Why Hydrogen?

American Gas Association (AGA)
2020 Renewable Natural Gas Workshop

September 22, 2020
Outline

• Why we need hydrogen?
  o 12 key features
  o Magnitude of storage
  o Available materials on earth
  o Long duration storage
  o Lower cost energy storage
  o Energy demand dynamics
  o Resiliency
  o Zero emissions fuels required in some applications
  o Industry needs for heat, feedstock, gas, ...

• Key technologies
  o Electrolyzer
  o Fuel cell
  o Hydrogen turbine
  o Underground storage
  o Pipelines
Why Hydrogen?

Hydrogen offers 12 features that are required for 100% zero GHG & pollutant emissions

- Zero emissions (GHG & pollutant) conversion technologies
- Naturally recycled (in short period of time) on earth
- Massive energy storage potential
- Rapid vehicle fueling
- Long vehicle range
- Heavy vehicle/ship/train payload
- Seasonal (long duration) storage potential
- Sufficient raw materials on earth
- Feedstock for industry heat
- Feedstock for industry chemicals (e.g., ammonia)
- Pre-cursor for high energy density renewable liquid fuels
- Re-use of existing infrastructure (lower cost)

Why Hydrogen? Magnitude of Storage Required

- Wind dominant case (37 GW solar capacity, 80 GW wind capacity)

Batteries are not BIG enough
Why Hydrogen? Availability of Materials on Earth

Simulate meeting of TOTAL world electricity demand w/ Solar & Wind

<table>
<thead>
<tr>
<th></th>
<th>Solar contribution</th>
<th>Wind contribution</th>
<th>Consumption and storage ratio</th>
<th>Consumption (TWh)</th>
<th>Storage (TWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Africa</td>
<td>0.70</td>
<td>0.30</td>
<td>8.39</td>
<td>9</td>
<td>1,088</td>
</tr>
<tr>
<td>America</td>
<td>0.45</td>
<td>0.55</td>
<td>7.83</td>
<td>4,919</td>
<td></td>
</tr>
<tr>
<td>Asia</td>
<td>0.50</td>
<td>0.50</td>
<td>7.95</td>
<td>10,178</td>
<td></td>
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<tr>
<td>Europe</td>
<td>0.30</td>
<td>0.70</td>
<td>7.50</td>
<td>3,592</td>
<td></td>
</tr>
<tr>
<td>Oceania</td>
<td>0.50</td>
<td>0.50</td>
<td>19,981 TWh</td>
<td>205</td>
<td></td>
</tr>
<tr>
<td>TOTAL</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- To build one Li-ion battery requires: Li: 3,144 Mt, Co: 25,815 Mt
- World Li resources: 53 Mt
- World Co resources: 25 Mt (terrestrial), 120 Mt (ocean floor)
- 40% of Co comes from the Democratic Republic of the Congo

There is not enough lithium or cobalt in the world

Source: U.S. Geological Survey, 2018
Why Hydrogen? Long Duration Storage

Round-Trip Efficiency (>90% in Laboratory Testing)
• Measured battery system performance in Utility Applications

Batteries not EFFICIENT enough & suffer SELF-DISCHARGE

• Self-Discharge (the main culprit), plus cooling, transforming, inverting/converting, and other balance of plant

From: 2017 SGIP Advanced Energy Storage Impacts, Itron,
Average RTE ~60%
Why Hydrogen? Lower Cost Energy Storage

HES Better for long-term storage – separate power & energy scaling

Batteries will be TOO EXPENSIVE
• Northwestern U.S. Energy Dynamics

Why Hydrogen? Energy Demand Dynamics

Gas Peak ~ 70 GWh
Electric Peak ~ 30 GWh
Combined Peak ~ 95 GWh

Must TRIPLE Full Electrification Infrastructure is electrified again if transportation

DOUBLE
Why Hydrogen? Energy System Resiliency

- Always more resilient to deliver energy through multiple infrastructure sets

San Diego Blackout, 9/28/11
Winter Storm Alfred, 10/29/11
Hurricane Sandy, 10/29/12
CA Earthquake, 8/24/14

Data Center Utility Outage, 4/16/15
Hurricane Joaquin, 10/15/15
Napa Fire, 10/9/17
Japanese Super-Typhoon, 10/23/15

Hurricane Michael, 10/15/18
Ridgecrest Earthquakes, 7/4-5/19
Manhattan Blackout, 7/13/19
Why Hydrogen? Zero Emission Fuels Required for Some End-Uses

• Provide zero emissions fuel to difficult end-uses

Anything that requires (1) rapid fueling, (2) long range, (3) large payload

Aircraft

Shippin

Fuel Cell Buses

Fuel Cell Trains & Locomotives

Toyota Fuel Cell: Zero Emissions Big Rig
Why Hydrogen? Industry Requirements for Heat, Feedstock, Gas, ...

- Many examples of applications that cannot be electrified

  Steel Manufacturing & Processing
  Cement Production
  Plastics
  Ammonia & Fertilizer Production
  Computer Chip Fabrication
  Pharmaceuticals

(Photos: Galveston County Economic Development, ABB Cement, DowDuPont Inc., American Chemical Society, Geosyntec Consultants)
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  o Long duration storage
  o Lower cost energy storage
  o Energy demand dynamics
  o Resiliency
  o Zero emissions fuels required in some applications
  o Industry needs for heat, feedstock, gas, ...

• Key technologies
  o Electrolyzer
  o Fuel cell
  o Hydrogen turbine
  o Underground storage
  o Pipelines
Electrolysis – like charging a battery

**Electrolysis**

- $2 \text{H}_2\text{O} + \text{Electricity} \rightarrow 2 \text{H}_2 + 1 \text{O}_2$
- 1 liter of Water yields ~ 1 Nm$^3$ H$_2$
- Typical efficiency: 45 – 78 kWh/kg (60 – 78%)

**Various Types:**
- **Alkaline**
  - Currently lowest cost, highest efficiency
- **Proton Exchange Membrane (PEM)**
  - Pressurized, dynamic operation capabilities
- **Solid Oxide**
  - Most efficient (can also use heat)

From: U.S. DOE, 2020
Electrolysis

A Commercially Available & Widely Used Flexible Load

- Electrolyzers (PEM, alkaline) interconnected with inverters
- Provide load when wind or solar would otherwise be curtailed or when cheaply available
- Fast response allows for use with variable input
- Fast response can provide other ancillary services (e.g., regulation, Volt/VAR support)
- Sizes range from 10’s of KW to 10’s MW (today)
Fuel Cell – like discharging a battery

**Fuel Cell**
- $2 \text{H}_2 + 1 \text{O}_2 \rightarrow 2 \text{H}_2\text{O} + \text{Electricity}$
- Typical electrical efficiency: $45 - 65\%$
- Combined heat/cooling & power efficiency: $>90\%$

**Various Types:**
- **Proton Exchange Membrane (PEM)**
  - Pressurized, dynamic operation capabilities, direct H2
- **Solid Oxide**
  - Most efficient & fuel flexible
- **Phosphoric Acid**
  - Direct hydrogen use today
- **Molten Carbonate**
  - Carbon capture features

From: U.S. DOE, 2020
Fuel Cell

• Highest efficiency of conversion, lowest GHG emissions of conversion, zero pollutants
Massive Underground Storage Facilities

Salt Caverns already widely used and proven

- Air Liquide & Praxair operating H2 salt cavern storage in Texas since 2016
  - Very low leakage rate
  - Massive energy storage
  - Safe & Low-cost storage

- Similar success in Europe
- Magnum working with LADWP to adopt similar salt cavern H2 storage in Utah

Current CA depleted oil and gas fields not yet used or proven for H₂ use

- Several research and development needs
  - H₂ leakage
  - H₂ reaction with petroleum remnants
  - H₂ biological interactions
  - H₂ storage capacity
  - H₂ safety
Hydrogen Gas Turbines

- Gas Turbines reflect state-of-the-art technology for large scale power generation

800 MW
Power for ~650,000 households

From: McDonell, UCI, 2020
Example H₂ Gas Turbine : GE Aeroderivatives

Experience on Hydrogen

Table 3 – Aeroderivative experience on hydrogen fuels

<table>
<thead>
<tr>
<th>Engine</th>
<th>Country</th>
<th>Fuel LHV</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>BTU/lbm</td>
</tr>
<tr>
<td>LM2500</td>
<td>USA</td>
<td>18,148</td>
</tr>
<tr>
<td>LM2500+</td>
<td>Brazil</td>
<td>18,974</td>
</tr>
<tr>
<td>LM2500+ and +G4</td>
<td>China</td>
<td>17,363</td>
</tr>
<tr>
<td></td>
<td></td>
<td>15,385</td>
</tr>
<tr>
<td>LM5000</td>
<td>Germany</td>
<td>24,893</td>
</tr>
<tr>
<td></td>
<td>USA</td>
<td>18,016</td>
</tr>
<tr>
<td>LM6000</td>
<td>USA</td>
<td>19,185</td>
</tr>
<tr>
<td></td>
<td>Japan</td>
<td>21,994</td>
</tr>
</tbody>
</table>

From: Goldmeer et al., GE Gas Power, 2019
Example H$_2$ Gas Turbine: MHPS J-Series

- Advanced Technology—M501 JAC
- 30% H$_2$/NG capable today – targeting 100% H2 in future offerings

-- 425 MW
-- 44.0% Simple Cycle (SC) Efficiency
-- ~64% Combined Cycle (CC) Efficiency
-- 2 ppm NOx at the Stack
-- 50% turndown
-- 42 MW/min ramp rate
-- 30 min cold start
-- Air Cooled

---MHPS: (>1.0 million AOH* experience on the J Class equipment)
--MHPS: (>3.5 million AOH* of experience with hydrogen containing fuels)

* - AOH = Actual Operating Hours

https://www.mhps.com/products/gasturbines/lineup/m501j
Many jurisdictions around the world agree – objective analysis always points to transformation of both “electric grid” AND “gas grid” to zero emissions

- Consider both greenhouse gas (GHG) emissions AND air quality
- Consider all sectors of economy
- Consider all communities (especially disadvantaged communities)
- Consider reliability & safety of current gas grid
- Must deal with bio-waste streams in perpetuity
- Current use of natural gas has enabled electric grid transformation
- Current use of natural gas (and weaning off over time) can immediately deliver air quality and health benefits and usher in the zero emissions hydrogen future
Pipeline Storage & Transmission/Distribution Resource

- Natural Gas Transmission, Distribution & Storage System

<table>
<thead>
<tr>
<th></th>
<th>Annual Tuition &amp; Fees</th>
<th>Total OC Population</th>
<th>4 years for entire population</th>
</tr>
</thead>
<tbody>
<tr>
<td>U.C. Irvine</td>
<td>$17,331</td>
<td>2,246,000</td>
<td>$39 billion</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Average Annual Tuition &amp; Fees</th>
<th>Total Student Population</th>
<th>4 years for entire population</th>
</tr>
</thead>
<tbody>
<tr>
<td>All University of California Schools</td>
<td>$17,800</td>
<td>265,000</td>
<td>$4.7 billion</td>
</tr>
</tbody>
</table>

Carona, Adrian, M.S. Thesis Project, UC Irvine, J. Brouwer advisor, 2014.
Magnitude of Pipeline, Storage, and Power Plant Resources

• Note storage AND Transmission & Distribution functions

20x20 miles solar, H2 in gas system from 35% to 75% zero!

Close valves here!
Hydrogen Pipeline Injection & Leakage

H2 injection into existing natural gas infrastructure (low pressure)

- NG, H2/NG mixtures, H2 leak at same rate
Hydrogen Pipeline Injection & Leakage

- Results from a previous study (1992) support our recent findings!


<table>
<thead>
<tr>
<th>Leakage Flow Regime</th>
<th>Ratio of flow between H₂ and CH₄</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diffusion (diffusion constant)</td>
<td>3.15</td>
</tr>
<tr>
<td>Laminar (viscosity)</td>
<td>1.29</td>
</tr>
<tr>
<td>Turbulent (density)</td>
<td>2.83</td>
</tr>
</tbody>
</table>

Entrance effects? Compressibility?

H₂, CH₄, and C₃H₈ can leak at the same rate.
Pipeline Leak Mitigation Evaluation

H2 injection into existing natural gas infrastructure (low pressure)

- Copper epoxy applied (Ace Duraflow®)
Pipeline Materials Impacts

Simulation of H2 embrittlement and fatigue crack growth with UIUC

- Fatigue crack growth in 6” SoCalGas pipeline

0.188” wall thickness: \( h = 0.188” = 4.8 \text{ mm} \)

Hydrogen gas

\[ \frac{a_0^{cr}}{h} = 0.53 \]

Not a Show Stopper - Manageable
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