Hydrogen as an Energy Carrier
Jacob Thorson       February 17th, 2021

Images: NREL
Making Hydrogen with Electrolysis

- Alkaline electrolysis cell (AEC)
- Anion exchange membrane electrolysis cell (AEMEC)
- Proton exchange membrane electrolysis cell (PEMEC)
- Direct seawater electrolysis (DSE)
- Solid oxide electrolysis cell (SOEC)
Supporting Equipment for Hydrogen Production and Storage

Images: NREL
Storing Hydrogen

- Physical: Compressed, liquified
- Material: Chemical (NH₃, CH₃OH, etc.) & Reversible (metal hydrides, adsorption)

Images: NREL

Data from GREET and REFPROP
Using Complementary Energy Storage Technologies to Meet Storage and Power Requirements


1 Pumped hydro capacity is limited due to geographic constraints. Estimated maximum potential is <1% of U.S. electrical energy demand
2 As hydrogen, ammonia, or synthetic natural gas
So, Why Hydrogen?

• Like electricity, hydrogen is an energy vector
• Hydrogen is flammable but nontoxic and dissipates quickly in the atmosphere
• Electrolyzers can utilize highly variable power and have been demonstrated at a range of scales
• Hydrogen fuel cells produce electricity with zero local emissions and low noise
• Fast-fueling supports existing logistics and operations
• Hydrogen has a very high energy density [energy/mass] (but low volumetric density [energy/volume])
• Hydrogen can be used as a renewable feedstock for alternative fuels and other industrial products
Thank you!
Jacob Thorson  jthorson@nrel.gov
## Storage Characteristics

<table>
<thead>
<tr>
<th>Technology</th>
<th>Pressure (MPa)</th>
<th>Water Volume (m³)</th>
<th>Mass Stored (kg-H₂)</th>
<th>Cost Estimate ($/kWh)</th>
<th>Cost Estimate ($/kg-H₂)</th>
<th>Technology Status</th>
<th>Deployment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel Tank (Type I)</td>
<td>1 – 100</td>
<td>0.7</td>
<td>32</td>
<td>45</td>
<td>900</td>
<td>Current</td>
<td>Onshore</td>
</tr>
<tr>
<td>Pre-stressed Concrete</td>
<td>0.7 – 87.5</td>
<td>22</td>
<td>1000</td>
<td></td>
<td></td>
<td>Large LNG Systems</td>
<td>Onshore</td>
</tr>
<tr>
<td>Wrapped Steel Tank (Type II, II-S)</td>
<td>0.7 – 87.5</td>
<td>0.77</td>
<td>35.4</td>
<td></td>
<td></td>
<td>Current</td>
<td>Onshore</td>
</tr>
<tr>
<td>Pipeline Storage</td>
<td>0.7 – 10</td>
<td>6,100</td>
<td>50,000</td>
<td>25.8</td>
<td>516</td>
<td>Current/ Natural Gas</td>
<td>Onshore/ Underwater</td>
</tr>
<tr>
<td>Undersea Inflatable</td>
<td>0.6 – 8</td>
<td>35,705</td>
<td>22,500</td>
<td></td>
<td></td>
<td>Air prototype 29.5 m³</td>
<td>Underwater</td>
</tr>
<tr>
<td>Undersea Concrete Lined c</td>
<td>0.7 – 87.5</td>
<td>22</td>
<td>1000</td>
<td></td>
<td></td>
<td>Future</td>
<td>Underwater</td>
</tr>
<tr>
<td>Underground, Lined Cavern</td>
<td>1 – 23</td>
<td>40,000</td>
<td>672,000</td>
<td>3.6</td>
<td>72</td>
<td>Future</td>
<td>Onshore</td>
</tr>
<tr>
<td>Underground Salt Cavern</td>
<td>5.5 – 15.2</td>
<td>566,000</td>
<td>6,000,000</td>
<td>1.75</td>
<td>35</td>
<td>Current</td>
<td>Onshore</td>
</tr>
<tr>
<td>Spherical Vessels</td>
<td>0.1 – 1</td>
<td>32,000</td>
<td>27,000</td>
<td></td>
<td></td>
<td>Natural Gas</td>
<td>Onshore</td>
</tr>
<tr>
<td>Aquifer Storage</td>
<td>15 – 17</td>
<td>4,141,000</td>
<td>54,000,000</td>
<td></td>
<td></td>
<td>Natural Gas</td>
<td>Onshore</td>
</tr>
<tr>
<td>Cryogenic Storage</td>
<td>2</td>
<td>3,400</td>
<td>230,000</td>
<td></td>
<td></td>
<td>Current</td>
<td>Onshore</td>
</tr>
</tbody>
</table>

Data collected from (FIBA 2021; Penev 2013; Pimm, Garvey, and de Jong 2014)
## Electrolysis Technologies

<table>
<thead>
<tr>
<th>Technology:</th>
<th>Alkaline</th>
<th>PEM</th>
<th>SOEC</th>
<th>AEM</th>
<th>DSE</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Operating Temperature</strong></td>
<td>60°-100°C</td>
<td>50°-90°C</td>
<td>650°-1000°C</td>
<td>40°-60°C</td>
<td>TBD</td>
</tr>
<tr>
<td><strong>Typical Outlet Pressure</strong></td>
<td>&lt; 435 psi (3 MPa)</td>
<td>&lt; 2900 psi (20 MPa)&lt;sup&gt;a&lt;/sup&gt;</td>
<td>&lt; 363 psi (2.5 MPa)</td>
<td>&lt; 508 psi (3.5 MPa)</td>
<td>-</td>
</tr>
<tr>
<td><strong>System Electrical Conversion (kWh/kg)&lt;sup&gt;b&lt;/sup&gt;</strong></td>
<td>50-79</td>
<td>50-83</td>
<td>39.8-50&lt;sup&gt;c&lt;/sup&gt;</td>
<td>57-69</td>
<td>-</td>
</tr>
<tr>
<td><strong>Dynamic Response Speed</strong></td>
<td>Seconds</td>
<td>Milliseconds</td>
<td>Seconds</td>
<td>Milliseconds</td>
<td>-</td>
</tr>
<tr>
<td><strong>Electrolyte</strong></td>
<td>Aqueous alkaline electrolyte</td>
<td>Polymer membrane</td>
<td>Ceramic membrane</td>
<td>Polymer membrane</td>
<td>Seawater</td>
</tr>
<tr>
<td><strong>Demonstrated Stack Durability</strong></td>
<td>60,000-90,000 hr</td>
<td>20,000-80,000 hr</td>
<td>&lt; 35,000 hr</td>
<td>&gt; 5,000 hr</td>
<td>-</td>
</tr>
<tr>
<td><strong>Produced H₂ Gas Purity (%)</strong></td>
<td>&gt; 99.3</td>
<td>&gt; 99.9</td>
<td>&gt; 99.9</td>
<td>&gt; 99.9</td>
<td>-</td>
</tr>
<tr>
<td><strong>Cold Start Time (min)</strong></td>
<td>&lt; 60</td>
<td>&lt; 20</td>
<td>&lt; 60 - 600</td>
<td>&lt; 20</td>
<td>-</td>
</tr>
<tr>
<td><strong>Lower Dynamic Range (%)</strong></td>
<td>10–40</td>
<td>0–10</td>
<td>30</td>
<td>5</td>
<td>-</td>
</tr>
<tr>
<td><strong>System Capital Cost ($/kW)</strong></td>
<td>~500-1,600</td>
<td>~450-2,800</td>
<td>~500-2,400+</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

<sup>a</sup> High pressure PEM electrolysis, >70 MPa outlet pressure has been demonstrated (Martin et al. 2019)

<sup>b</sup> The HHV and LHV of hydrogen is 39.4 kWh/kg and 33.3 kWh/kg respectively

<sup>c</sup> Additional thermal energy usage of 5 to 12 kWh/kg
Examples Applications at a Hydrogen Hub Port

1. Air transport
2. Unmanned vehicles
3. Chemical processing
4. Backup/Auxiliary power
5. Remote monitoring and Navigational aids
6. Underwater computing
7. Marine vessel auxiliary power
8. Marine vessel primary power
9. Rail transport
10. Material handling
11. Heavy duty vehicles
12. Liquid fuel production
13. Local \( \text{H}_2 \) production
14. Pipeline injection
15. Underground storage
16. Aquaculture
17. Ocean mineral extraction

Icons from Noun Project with Credit to:
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