H₂ at Scale: Deeply Decarbonizing our Energy System

HTAC Presentation
April 6, 2016

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Overview of Talk

• Provide ‘Big Idea’ perspective

• Describe current vision on H2 @ Scale as a ‘Big Idea’
  o What we’ve learned
  o Challenges encountered
  o Momentum gained

• Solicitation of support to/from HTAC/individual entities
  o Industry engagement
H₂ at Scale a National Lab led ‘Big Idea’

• ‘Big Ideas’ are identified by National Lab teams as high impact areas that are currently underemphasized or missed within DOE portfolio

• Culminate in a DOE/National Lab Big Idea Summit

• Have led to large programs, increased visibility for specific topics
H₂ at Scale Big Idea Timeline

**2014**
- Jan: 1st Big Idea Meeting
- Mar: National Lab Working Group Meeting at AMR
- Aug: 1st TWG meeting
- Oct: Grid-Scale Hybrid Hydrogen Systems presented to TWG
- Dec: TWG update (ORNL, 11/9)

**2015**
- Jan: 2nd Big Idea Mtg
- Apr: FY16 Lab Call
- May: TWG meeting (Aug 4, ORNL)
- Jun: Updated slide deck
- Jul: Renewable Power Hollett (10/2)
- Oct: H₂ Community (11/4)
- Dec: ARPA E (11/6)

**2016**
- Jan: Team face to face (3/24)
- Apr: CRO Red Team (4/8)
- May: Big Idea Summit 3 (April 21-22)
- Jun: HTAC (4/6)

**Events**
- Reuben starts (2014)
- TWG (DC, 1/19)
- Solar (1/19)
- TWG LBL (2/17)
- White Paper (2/22)
- CRO Review (3/8)
- CRO Red Team (4/8)
- Big Idea Summit 3 (April 21-22)
Motivation - Major Administration Energy Goals

1. Reduce GHG emissions by 17% by 2020, 26-28% by 2025 and 83% by 2050 from 2005 baseline

2. Reduce net oil imports by half by 2020 from a 2008 baseline

3. Double energy productivity by 2030

4. By 2035, generate 80% of electricity from a diverse set of clean energy resources

5. Reduce CO\textsubscript{2} emissions by 3 billion metric tons cumulatively by 2030 through efficiency standards set between 2009 and 2016

H\textsubscript{2} at Scale strongly impacts 1 and 4, also impacts 2.
Problem

- Climate change → deep decarbonization
  - Limited options

- Multi-sector challenges
  - Transportation
  - Industrial
  - Grid

- Renewable challenges
  - Variable
  - Concurrent generation

Over half of U.S. CO$_2$ emissions come from the industrial and transportation sectors
Impact

H₂ at scale can enable increased renewable penetration that results in a:

45% reduction in total U.S. carbon emissions by 2050*

*compared to EIA AEO 2040 “Business as usual” case
Future H₂ at Scale Energy System
• Today’s electrolysis technology (scaled up) is not cost competitive with today’s SMR.

• This is expected—it’s driven by electricity cost tied to burning fossil fuels and two inefficient processes.
Clean Power Plan
reduce carbon dioxide emissions by 32% by "President’s Climate Action Plan
80% reduction in transportation GHG by 2050

What has changed, is changing, or will change that has an impact

Renewable Energy Standards
37 states with renewable portfolio standards or goals

Growing Renewable Energy Penetration
Since 2008, US solar >20x increase, wind >3x increase. Other countries >30% total RE penetration.
Even at low penetrations, instantaneous demand can be met by solar power.
Hydrogen Value Proposition for RE Penetration

PV has decreasing value with increased penetration.

An increased value proposition is needed for higher market penetration of variable renewables.

A tipping point is reached due to increased use of low cost renewable energy.

Curtailment will lead to an abundance of low value electrons, and we need solutions that will service society’s multi-sector demands.

Future H₂ Demand

The H₂ at Scale team projects a 5x increase in H₂ use could be achieved by 2050 with high renewable penetration.

<table>
<thead>
<tr>
<th>Potential Hydrogen Demand in 2050*</th>
<th>Quads</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen for direct use in LDVs</td>
<td>3.2</td>
</tr>
<tr>
<td>Hydrogen for direct use in HDVs</td>
<td>0.5</td>
</tr>
<tr>
<td>Hydrogen for biofuel upgrading</td>
<td>0.4</td>
</tr>
<tr>
<td>Hydrogen for oil refining</td>
<td>0.4</td>
</tr>
<tr>
<td>Ammonia production</td>
<td>2.5</td>
</tr>
<tr>
<td>Steel refining</td>
<td>1.0</td>
</tr>
<tr>
<td>Total</td>
<td>7.9</td>
</tr>
</tbody>
</table>

* Based on H2 at Scale Analysis Team projections

Current Energy Flow

Estimated U.S. Energy Use in 2014: ~98.3 Quads

Source: LLNL 2015. Data is based on DOE/EIA-0035(2015-03), March, 2014. If this information or a reproduction of it is used, credit must be given to the Lawrence Livermore National Laboratory and the Department of Energy, under whose auspices the work was performed. Distributed electricity refers only to retail electricity sales and does not include self-generation. EIA reports consumption of renewable resources (i.e., hydro, wind, geothermal and solar) for electricity in BTU equivalent values by assuming a typical fossil fuel plant "heat rate." The efficiency of electricity production is calculated as the total retail electricity delivered divided by the primary energy input into electricity generation. End use efficiency is estimated as 65% for the residential and commercial sectors, 80% for the industrial sector, and 21% for the transportation sector. Totals may not equal sum of components due to independent rounding. LLNL-MI-410327
Please note, all results presented on this slide are PRELIMINARY and may be subject to corrections and/or changes. A cursory analysis was performed using available information and estimates of impacts due to changes to the modeled energy systems.
Energy Flow 2040 Business as Usual

2040 EIA AEO Estimated U.S. Annual Energy Use - Hydrogen Contributions Broken Out ~ 108 Quads

Solar 0.95
Nuclear 8.5
Hydro 2.9
Wind 2.4
Geothermal 0.68
Natural Gas 32.3
Coal 18.7
Biomass 6.2
Petroleum 35.3

Source: LLNL March 2016. Data is based on DOE/EIA-0335(2015-03) and Annual Energy Outlook DOE/EIA-0383(A2016). If this information or a reproduction of it is used, credit must be given to the Lawrence Livermore National Laboratory and the Department of Energy, under whose auspices the work was performed. Distributed electricity represents only retail electricity sales and does not include self-generation. EIA reports consumption of renewable resources (i.e., hydro, wind, geothermal and solar) for electricity in BTU-equivalent values by assuming a typical fossil fuel plant "heat rate". The efficiency of electricity production is calculated as the total retail electricity delivered divided by the primary energy input into electricity generation. End use efficiency is estimated as 65% for the residential sector, 65% for the commercial sector, 80% for the industrial sector, and 25% for the transportation sector. Totals may not equal sum of components due to independent rounding. LLNL-M0-074957

Please note, all results presented on this slide are PRELIMINARY and may be subject to corrections and/or changes. A cursory analysis was performed using available information and estimates of impacts due to changes to the modeled energy systems.
Energy Flows – 2050 High RE/H₂

2050 Estimated U.S. Annual Energy Use with High Hydrogen Contributions Broken Out ~ 77 Quads

Please note, all results presented on this slide are PRELIMINARY and may be subject to corrections and/or changes. A cursory analysis was performed using available information and estimates of impacts due to changes to the modeled energy systems.
BAU vs. High RE/H₂ – Energy Differences*

Energy Use Difference between 2050 High Hydrogen Scenario and AEO 2040 Scenario (Quadrillion BTUs)
Red Flows Represent a Reduction (Negative Values)
Black Flows Represent an Increase (Positive Values)

* Only differences >1.5 quad shown for clarity purposes, case study data included in backup slides

Please note, all results presented on this slide are PRELIMINARY and may be subject to corrections and/or changes. A cursory analysis was performed using available information and estimates of impacts due to changes to the modeled energy systems.
BAU vs. High RE/H₂ – CO₂ Emissions

Emissions Difference between 2050 High Hydrogen Scenario and AEO 2040 Scenario (Million metric tonnes)

Red Flows Represent a Reduction (Negative Values)

45% reduction in CO₂ emissions

Grid 75%, Transportation 25%, Industrial 25%

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## H2 @ Scale Technical Framework

### Renewable Energy Conversion, Storage, and Use

<table>
<thead>
<tr>
<th>Low T H₂ Generation</th>
<th>High T H₂ Generation</th>
<th>Hydrogen Storage and Distribution</th>
<th>H2 End Use</th>
</tr>
</thead>
</table>

- **Low T H₂ Generation**
  - Development of low cost, durable, and intermittent H₂ generation.

- **High T H₂ Generation**
  - Development of thermally integrated, low cost, reliable, and efficient H₂ generation.

- **Hydrogen Storage and Distribution**
  - Development of reliable, efficient, and economic storage and distribution of hydrogen (energy).

- **H2 End Use**
  - H2 as a game changing energy carrying currency, revolutionizing industry and the energy sector.
**H2 at Scale Framework**

Intermittent Hydrogen Deeply Decarbonizing our Energy System

<table>
<thead>
<tr>
<th>Low T generation</th>
<th>High T generation</th>
<th>Storage and Distribution</th>
<th>Industrial/End use</th>
</tr>
</thead>
<tbody>
<tr>
<td>Develop non-noble metals OER catalyst</td>
<td>Durable corrosion resistant conductive materials</td>
<td>GWh-month scale geologic storage</td>
<td>Process heat integration with intermittent hydrogen generation</td>
</tr>
<tr>
<td>Low-cost durable high-conductivity membranes</td>
<td>Front end controls for thermal management with cyclic operation</td>
<td>Develop novel materials and processes for chemical Storage</td>
<td>New process chemistry with hydrogen as reductant</td>
</tr>
<tr>
<td>Develop alkaline membranes enabling noble metal replacement</td>
<td>Technologies for high temperature thermal storage</td>
<td>Integration with renewable grid/System optimization</td>
<td>Ammonia production beyond Haber Bosch</td>
</tr>
<tr>
<td>Low-cost, corrosion resistant, thin film metal coatings</td>
<td>CO2 electrochemical reduction</td>
<td>Novel compression/liquefaction technologies</td>
<td>Hydrogen/ hydrogen-rich combustion</td>
</tr>
<tr>
<td>Develop durable systems for intermittent operation</td>
<td>Material systems for advanced redox cycles</td>
<td>Leak Detection/Purification</td>
<td></td>
</tr>
<tr>
<td></td>
<td>System integration</td>
<td>Material compatibility for pipelines and compressors</td>
<td></td>
</tr>
</tbody>
</table>

**Analysis**

**Fundamental Science**

**Grid Connection/Integration**
# Improving the Economics of Renewable H₂

## Intermittent Integration

## R&D Advances

<table>
<thead>
<tr>
<th>Cost of Hydrogen Production ($/kg)</th>
<th>Capacity Factor</th>
<th>Cost of Electricity</th>
<th>Capital Cost Efficiency (LHV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.20</td>
<td>97%</td>
<td>$6.6/kWh</td>
<td>$400/kW 66%</td>
</tr>
<tr>
<td>3.46</td>
<td>40%</td>
<td>$1/kWh</td>
<td>$400/kW 66%</td>
</tr>
<tr>
<td>2.24</td>
<td>40%</td>
<td>$1/kWh</td>
<td>$100/kW 60%</td>
</tr>
<tr>
<td>1.95</td>
<td>90%</td>
<td></td>
<td>Steam Methane Reforming (SMR)</td>
</tr>
</tbody>
</table>

- Other Costs
- Feedstock Costs
- Fixed O&M
- Capital Costs
Investments to Enable H₂ at Scale

R&D Impact on Fuel Cell Costs

Projected Transportation Fuel Cell System Cost

at high-volume (500,000 units per year)

Fuel Cell R&D has decreased projected costs by 80%

Data from FCTO AMR presentations.
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  - What we’ve learned
  - Challenges encountered
  - Momentum gained
- Solicitation of support to/from HTAC/individual entities
  - Industry engagement
H₂ at Scale Summary

- Reducing emissions (GHG, criteria pollutants)
- Cross-energy-sector synergetic opportunities (electricity, industrial, transportation)
- Support needs of dynamic, variable power systems

Unique potential of H₂ to positively impact all these areas

- Other benefits
  - Energy security (diversity/domestic)
  - Manufacturing competitiveness/job creation