrons ($e^-$) to the external circuit and form oxygen gas ($\text{O}_2$).
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
The two public H2A cases use this input data, which is based on performance data from a six member expert panel.

<table>
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<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>

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<tr>
<th>Direct Capital Costs</th>
<th>Current</th>
<th>Future</th>
<th>Value Basis</th>
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</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$/kW) - (with approx. subsystem breakdown)</td>
<td>789</td>
<td>414</td>
<td>Ind. Questionnaire</td>
</tr>
<tr>
<td>Stacks</td>
<td>35%</td>
<td>23%</td>
<td>Ind. Questionnaire</td>
</tr>
<tr>
<td>BoP Total</td>
<td>65%</td>
<td>77%</td>
<td>Ind. Questionnaire</td>
</tr>
<tr>
<td>Installation factor (a multiplier on unpacked capital cost)</td>
<td>1.12</td>
<td>1.10</td>
<td>H2A/Eng. Judg.</td>
</tr>
</tbody>
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<tr>
<th>Indirect Capital Costs</th>
<th>Current</th>
<th>Future</th>
<th>Value Basis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Project contingency ($)</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>

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<th>Replacement Schedule</th>
<th>Current</th>
<th>Future</th>
<th>Value Basis</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 two public H2A cases use this input data, which is based on performance data from a six member expert panel.

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<th>Parameters</th>
<th>Current</th>
<th>Future</th>
<th>Value Basis</th>
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<tbody>
<tr>
<td><strong>O&amp;M Costs - Fixed</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yearly maintenance costs ($/kg H2)</td>
<td>3%</td>
<td>3%</td>
<td>H2A/Eng. Judge.</td>
</tr>
<tr>
<td><strong>O&amp;M Costs - Variable</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total plant staff (total FTE's)</td>
<td>10</td>
<td>10</td>
<td>H2A/Eng. Judge.</td>
</tr>
<tr>
<td>Total Annual Unplanned Replacement Cost</td>
<td>0.50%</td>
<td>0.50%</td>
<td>H2A</td>
</tr>
<tr>
<td>(% of total direct depreciable costs/year)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Feedstocks and Other Materials</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>System Electricity Usage (kWh/kg H2)</td>
<td>36.8</td>
<td>35.1</td>
<td>Ind. Questionnaire</td>
</tr>
<tr>
<td>System Heat Usage (kWh/kg H2)</td>
<td>14.10</td>
<td>11.50</td>
<td>Ind. Questionnaire</td>
</tr>
<tr>
<td>Total Energy Usage (kWh/kg H2)</td>
<td>50.9</td>
<td>46.6</td>
<td>Ind. Questionnaire</td>
</tr>
<tr>
<td>Process water usage (gal/kg H2)</td>
<td>2.38</td>
<td>2.38</td>
<td>H2A/Eng. Calc.</td>
</tr>
<tr>
<td><strong>By-Product Revenue or Input Streams</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electricity cost (2007$/kWh)</td>
<td>0.0624</td>
<td>0.0689</td>
<td>AEO/Eng. Calc.</td>
</tr>
<tr>
<td>Heating cost (2007$/kWh)</td>
<td>0.036</td>
<td>0.041</td>
<td>DOE/Eng. Calc.</td>
</tr>
<tr>
<td>Process water cost (2007$/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>H2A</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.
# Degradation Values

<table>
<thead>
<tr>
<th></th>
<th>Units</th>
<th>Current Case</th>
<th>Future Case</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Current Density (BOL)</strong></td>
<td>A/cm</td>
<td>1.0</td>
<td>1.5</td>
</tr>
<tr>
<td><strong>Cell Voltage</strong></td>
<td>V/cell</td>
<td>1.28</td>
<td>1.28</td>
</tr>
<tr>
<td><strong>Voltage Degradation</strong></td>
<td>%/1000h</td>
<td>0.9%</td>
<td>0.25%</td>
</tr>
<tr>
<td><strong>Voltage Degradation</strong></td>
<td>mv/1000h</td>
<td>11</td>
<td>3.15</td>
</tr>
<tr>
<td><strong>Ohmic Degradation Rate</strong></td>
<td>mOhm-cm²/1000h</td>
<td>11</td>
<td>2.1</td>
</tr>
<tr>
<td><strong>Stack Service Lifetime</strong></td>
<td>years</td>
<td>4</td>
<td>7</td>
</tr>
<tr>
<td><strong>% of Design Capacity at End</strong></td>
<td>%</td>
<td>83.2%</td>
<td>94.5%</td>
</tr>
<tr>
<td><strong>H2A Plant Capacity Factor</strong></td>
<td>%</td>
<td>90%</td>
<td>90%</td>
</tr>
<tr>
<td><strong>Overall Effective Plant Capacity Factor</strong></td>
<td>%</td>
<td>82.4%</td>
<td>87.5%</td>
</tr>
<tr>
<td><strong>BoP Service Lifetime</strong></td>
<td>years</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td><strong>BoP Replacement Cost</strong></td>
<td>%</td>
<td>100%</td>
<td>100%</td>
</tr>
</tbody>
</table>

We use Ohmic degradation rate to assess the annual impact on H₂ production rate. Rates calculated by methods described in Hjelm[3]

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[1] BOL = Beginning of Life
[2] Absolute ASR degradation rate computed using secant method based on 0.85V open circuit voltage, BOL conditions and voltage degradation as stated.
SOEC Costs

SOEC H2A Case Cost Summary

Current Central: $4.95/kg
Future Central: $3.83/kg

Cost Breakdown:
- Stack Capital Costs
- BoP Capital Costs
- Indirect Capital Costs and Replacement Costs
- Decommissioning Costs
- Fixed O&M
- Other Variable Costs
- Thermal Energy Feedstock Costs (includes heat at 3.6 and 4.1 c/kWh)
- Electricity Utility (6.24 and 6.89 c/kWh - Effective Price over Plant Life)

*Error bars represent ±50% capital cost (solid line) and 90% confidence interval based on Monte Carlo simulation (dashed line).
Photoelectrochemical
PEC Design Concepts

Colloidal Suspensions

- Single Bed (Mixed $\text{H}_2$/O$_2$) Type 1
- Dual Bed (Separate $\text{H}_2$ and O$_2$) Type 2

PEC Electrode

- Fixed Panel Type 3
- Tracking Concentrator Type 4

Photons
$\text{H}_2$ gas
$\text{O}_2$ gas
Water

$\text{H}_2$ and O$_2$ Capture
KOH Solution

$\text{H}_2$ gas
$\text{O}_2$ gas
Basic PEC System Design
Type 2 Colloidal Suspension System

Plant Capacity = 1 TPD Module x 10

Photoreactive Nanoparticles
40nm base with two 5nm coatings

\[ 4 \text{ photons} + 4A + 2H_2O \rightarrow \]
\[ O_2 + 4H^+ + 4A^- \]

\[ 4 \text{ photons} + 4H^+ 4A^- \rightarrow \]
\[ 2H_2 + 4A \]

[ A is Iodine, Iron (III), Iron (II), or other]

\[ O_2 \text{ vented from end of } O_2 \text{ bed} \]
\[ H_2 \text{ removal from end of } H_2 \text{ bed} \]
\[ \text{Active circulation of solution within beds} \]

Gas Capture Subassembly

Compressor
HX/Condensor
Hydrogen Flow Meter
Hydrogen Pipeline

Gas Capture Subassembly

Compressor
HX/Condensor

Hydrogen Flow Meter
Hydrogen Pipeline

\[ \text{Hydrogen Flow Meter} \]

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\[ \text{Gas Capture Subassembly} \]

\[ \text{Compressor} \]

\[ \text{HX/Condensor} \]

\[ \text{Hydrogen Flow Meter} \]

\[ \text{Hydrogen Pipeline} \]
Basic Assumptions: Type 2 Colloidal Suspension System: Dual Bed Photocatalyst

- Coated Nanoparticles in in shallow plastic (HDPE) bags of 0.1M KOH Electrolyte Solution
- Two bed system: one for $H_2$ generation, one for $O_2$ generation
- 5% (2020) Solar-to-Hydrogen Efficiency
- Product Gas after condenser: 99% $H_2$, 1% water
- $H_2$ compression to 300psi (external compressor)
- LDPE fibrous mat is liquid permeable “window” between beds
- 6 mil HDPE transparent bags (90% optical transparency)
- Fabricated in factory: unrolled in field
- Perforated PVC pipes for mixing

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Units</th>
<th>2020 Target</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar to Hydrogen (STH) Energy Conversion Ratio</td>
<td>%</td>
<td>5%</td>
</tr>
<tr>
<td>PEC particle cost</td>
<td>$/kg</td>
<td>500</td>
</tr>
<tr>
<td>Particle Replacement Lifetime</td>
<td>Years</td>
<td>1</td>
</tr>
<tr>
<td>Capital cost of reactor bed system (excluding installation and PEC particles)</td>
<td>$/m$²</td>
<td>$7$</td>
</tr>
<tr>
<td>Balance of Plant Cost per TPD $H_2$</td>
<td>$/TPD</td>
<td>$1.0M</td>
</tr>
</tbody>
</table>
Bottom-Up Technology Status: Type 2 PEC 2020 Target

- Levelized Cost of Hydrogen: $\text{4.07} / \text{kg (2007\$)}$
- Installed Equipment Cost: $\text{2.7M} \text{ (for 1 TPD module)}$
- Total Capital Investment: $\text{3.7M} \text{ (for 1 TPD module)}$
- Capital Costs represent the majority (70.4\%) of H_2 cost.

### Specific Item Cost Calculation

<table>
<thead>
<tr>
<th>Cost Component</th>
<th>Cost Contribution ($/kg)</th>
<th>Percentage of H_2 Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capital Costs</td>
<td>$2.87</td>
<td>70.4%</td>
</tr>
<tr>
<td>Decommissioning Costs</td>
<td>$0.00</td>
<td>0.1%</td>
</tr>
<tr>
<td>Fixed O&amp;M</td>
<td>$1.06</td>
<td>26.1%</td>
</tr>
<tr>
<td>Feedstock Costs</td>
<td>$0.00</td>
<td>0.0%</td>
</tr>
<tr>
<td>Other Raw Material Costs</td>
<td>$0.00</td>
<td>0.0%</td>
</tr>
<tr>
<td>Byproduct Credits</td>
<td>$0.00</td>
<td>0.0%</td>
</tr>
<tr>
<td>Other Variable Costs (including utilities)</td>
<td>$0.14</td>
<td>3.4%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>$4.07</strong></td>
<td></td>
</tr>
</tbody>
</table>

- Capital cost is majority cost contributor
- Fixed O&M is mostly labor.
Solar Thermochemical Hydrogen Production
STCH Concept: Solar Dishes

Large field of STCH dishes:
- ~30,000 dishes (for 100TPD $H_2$)
- ~4,400 acres

Each dish:
- 11m (37ft) in diameter
- 88 m$^2$ of solar capture area
- ~3.2 kg$H_2$/day (average)

Line/Pipe connections for:
- $H_2$
- Power
- Water (although one variant uses abs. chillers to capture environmental water vapor)

Latest Sandia Reactor Concept (moving packed bed, spatial pressure separation)
Example STCH System Configuration

Figure from TIAX 2009.

Figure from NREL/SR-550-34440, 2003.
Three H2A Case Studies on STCH

Nominal plant size for Central cases is 100 metric tons H₂ per day (enough to support ~131,000 vehicles). Intent is to be a “large” plant. The H2A analysis reviews a STCH system producing 100,000 kg of H₂ per day

2015 Case
- The 2015 case is a projection from current STCH technology
- Assumes the optimal performance of the Ceria redox cycle
- Increased solar to H₂ conversion efficiency
- Reduction in capital cost from currently accepted values

2020 Case (Data in this presentation represents this case)
- More advanced material used for redox cycle, some type of perovskite
  - Shorter cycle time (time to split H₂O into O₂ and H₂)
  - Longer lifetime
  - Increased H₂ evolution (moles of H₂ produced per gram of ceria).
- The solar to H₂ conversion efficiency increases
- Reductions in capital cost.

Ultimate Target Case
- Assumptions based on expected limit of technology.
- Generally expected to reach/approach DOE target of $2/kgH₂.
2020 Case Study Results

Levelized Cost of Hydrogen (production only): $8.83/kg (2007$)
Uninstalled STCH System Cost: $783,405,000
Total Installed Capital Investment: $1,177,742,181
Lang Factor = 1.5
STH Efficiency of System: 16.7%
Electricity Use: 6.855 kWh / kg H₂ produced
Electricity Price in Startup Year: 5.9¢/kWh

Breakdown of Levelized Costs:

<table>
<thead>
<tr>
<th>Specific Item Cost Calculation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cost Component</strong></td>
</tr>
<tr>
<td>Capital Costs</td>
</tr>
<tr>
<td>Decommissioning Costs</td>
</tr>
<tr>
<td>Fixed O&amp;M</td>
</tr>
<tr>
<td>Feedstock Costs</td>
</tr>
<tr>
<td>Other Raw Material Costs</td>
</tr>
<tr>
<td>Byproduct Credits</td>
</tr>
<tr>
<td>Other Variable Costs (including utilities)</td>
</tr>
<tr>
<td><strong>Total</strong></td>
</tr>
</tbody>
</table>
Focus on Key Parameters:
STCH Efficiency Example

<table>
<thead>
<tr>
<th>Component Efficiency</th>
<th>2015 Value</th>
<th>Definition</th>
<th>2020 Value</th>
<th>Ultimate Target Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optical Efficiency</td>
<td>75%</td>
<td>Energy fraction of total solar that is reflected to receiver</td>
<td>75%</td>
<td>75%</td>
</tr>
<tr>
<td>Receiver Thermal Efficiency</td>
<td>82%</td>
<td>Energy fraction of reflected light that is absorbed by active material</td>
<td>89%</td>
<td>91%</td>
</tr>
<tr>
<td>Reactor Conversion Efficiency</td>
<td>10%</td>
<td>Energy fraction of absorbed energy that is converted to H$_2$ (LHV)</td>
<td>25%</td>
<td>50%</td>
</tr>
<tr>
<td>STH Efficiency</td>
<td>6.2%</td>
<td>Product of above.</td>
<td>16.7%</td>
<td>34.3%</td>
</tr>
</tbody>
</table>

- Receiver thermal efficiency: scales with $T^4$ thermal radiation losses
- Reactor conversion efficiency: based on 70% heat recovery

Calculate STH efficiency from sub-component efficiencies. Explanation of basis is good for each estimate/value.
STH Efficiency Is a Key Parameter

STH Efficiency = Solar-to-Hydrogen Conversion Efficiency

\[
\text{STH Efficiency} = \frac{\text{(LHV of Net } \text{H}_2 \text{ out of System)}}{\text{(total solar energy input into system collector)}}
\]

Full spectrum energy

(If STH efficiency varies with light intensity, report average conversion.)

Solar Insolation assumptions can be tricky.

Key point is to make sure major terms are consistent with each other:

- solar energy/intensity
  Generally 7.46 kWh/m²/day (yearly average)
  1 kWh/m² (hourly peak)
- collection area
  Also consider: direct/indirect insol., tracking, blockage
- capital cost
  Sized for hourly peak production (or have explicit alternative story)
- \( \text{H}_2 \) Production Rate
  Must reconcile hourly peak, daily & seasonal variations
Metrics
Metrics

• Metrics must be meaningful and useful

• Two types
  – **System metrics** to assess the planned final large-scale operation
    • System metrics/ performance are what ultimately matter
  – **Local/Component metrics** to assess narrow-field progress
    • Are a means to an end (to achieve high system performance)
    • Can “miss” one (or more) local metrics to achieve high system performance
    • Don’t have to capture all performance aspects in each metric
    • Ideally applies to multiple technologies (but doesn’t have to)
    • Ideally will be easy to measure

It’s surprisingly hard to come up with clear, concise, workable metrics.
# Common System Metrics

<table>
<thead>
<tr>
<th>Metric</th>
<th>Unit</th>
<th>Ultimate Target</th>
<th>PEC</th>
<th>STCH</th>
<th>SOEC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost of H₂</td>
<td>$/kg</td>
<td>2.00</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Electrical Usage</td>
<td>kWh/kg H₂</td>
<td>Not listed</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Solar to H₂ Conversion</td>
<td>%</td>
<td>25-26</td>
<td>✓</td>
<td>✓</td>
<td>❌</td>
</tr>
<tr>
<td>Green House Gas</td>
<td>KgCo₂eqiv/kgH₂</td>
<td>-</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Active Material (Electrode) Cost</td>
<td>$/(TPD H₂·yr)</td>
<td>Varies</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>H₂ production rate</td>
<td>kg H₂/(s·m²)</td>
<td>Varies</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

- Cost is King and can be calculated in H2A with normalized and transparent assumptions
- System efficiency includes all energy provided to the system (thermal, solar, electrical, etc.) ratioed to the LHV of H₂
- Values for Active Material provide accounting for useful life span
- Units with a per area basis may help in selecting technologies based on land available

Values taken from 2015 MYRDD. [https://www1.eere.energy.gov/hydrogenandfuelcells/mypp/index.html](https://www1.eere.energy.gov/hydrogenandfuelcells/mypp/index.html)
<table>
<thead>
<tr>
<th>Category</th>
<th>Metric</th>
<th>Units</th>
<th>STCH</th>
<th>PEC</th>
<th>SOEC</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Subsystem/Component Cost</strong></td>
<td>Particle/Electrode Cost</td>
<td>$/kg</td>
<td>✓</td>
<td>✓</td>
<td>✗</td>
</tr>
<tr>
<td></td>
<td>Stack Cost</td>
<td>$/stack</td>
<td>✗</td>
<td>✗</td>
<td>✓</td>
</tr>
<tr>
<td></td>
<td>Active Mat. Cost per kg H₂</td>
<td>$/kg H₂</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td></td>
<td>Active Material to H₂</td>
<td>kg mat/kg H₂</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td><strong>Material Lifetime</strong></td>
<td>Particle/Electrode Lifetime</td>
<td>Yrs</td>
<td>✓</td>
<td>✓</td>
<td>✗</td>
</tr>
<tr>
<td></td>
<td>Stack Lifetime or Voltage degrad./1000 hrs</td>
<td>Yrs</td>
<td>✗</td>
<td>✗</td>
<td>✓</td>
</tr>
<tr>
<td></td>
<td>Active Mat. Degrad. Rate</td>
<td>%/hr</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td><strong>Performance</strong></td>
<td>H₂ production efficiency</td>
<td>%</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td></td>
<td>Component Elect. Usage</td>
<td>kWh/kg</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td></td>
<td>Cycle time</td>
<td>min/cycle</td>
<td>✓</td>
<td>✗</td>
<td>✗</td>
</tr>
<tr>
<td></td>
<td>Reactor Conv. Efficiency</td>
<td>%</td>
<td>✓</td>
<td>✗</td>
<td>✗</td>
</tr>
<tr>
<td></td>
<td>O₂ Transfer</td>
<td>Mol O/mol act. Mat.</td>
<td>✓</td>
<td>✗</td>
<td>✗</td>
</tr>
<tr>
<td></td>
<td>Power Density/Current</td>
<td>mW/cm², A/cm²</td>
<td>✗</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>
DOE Multi-Year Research, Development, and Demonstration (MYRDD) Technical Target Tables: STCH

https://www1.eere.energy.gov/hydrogenandfuelcells/mypp/index.html

**Table 3.1.7 Technical Targets: Solar-Driven High-Temperature Thermochemical Hydrogen Production**

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Units</th>
<th>2011 Status</th>
<th>2015 Target</th>
<th>2020 Target</th>
<th>Ultimate Target</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar-Driven High-Temperature Thermochemical Cycle Hydrogen Cost</td>
<td>$/kg</td>
<td>NA</td>
<td>14.80</td>
<td>3.70</td>
<td>2.00</td>
</tr>
<tr>
<td>Chemical Tower Capital Cost (installed cost)</td>
<td>$/TPD H₂</td>
<td>NA</td>
<td>4.1MM</td>
<td>2.3MM</td>
<td>1.1MM</td>
</tr>
<tr>
<td>Annual Reaction Material Cost per TPD H₂</td>
<td>$/yr.-TPD H₂</td>
<td>NA</td>
<td>1.47M</td>
<td>89K</td>
<td>11K</td>
</tr>
<tr>
<td>Solar to Hydrogen (STH) Energy Conversion Ratio</td>
<td>%</td>
<td>NA</td>
<td>10</td>
<td>20</td>
<td>26</td>
</tr>
<tr>
<td>1-Sun Hydrogen Production Rate</td>
<td>kg/s per m²</td>
<td>NA</td>
<td>8.1E-7</td>
<td>1.6E-6</td>
<td>2.1E-6</td>
</tr>
</tbody>
</table>

**Table 3.1.7.A Example Parameter Values to Meet Cost Targets: Solar-Driven High-Temperature Thermochemical Hydrogen Production**

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Units</th>
<th>2011 Status</th>
<th>2015 Target</th>
<th>2020</th>
<th>Ultimate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar to Hydrogen (STH) Energy Conversion Ratio</td>
<td>%</td>
<td>NA</td>
<td>10</td>
<td>20</td>
<td>26</td>
</tr>
<tr>
<td>Cycle Time</td>
<td>minutes/cycle</td>
<td>NA</td>
<td>5</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>Reaction Material Cost</td>
<td>$/kg</td>
<td>270</td>
<td>270</td>
<td>270</td>
<td>270</td>
</tr>
<tr>
<td>Reaction Material Replacement Lifetime</td>
<td>years</td>
<td>NA</td>
<td>1</td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>Heliostat Capital Cost (installed cost)</td>
<td>$/m²</td>
<td>200</td>
<td>140</td>
<td>75</td>
<td>75</td>
</tr>
</tbody>
</table>
## DOE MYRDD Technical Target Tables: PEC (Photoelectrode)

https://www1.eere.energy.gov/hydrogenandfuelcells/mypp/index.html

### Table 3.1.8 Technical Targets: Photoelectrochemical Hydrogen Production: Photoelectrode System with Solar Concentration

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Units</th>
<th>2011 Status</th>
<th>2015 Target</th>
<th>2020 Target</th>
<th>Ultimate Target</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photoelectrochemical Hydrogen Cost</td>
<td>$/kg</td>
<td>NA</td>
<td>17.30</td>
<td>5.70</td>
<td>2.10</td>
</tr>
<tr>
<td>Capital cost of Concentrator &amp; PEC Receiver (non-installed, no electrode)</td>
<td>$/m²</td>
<td>NA</td>
<td>200</td>
<td>124</td>
<td>63</td>
</tr>
<tr>
<td>Annual Electrode Cost per TPD H₂</td>
<td>$/yr-TPDH₂</td>
<td>NA</td>
<td>2.0M</td>
<td>255K</td>
<td>14K</td>
</tr>
<tr>
<td>Solar to Hydrogen (STH) Energy Conversion Ratio</td>
<td>%</td>
<td>4 to 12%</td>
<td>15</td>
<td>20</td>
<td>25</td>
</tr>
<tr>
<td>1-Sun Hydrogen Production Rate</td>
<td>kg/s per m²</td>
<td>3.3E-7</td>
<td>1.2E-6</td>
<td>1.6E-6</td>
<td>2.0E-6</td>
</tr>
</tbody>
</table>

### Table 3.1.8.A Example Parameter Values to Meet Cost Targets: Photoelectrochemical Hydrogen Production (Photoelectrode System)

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Units</th>
<th>2011 Status</th>
<th>2015</th>
<th>2020</th>
<th>Ultimate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar to Hydrogen (STH) Energy Conversion Ratio</td>
<td>%</td>
<td>NA</td>
<td>15</td>
<td>20</td>
<td>25</td>
</tr>
<tr>
<td>PEC Electrode cost</td>
<td>$/m²</td>
<td>NA</td>
<td>300</td>
<td>200</td>
<td>100</td>
</tr>
<tr>
<td>Electrode Cost per TPD H₂</td>
<td>$/TPD</td>
<td>NA</td>
<td>1.0M</td>
<td>510K</td>
<td>135K</td>
</tr>
<tr>
<td>Electrode Replacement Lifetime</td>
<td>Years</td>
<td>NA</td>
<td>0.5</td>
<td>2</td>
<td>10</td>
</tr>
<tr>
<td>Balance of Plant Cost per TPD H₂</td>
<td>$/TPD</td>
<td>NA</td>
<td>420K</td>
<td>380K</td>
<td>310K</td>
</tr>
</tbody>
</table>
# DOE MYRDD Technical Target Tables:

**PEC (Colloidal, Dual Bed)**

https://www1.eere.energy.gov/hydrogenandfuelcells/mypp/index.html

### Table 3.1.9 Technical Targets: Photoelectrochemical Hydrogen Production: Dual Bed Photocatalyst System

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Units</th>
<th>2011 Status</th>
<th>2015 Target</th>
<th>2020 Target</th>
<th>Ultimate Target</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photoelectrochemical Hydrogen Cost</td>
<td>$/kg</td>
<td>NA</td>
<td>28.60</td>
<td>4.60</td>
<td>2.10</td>
</tr>
<tr>
<td>Annual Particle Cost per TPD H₂</td>
<td>$/yr-TPDH₂</td>
<td>NA</td>
<td>1.4M</td>
<td>71K</td>
<td>4K</td>
</tr>
<tr>
<td>Solar to Hydrogen (STH) Energy Conversion Ratio</td>
<td>%</td>
<td>NA</td>
<td>1</td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>1-Sun Hydrogen Production Rate</td>
<td>kg/s per m²</td>
<td>NA</td>
<td>8.1E-8</td>
<td>4.1E-7</td>
<td>8.1E-7</td>
</tr>
</tbody>
</table>

### Table 3.1.9.A Example Parameter Values to Meet Cost Targets: Photoelectrochemical Hydrogen Production (Dual Bed Photocatalyst)

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Units</th>
<th>2011 Status</th>
<th>2015</th>
<th>2020</th>
<th>Ultimate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar to Hydrogen (STH) Energy Conversion Ratio</td>
<td>%</td>
<td>NA</td>
<td>1</td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>PEC particle cost</td>
<td>$/kg</td>
<td>NA</td>
<td>1000</td>
<td>500</td>
<td>300</td>
</tr>
<tr>
<td>Particle Replacement Lifetime</td>
<td>Years</td>
<td>NA</td>
<td>0.5</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>Capital cost of reactor bed system (excluding installation and PEC particles)</td>
<td>$/m²</td>
<td>NA</td>
<td>7</td>
<td>7</td>
<td>5</td>
</tr>
<tr>
<td>Balance of Plant Cost per TPD H₂</td>
<td>$/TPD</td>
<td>NA</td>
<td>6.4M</td>
<td>1.0M</td>
<td>0.6M</td>
</tr>
</tbody>
</table>
Conclusions

- New materials for H$_2$ production are a high priority for DOE
  - SOEC
  - PEC
  - STCH

- Metrics must be meaningful and useful
  - **System metrics** for assessment of final large-scale operations
    - System metrics/performance are what ultimately matter
  - **Local/Component metrics** for assessment of narrow-field progress
    - Are a means to an end (good system performance)
    - Must be fair but don’t have to capture all performance and cost aspects
    - Ideally apply to multiple technologies (but don’t have to)
    - Ideally will be easy to measure
Thank You