H2@Scale Overview

Golden, CO
November 16, 2016
Energy Consumption in 2015

U.S. Energy Consumption* in 2015

- Residential: 29%
- Commercial: 21%
- Industrial: 32%
- Transportation: 18%

Approximately 100 quads

World Energy Consumption

Approximately 600 quads

*Includes electrical losses

Source: EIA

Transportation and industry account for consumption
Hydrogen - A Clean, Flexible Energy Carrier

Diverse Energy Sources

- Natural Gas
- Renewable Sources (wind, solar, biomass, hydro, geothermal)
- Nuclear
- Coal (with carbon sequestration)

Diverse Applications

- Fuel Cells
- Engines / Turbines
- Energy Storage
- Petroleum Recovery & Refining ~47%
- Methanol Production 4%
- Electronics
- Ammonia Production ~45%
- Metal Production & Fabrication 2%
- Cosmetics
- Food Processing
- Electronics

Services all energy sectors AND improves Energy Security and Domestic Economy

Source: DOE, NREL, Hydrogen and Fuel Cell Program
We produce \textbf{\~10M} metric tons H$_2$/yr and have \textbf{\>1600 mi.} of H$_2$ pipeline

\textbf{\~50 fueling stations} (~20 public)- 100 planned in CA, 12 in the Northeast

Centralized H$_2$ Production Facilities

\textit{Many states already produce many metric tons of hydrogen}
Fuel Cell Technologies Office

Oil Dependency is Dominated by Vehicles

Well-to-Wheels Oil Consumption/Mile

- 2012 Gasoline
- Gasoline
- Gasoline
- BEV100 Grid Mix...
- BEV100 Renewable Electricity

Hydrogen from
- Distributed Natural Gas
- Coal Gas. w/ Sequestration
- Biomass Gasification (Central)
- Wind Electricity (Central)

Conventional Internal Combustion Engine Vehicles
- Petroleum Btu per mile

- 3150

Hybrid Electric Vehicles
- 2620

Battery Electric Vehicles (100-mile)
- 5230

Source: [http://hydrogen.energy.gov/pdfs/13005_well_to_wheels_ghg_oil_ldvs.pdf](http://hydrogen.energy.gov/pdfs/13005_well_to_wheels_ghg_oil_ldvs.pdf)
Advanced 2035 technologies

If DOE targets are met, petroleum use by LDVs would decline by 80% by 2050.
### How much H₂ is needed?

<table>
<thead>
<tr>
<th>How much hydrogen for 1 car?</th>
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</thead>
<tbody>
<tr>
<td>12,000 miles per year</td>
</tr>
<tr>
<td>60 miles per kilogram</td>
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<tr>
<td>= 200 kg or 0.2 tonnes per year</td>
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</table>

<table>
<thead>
<tr>
<th>How much hydrogen for many cars?</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 M cars</td>
</tr>
<tr>
<td>0.2 M tonnes H₂ per year</td>
</tr>
<tr>
<td>200 M kg H₂ per year</td>
</tr>
<tr>
<td>100 M cars</td>
</tr>
<tr>
<td>20M tons H₂ per year</td>
</tr>
<tr>
<td>20 B kg H₂ per year</td>
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</tbody>
</table>

= 100,000 cars

= 10 M cars
How much electricity would that take?

How to get hydrogen for 100M cars?

Solar/Wind Electrolysis

- 50 kWh per kilogram \( \times \) 20B kg \( H_2 \) per year \( = \) 1,000 TWh per year

How much electricity would that take?

How does that compare with our current electricity use?

U.S. Electricity Consumption \( = \) Approximately 3,900 TWh per year*

*2015 consumption. Source: EIA AEO 2016
## How to get hydrogen for 100M cars?

### Solar/Wind Electrolysis

| 50 kWh per kilogram | × | 20B kg H₂ per year | = | 1,000 TWh per year |

### High Temperature Nuclear + Electrolysis

| 67.2 mg U per kilogram | × | 20B kg H₂ per year | = | 1.3 kT U per year |

### Natural Gas Steam Methane Reforming

| 167.5 scf per kilogram | × | 20B kg H₂ per year | = | 3.4 Tcfd per year |

### Coal with CCS

| 14 kg coal per kg H₂ | × | 20B kg H₂ per year | = | 274 MT coal per year |

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How much H₂ is needed?

How to get hydrogen for 100M FCEVs?

Quads of Annual U.S. Energy Consumption

- Natural Gas: 28.3 quads, 1.1 x 3.4 quads
- Coal: 15.5 quads, 1.3 x 5.4 quads
- Nuclear/Uranium: 8.3 quads, 1.7 x 5.8 quads
- Biomass: 4.8 quads, 2.7 x 2.8 quads
- Wind: 9.0 quads, 6.1 x 1.8 quads
- Solar: 0.5 quads, 18.2 x 0.5 quads

Base Load: Natural Gas, Coal, Nuclear/Uranium
Intermittent: Biomass, Wind, Solar

Solar Sources: Opportunity for Renewable H₂

Solar water-splitting is an important longer term option.
Bio-feedstock reforming is a near term option
FY17 H2@Scale Analysis Project

Key Tasks:

1. **Economic criteria that must be met** for H2@Scale.
2. Forecast **hydrogen supply curves**.
3. Forecast **hydrogen demand curves**.
4. Determine **economic penetration of hydrogen**.
5. Develop **Sankey diagrams**, and down-select scenarios.
6. Analysis of **down-selected scenarios**.
7. Analyze **spatial issues of H2@Scale** (e.g. proximity of supply and demand).
8. Comparison of **H2@Scale impact with base case business as usual**.

*Techno-economic analysis will forecast the resource requirements and impact of H2@Scale.*
Business case assessment for electrolytic $H_2$ production

Integration with the electric grid, capital cost reductions and credit market opportunities help provide a path to low cost $H_2$.
Demonstration of Electrolyzer Grid Integration

FCTO is validating electrolyzer potential in energy storage.
H2@Scale RFI Key Themes – Interest in:

1. **Innovative H₂ production technologies**
   - Electrolyzer cost reduction
   - Alternative feedstocks (e.g. solid and liquid waste, process gases)
   - Integrate H₂ production with waste heat (e.g. from nuclear or steelmaking)

2. **Integrated H₂ systems (e.g., reversible fuel cells,)**

3. **Innovative H₂ storage and delivery technologies**
   - Liquid organic carriers, metal organic frameworks; bulk storage

4. **Use of H₂ to enable grid stability and energy storage**

5. **Data collection & sharing on the value proposition and feasibility of H2@Scale**
   - Demonstration of electrolyzer integration with the grid; RD&D on power-to-gas

6. **Deployments of H₂ in near-term markets, including for buses, ammonia, & steel**

*RFI & workshop will guide cross-cutting H2@Scale RD&D Roadmap.*
Next Steps...

H2@Scale RD&D Roadmap that addresses issues including:

✓ Hydrogen production from diverse domestic sources

✓ Hydrogen for grid stability and energy storage

✓ Development of industrial scale hydrogen delivery and storage infrastructure

✓ Penetration of clean/sustainable (including renewable) hydrogen in current and future end-use markets- e.g. industrial applications

H2@Scale requires collaboration across stakeholders!
Thank you

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hydrogenandfuelcells.energy.gov
Oil Dependency is Dominated by Vehicles

- Transportation is responsible for 66% of U.S. petroleum usage
- 27% of GHG emissions
- On-Road vehicles responsible for 85% of transportation petroleum usage

16.0M LDVs sold in 2014.
240 million light-duty vehicles on the road in the U.S

10-15 years for annual sales penetration
10-15 years to turn over fleet

Poses significant economic, energy and environmental risks to U.S.

Photos courtesy of Spc. Jordan Huettl, U.S. Army; U.S. Environmental Protection Agency; and M. Studinger, NASA

It takes decades of sustained effort to turn over the fleet
Key barriers:
- Technical and economic viability
- Ability of hydrogen to serve multiple end uses
- Unified supportive policy
- Partnerships and coordination

Next Steps:
- Demonstration/pilot projects
- Partnerships/co-ordination
- Assess technical viability
- Education/outreach
- Pathway to successful business case - upcoming lab project!
- Develop roadmap and implement H2 plan and targets - 2016 RFI!
- Develop/revise policy, regulations, codes and standards
- Determine probability of success

FCTO has been addressing previously identified barriers through collaborative RD&D.
Key Barriers for Commercial Electrolysis:

- Stack performance, durability, cost, and efficiency
- Scale-up to megawatt capacity
- High-pressure performance to reduce downstream compression
- Identifying best markets to penetrate
  - Power-to-gas
  - Ancillary grid services
  - Renewable hydrogen for petroleum refining
  - Material handling equipment
- Grid Integration

Consortium on water splitting R&D, including low- and high-temperature electrolysis

- MW-scale electrolyzers now in commercial use!
- BMW plant using H₂ from landfill gas
- Testing of electrolyzer performance under variable load, and innovative drying technologies at NREL

Key barriers to commercial electrolysis are being addressed by DOE and industry.
More Renewable Energy in Grid of Future

- Current RPS Standards on books, CA is most aggressive.
- Many studies suggest much greater grid decarbonization necessary.

Emissions pathways

Need to be here

We are here

Meeting COP 21 Climate Goals Requires Further Reduction in Emissions
H₂ for Seasonal Energy Storage

• Work from the Deep Decarbonization Pathways Project shows pathways to reduce U.S. GHG emissions 80% by 2050.

• Hydrogen and synthetic methane production can balance electricity grid and provide low carbon fuels.

Source: B. Haley, R. Jones, G. Kwok, J. Williams, “Pathways to Deep Decarbonization,” 9/1/16
H2 for Short Term Balancing

Hydrogen may be produced from a variety of renewable resources, and hydrogen-based energy storage could provide value to many applications and markets.

Ongoing work at U. Hawaii and NREL has shown potential for grid frequency modulation using dispatchable electrolyzers.

Adapted from: www.hydrogen.energy.gov/pdfs/review12/mt008_ewan_2012_o.pdf
Hawaii Natural Energy Institute Mitch Ewan, GE Transient PSLF™

Models indicate modest energy storage mitigates negative effects of wind penetration
**Significant R&D Achievements: Low-Temp PEM Electrolysis**

### H₂ Production High Volume Cost Projections for PEM Electrolysis

<table>
<thead>
<tr>
<th></th>
<th>Low Range ($/kg H₂)</th>
<th>Baseline Cost ($/kg H₂)</th>
<th>High Range ($/kg H₂)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Forecourt</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Current Case</td>
<td>$4.79</td>
<td>$5.14</td>
<td>$5.49</td>
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<tr>
<td>Future Case</td>
<td>$4.08</td>
<td>$4.23</td>
<td>$4.37</td>
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<tr>
<td><strong>Central</strong></td>
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<tr>
<td>Current Case</td>
<td>$4.80</td>
<td>$5.12</td>
<td>$5.45</td>
</tr>
<tr>
<td>Future Case</td>
<td>$4.07</td>
<td>$4.20</td>
<td>$4.33</td>
</tr>
</tbody>
</table>

### PEM Electrolysis H2A Case Cost Summary

- Bars around the baseline costs reflect the potential spread of stack and BOP capital cost (based on sensitivity analysis).

### Electricity feedstock cost is largest cost driver

### Sensitivity Analysis for Current Central PEM Electrolysis H₂ Production

- Average Electricity Price over Life of Plant (2007¢/kWh) [3.11, 6.22, 9.33]
- Electricity Usage (kWh/kg) [50, 54.3, 65]
- Uninstalled Capital Costs (2012$/kW) [720, 900, 1080]
- Site Prep (% of installed capital) [1%, 2%, 40%]
- Replacement Interval (years) [20, 7, 4]
- Replacement Costs (% of installed capital) [10%, 15%, 25%]

### H₂ Production Cost Breakdown

- Capital Cost 15%
- Fixed O&M 5%
- Other Costs 2%
- Electricity 78%
H₂@Scale as Key Part of Solution

- 23 H₂ stations in California open
- 20 H₂ stations in development in California
- 12 H₂ stations planned for Northeast

> 17,000 kg/day fueling capacity expected by 2022.
Life-Cycle GHG Emissions - Today’s Cars

Almost 50% reduction in GHG can be achieved with today’s FCEVs.

Source: Program Record 16004
(https://www.hydrogen.energy.gov/pdfs/16004_life-cycle_ghg_oil_use_cars.pdf)
Wastewater treatment plants alone have the potential to provide enough hydrogen to support over ~1-3M FCEVs/year