Renewable Hydrogen Production: Leveraging Today’s Knowledge for Tomorrow’s Solutions

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Outline

• Decarbonization and the role of hydrogen
  – Not just a fueling/transportation question
• Today’s water splitting technologies
• Why are we not where we want to be?
• Stepping stones forward
Where is Hydrogen Used?

• ~50 million MT H₂/yr globally
• 2% of US energy goes through H₂

National Renewable Energy Lab, 2016
Where Does Hydrogen Come From?

- Only 4% from non-fossil fuel feedstocks
- \( \text{H}_2 \) is primarily produced via SMR (Steam methane reforming)

Converting \( \text{H}_2 \) to renewable sources cuts:
- 45% of all US carbon emissions
- 2500 M metric tons of \( \text{CO}_2 \)

- 18 products require 80% of energy and produce 75% of GHGs - Ammonia is largest by far, mainly due to \( \text{H}_2/\text{SMR} \) step
- 80% decarbonization by 2050 has to involve green hydrogen
Energy Storage

- Adding more renewables to grid requires storage
- Already have overcapacity in some areas
- Further growth expected in all geographies

Global installed wind ~400 GW
‘H2@Scale’

Linked solution for renewable hydrogen and energy storage

- Diversity of applications provides flexibility
- Low cost electricity makes economic case
### Relative Technology Maturity

<table>
<thead>
<tr>
<th>Natural Gas</th>
<th>Commercial Electrolysis</th>
<th>Advanced Electrolysis</th>
<th>New Technology</th>
</tr>
</thead>
<tbody>
<tr>
<td>10,000+ kg/day</td>
<td>100-1000 kg/day</td>
<td>g-kg/day</td>
<td>mg-g/day</td>
</tr>
</tbody>
</table>

**SMR plant**

**1 MW electrolyzer**

**Photoelectrochemical**

[Source](http://www.fgcsic.es/lychnos/en_EN/articles/hydrogen_production_methods)
Low Temperature Electrolysis Options

- **Liquid KOH:**
  - Corrosive electrolyte
  - Enables non-noble metals
  - Lower current density

- **Membrane-based:**
  - Solid electrolyte
  - Enables differential pressure
  - Room for development

![Diagram of electrolysis systems](image)

- **Commercial**
  - Hydrogen (left)
  - Oxygen (right)
  - Anode and Cathode reactions:
    - **Acid:**
      - Anode: $\text{O}_2 + 4\text{H}^+ \rightarrow 4\text{e}^- + 2\text{H}_2$
      - Cathode: $4\text{H}^+ + 4\text{e}^- \rightarrow 2\text{H}_2$
    - **Alkaline:**
      - Anode: $\text{OH}^- \rightarrow 2\text{e}^- + \text{H}_2 + 4\text{OH}^-$
      - Cathode: $2\text{H}_2 + 4\text{OH}^- \rightarrow 4\text{e}^- + 2\text{H}_2\text{O}$

- **Emerging**
  - Hydrogen (left)
  - Oxygen (right)
  - Anode and Cathode reactions:
    - **Acid:**
      - Anode: $\text{O}_2 + 4\text{H}^+ \rightarrow 4\text{e}^- + 2\text{H}_2$
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PEM Commercial Status

- Designed for life support ($O_2$)
- Basis for $H_2$ products
- High reliability demonstrated
- Overdesigned; behind vs. fuel cell investment/status

**Proton Testing and Field History**

**Cell Rework Summary, 2006 - 2015**

- Total Cells Replaced: 94%
- Original Cells in Operation: 6%

>80% of returns due to customer contamination

**Average Cell Potential (Volts, 50°C)**

- **2003 Stack Design:**
  - 1.3 A/cm$^2$
  - 4 µV/cell hr Decay Rate
- **2005 Stack Design:**
  - 1.6 A/cm$^2$
  - Non Detectable Decay Rate

**Operating Time (Hours)**

- 0, 10,000, 20,000, 30,000, 40,000, 50,000, 60,000

NASA OGA system: ISS
Platform Iterations

- Potential to get to GW scale in 4 product generations
- Likely ~12 for PEC (based on 10 mA/cm², 100 cm²)
# From Science to Product; a 20 year timeline

Starting from a well-established technology in 1996

<table>
<thead>
<tr>
<th>Product Type</th>
<th>S-Series</th>
<th>H-Series</th>
<th>C-Series</th>
<th>Megawatt</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input Power</td>
<td>6 kW</td>
<td>36 kW</td>
<td>180 kW</td>
<td>1 - 2 MW</td>
</tr>
<tr>
<td>Year Introduced</td>
<td>2000</td>
<td>2004</td>
<td>2010</td>
<td>2014</td>
</tr>
<tr>
<td>Units Sold</td>
<td>450+</td>
<td>200+</td>
<td>40+</td>
<td>NA</td>
</tr>
<tr>
<td>H2 output (Nm³/hr)</td>
<td>1</td>
<td>6</td>
<td>30</td>
<td>200–400</td>
</tr>
<tr>
<td>Generates</td>
<td>1 (June)</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Replaces</td>
<td>Six Pack</td>
<td>Tube Trailer</td>
<td>Jumbo Tube Trailer</td>
<td>Jumbo Tube Trailers</td>
</tr>
</tbody>
</table>

$/kW vs. S-Series

- 100%
- 43%
- 28%
- 13%
Only electrolysis can impact 1st 20 years

New technology 20-25 years from impact even with aggressive assumptions

Need larger contributions from all to make TW-scale impact
Why does development take so long?

- Not just about materials/performance
- Manufacturing is its own science
  - Cost and uniformity at scale
- Durability testing takes time
- Interactions can derail a system
  - Impact of tolerance extremes
- Design for safety and code compliance adds complexity
The Risks of Shortcutting Development

Laptop at Japan conference

Boeing 787 Dreamliner battery packs
http://aircraftrecognition.blogspot.com/

Navy stress test for submarine energy system
Need to Link Technology to Markets

- New products for specific applications
  
- Extremely difficult to go directly from lab to large scale
Implementation lags R&D considerably

Stack Progression

Internal $’s focused on scale up

Where we are

Where we could be

% of baseline (quantity/thickness/cost)

- bipolar assembly
- membrane
- catalyst loading
- scale (active area)

bipolar assembly - actual
membrane - actual
catalyst loading - actual

Active area scale (m²)

Year

1999

2015

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Perceptions vs. Potential of Electrolysis

• “The platinum problem”
  – Power per annual production (Rossmeisl, 2014):
    • Pt Fuel cells: ~0.3 TW; Ir Electrolysis: ~0.1 TW
  – See pathways to get to 1-2% loading

• Scale, cost, and reliability
  – MW scale and growing
  – Manufacturing is the cost issue (catalyst ~10%)
  – Cost competitive in industrial markets
  – 7-10 year stack life

National Renewable Energy Lab, 2016
Ongoing advancements leverage fuel cells

Advanced Technologies

Materials Development
- Advanced Catalyst
- Thinner Membranes
- Coatings and Composites

Advanced Manufacturing Methods
- Electrode Deposition
- Forming/Molding
- Automation

Expanded Product Features
Balance of Plant Improvements
Scale Up

Advanced Designs

Commercial Deployment
Importance of Collaboration

- Challenging cell environment: acidic, highly oxidizing (O$_2$ side), high pressure (H$_2$ side)
- Metallurgy, polymer, catalyst materials issues
- Importance of porosity and wetting properties
- Manufacturing and cell perspective from industry
Breaking down the problem for GW scale

• New technologies need to build from existing legacy
• Leverage knowledge across fields
• KOH $\rightarrow$ PEM $\rightarrow$ AEM
• Insurmountable cliff: Solar fuels and other electrolysis
• Need collaboration between industry and academics
Synergistic Technologies

Flow Batteries

Microbial Fuel Cells

Electrochemical Conversion of \( N_2 \) to Ammonia

Grid or Renewable Power Input

Stack & System Scale-up

Electrochemical Pumping/Compression/Conversion
Building Blocks

End system will leverage the most cost effective option

Develop transferable capability on existing platforms
- Follow manufacturing maturity/cost curve
- Large scale components
- Materials and form factors can be tailored later
Conclusions

- Hydrogen is an essential part of decarbonization
- Need to be realistic about timeframes for technology development and leverage what we have
- Address near term needs as well as new science/discovery
- Find synergies between both and drive progress