H₂ at Scale: Deeply Decarbonizing our Energy System

Touch Screen Presentation at AMR

Wardman Park Marriott
June 6–10, 2016
H₂ at Scale: Deeply Decarbonizing our Energy System

What is Hydrogen at Scale?
Why is it needed?
Why now/today?
What can it accomplish?
How will it be accomplished?
Who is the team?
Why national labs along with industry?
What does success look like?
Additional content/backup slides
What is H₂@Scale?
Conceptual H\(_2\) at Scale Energy System*

*Illustrative example, not comprehensive
Why is it needed?
Why?.....Our Cities/Energy System

need deep decarbonization
H₂@Scale enables green processes and increased renewable penetration that

Decrees all U.S. carbon emissions by about half (2050)

Significantly contributing to administration goal of 83% reduction of GHG emissions by 2050

PRESIDENT OBAMA’S PLAN TO ADDRESS CLIMATE CHANGE

Reduce carbon pollution from power plants and build cars that burn less fuel.
Energy System Challenges

• Multi-sector requirements
  - Transportation
  - Industrial
  - Grid

• Renewable challenges
  - Variable
  - Concurrent generation

Over half of U.S. CO₂ emissions come from the industrial and transportation sectors

Denholm et al. 2008
Why now?
Motivation – Major Administration Energy Goals

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

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

3. Double energy productivity by 2030
   - Department of Energy

4. By 2035, generate 80% of electricity from a diverse set of clean energy resources
   - Blueprint Secure Energy Future

5. Reduce CO₂ emissions by 3 billion metric tons cumulatively by 2030 through efficiency standards set between 2009 and 2016
   - CAP Progress Report

H₂ at Scale strongly impacts 1 and 4, also impacts 2.
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.
Carbon-Free Electricity Prices

Source: (Arun Majumdar) 1. DOE EERE Sunshot Q1’15 Report, 2. DOE EERE Wind Report, 2015
Curtailment will lead to an abundance of low value electrons, and we need solutions that will service our multi-sector demands.
Example: Germany Already Limiting RE Penetration Rate

Share of Renewable Electricity at Brut Electricity Consumption (Energy) in Germany

- Wind
- Photovoltaic
- Biomass
- Hydro
- Geothermal

Yearly Increase according to Legislation 2014:
- → 2.5 GW Wind onshore
- → 2.5 GW Wind offshore
- → 2.5 GW Photovoltaic

Long term target:
- 2050: 80%

Uncontrolled Increase resulting from Subsidy System till 2014:
- 2004: 9%
- 2014: 28%
- 2025: 40 - 45%
- 2035: 55 - 60%

Source: BMWi
What can it accomplish?
Current Energy Flow

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

Solar 0.427
Nuclear 8.33
Hydro 2.47
Wind 1.73
Geothermal 0.202
Natural Gas 27.5
Coal 17.9
Biomass 4.78
Petroleum 34.8

Electrical Generation 38.4
Net Electricity Imports 0.164

Residential 11.8
Commercial 8.93
Industrial 24.7
Transportation 27.1

Energy Services 38.9
Rejected Energy 25.8

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 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 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-410527
Current Energy Flow – w/Hydrogen

2014 Estimated U.S. Annual Energy Use - Hydrogen Contributions Broken Out ~ 98 Quads

Source: LLNL, September 2015. Data is based on DOE/EIA-0335(2015)-031 and Annual Energy Outlook DOE/EIA-0393(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, unless otherwise 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 MTOE-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, 69% for the commercial sector, 89% for the industrial sector, and 21% for the transportation sector. Totals may not equal sum of components due to independent rounding. LLNL-MA-676997

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

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.
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 (Business As Usual) vs. High H₂ – Energy Difference*

Energy Use difference between 2050 high-H₂ and AEO 2040 scenarios (Quad Btu)

Red flows represent a reduction (between scenarios)
Black flows represent an increase (between scenarios)

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

Reduction in rejected energy -27.3
Difference in energy services -3.8

-24.7 H₂
27.4 Elec.
9.2 H₂
-8.9 NG
17.2
-13 coal
4.8
-1.9
-4.4
-6.2
-2.1
-4.4
-8.9
gas
20.9
-2.5
-6.2
2.3 nuclear
-4.4
-6.2
2.9 solar
+10.4 wind
12.8
0.5 geother.
5.6 biomass
28.9 Petro.
BAU (Business As Usual) vs. High H₂ – CO₂ Difference*

Emissions difference between 2050 high-H₂ and AEO 2040 scenarios (million MT)

Red flows represent a reduction (between scenarios)

45% reduction in CO₂ emissions
Grid 75%, Transportation 25%, Industrial 25%
Improving the Economics of Renewable H₂

- **Intermittent integration**
- **R&D Advances**

### Projected Transportation Fuel Cell System Cost

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

### Cost of Hydrogen Production ($/kg)

- **Capacity Factor**
  - 97%: $6.6/kWh, $400/kW (66%)
  - 40%: $1/kWh, $400/kW (66%)
  - 40%: $1/kWh, $100/kW (60%)

### Other Costs
- Purple

### Feedstock Costs
- Green

### Fixed O&M Costs
- Red

### Capital Costs
- Blue

### Electrolyzer

### Steam Methane Reforming (SMR)

### SMR
- 90%
How will it be accomplished?
Conceptual $\text{H}_2$ at Scale Energy System*

*Illustrative example, not comprehensive
What is Needed to Achieve H₂ at Scale?

**Low and High Temperature H₂ Generation**
- Development of low cost, durable, and intermittent H₂ generation.
- Development of thermally integrated, low cost, durable, and variable H₂ generation.

**H₂ Storage and Distribution**
- Development of safe, reliable, and economic storage and distribution systems.

**H₂ Utilization**
- H₂ as game-changing energy carrier, revolutionizing energy sectors.

**Analysis**
- Foundational Science
- Future Electrical Grid

H₂ as game-changing energy carrier, revolutionizing energy sectors.
H₂ at Scale Value Summary

• Reducing emissions across sectors (GHG, criteria pollutants)

• Support needs of dynamic, variable power systems (dispatchable, scalable, ‘one-way’ storage)

  Unique potential of H₂ to positively impact all these areas

• Other benefits
  – Energy security (diversity/resiliency/domestic)
  – Manufacturing competitiveness/job creation
  – Decreased water requirements
Who is the team?
H₂ at Scale Big Idea Team

Steering Committee:
Bryan Pivovar (lead, NREL), Amgad Elgowainy (ANL), Richard Boardman (INL), Adam Weber (LBNL), Salvador Aceves (LLNL), Rod Borup (LANL), Mark Ruth (NREL), David Wood (ORNL), Jamie Holladay (PNNL), Art Pontau (SNL), Don Anton (SRNL), Mark Hartney (SLAC), Vitalij Pecharsky (Ames); Alex Harris (BNL); Geo (NREL)

Low T Generation:
Rod Borup (lead, LANL); Jamie Holladay (co-lead, PNNL); Christopher San Marchi (SNL); Hector Colon Mercado (SRNL); Kevin Harrison (NREL); Ted Krause (ANL); Adam Weber (LBNL); David Wood (ORNL)

High T Generation:
Jamie Holladay (lead, PNNL); Jim O’Brien (INL); Tony McDaniel (SNL); Ting He (INL); Mike Penev (NREL); Bill Summers (SRNL); Maximilian Gorensek (SRNL); Jeffery Stevenson (PNNL); Mo Khaleel (ORNL)

Storage and Distribution:
Don Anton (lead, SRNL); Chris San Marchi (SNL); Kristen Brooks (PNNL); Troy Semelsberger (LANL); Salvador Aceves (LLNL); Thomas Gennett (NREL); Jeff Long (LBNL); Mark Allendorf (SNL); Mark Bowden PNNL; Tom Autrey PNNL

Utilization:
Richard Boardman (lead, INL); Don Anton (SRNL); Amgad Elgowainy (ANL); Bob Hwang (SNL); Mark Bearden (PNNL); Mark Ruth (NREL); Colin McMillan (NREL); Colin McMillan (NREL); Ting He (INL); Michael Glazoff (INL); Art Pontau (SNL); Kristen Brooks (PNNL); Jamie Holladay (PNNL); Christopher San Marchi (SNL); Mary Biddy (NREL)

Future Electric Grid:
Art Pontau (lead, SNL); Art Anderson (NREL); Bryan Hansing (NREL); Ben McDaniel (SNL); Matt Bearden (PNNL); Mark Ruth (NREL); Colin McMillan (NREL); Ting He (INL); Michael Glazoff (INL); Art Pontau (SNL); Kristen Brooks (PNNL); Jamie Holladay (PNNL); Rob Hovsapian (INL)

Foundational Science:
Adam Weber (lead, LBNL); Voja Stamekovic (ANL); Nenad Markovic (ANL); Frances Houle (LBNL); Morris Bullock (PNNL); Aaron Appel (PNNL); Wendy Shaw (PNNL); Tom Jaramillo (SLAC); Jens Norskov (SLAC); Vitalij Pecharsky (Ames)

Analysis:
Mark Ruth (lead, NREL); Amgad Elgowainy (co-lead, ANL); Josh Eichman (NREL); Joe Cordaro (SRNL); Salvador Aceves (LLNL); Max Wei (LBNL); Karen Studarus (PNNL); Todd West (SNL); Steve Wach (SRNL); Richard Boardman (INL); David Tamburello (SRNL); Suzanne Singer (LLNL)
Why national labs along with industry?
Why National Labs Along with Industry?

• **NLs**: Unique skills/capabilities, ideally suited for addressing the challenges of tomorrow’s energy system. H2@Scale vision only possible through the NL efforts.

• **Gov’t**: No profit in developing this system in today’s market, but needs to be ready for future energy systems needs. Consideration of societal impacts/costs. Both global and local. Can enable or derail potentially.

• **Commercial/industrial engagement critical**: Focus on enabling the vision of the long-term, through the short-term and mid-term steps.
What does success look like?
What Does Success Look Like?

Going from 10 million MT of H₂ from SMR to 50 million MT from carbon-free sources, will enable a 50% decrease in CO₂ emissions by 2050.
H₂ @ Scale

Creating a sustainable future

50% fewer GHG emissions than today... by 2050

Reduction by Sector

75%
Grid

25%
Transportation

25%
Industrial

MORE
Jobs
Security
Resiliency
Additional Content/Backup Slides

- H₂@Scale components
- H₂@Scale history/timeline
- H₂@Scale connection to energy storage
- H₂@Scale safety perceptions/concerns
- H₂@Scale connection to grid
- Cross-DOE-office connections
- QTR connections
Conceptual H₂ at Scale Energy System*

*Illustrative example, not comprehensive
Low- and High-T H₂ Generation

Research Priorities
• Durability for intermittent operation
• Lower cost electrolysis
• Manufacturing at scale
• Thermal integration

Specific H₂ Production Technology Needs
• PEM electrolysis
  – Cell/Stack Components
  – Power electronics/BOP
• Advanced alkaline electrolysis (membranes)
• Solid oxide electrolysis/thermal chemical
  – Oxide conducting materials
  – Thermal integration

DOE Programs Impact: EERE (FCTO, Solar, Wind, AMO); OE/Grid; NE; FE; SC
H₂ Storage and Distribution

Specific Technology Needs
- Hydrogen Storage
  - Chemical/metal hydrides
  - Materials systems
  - Catalysis
  - Physical Storage
    - Geologic
    - Manufactured

Research Priorities
- Development of storage/delivery systems for large-scale grid and industrial use
- Assessment of potential for integration with existing technology and infrastructure
- System analysis, integration and optimization

- Direct Electro-Chemical Hydride Conversion

- Distribution
  - Compression
  - Liquefaction
  - Materials Compatibility (Hydrogen Embrittlement)
  - Leak Detection/Repair
  - Hydrogen Contamination/Purification
  - Materials Compatibility
  - Grid Integration/Optimization

DOE Programs Impact: EERE (FCTO, AMO); OE, FE; SC
H₂ Utilization

Research Priorities
• New process chemistry with H₂ used as a reductant
  – Chemical, Fuels, Metals Production
• Process efficiency improvement
  – Industry and power systems
• Process heat integration with intermittent H₂ generation
• H₂ / H₂-rich flame modeling

Specific H₂ Utilization Technology Needs
• Ammonia production
  – Distributed/modular
• Refineries and Biofuels
  – Process integration
• Metals and glass making
  – Game changing direct reduction
  – Reducing gases for annealing/
  – tempering
• Combustion Processes
  – Burner design and testing
  – Flame chemistry impacts
  – Use of oxygen
• H₂ Heat Pumps
  – Waste heat recovery
  – Heat amplification / cooling

DOE Programs Impact: EERE (AMO, FCTO, Wind/Solar); NE; FE; ARPA-E; SC
Fundamental understanding of potentially revolutionary technologies for other chemical bond energy storage/conversion.

Numerous chemistry/ materials issues:
- Catalysis/Reactions
  - Systems far from equilibrium
  - Confined catalysis
- Corrosion
  - Detection and understanding of rare events
- Material interactions (Embrittlement)
- User facilities
  - SNS, light sources, nanocenters, microscopy
  - ACSR and advanced computing
    - Big data
    - Algorithms for prediction multiscale physics
- JCAP leveraged science
- MGI (expansion)
  - dissolution, kinetics, solvents
Grid Integration

Specific Grid Integration Technology Needs

• **Affordability**
  - Modest capital investment for production and storage

• **Renewable hydrogen source for marketplace revenue**

• **Flexibility**—Scalable, deployable, multiple renewable hydrogen markets

• **Reliability**
  - Stable, sufficient power source
  - Inherently integrated element of grid

• **Resilience**—Distributed production and storage systems—large storage options

• **Sustainability**—Enable stable grid with abundant renewables-demand/response

• **Security**—Enable domestic, renewable energy resource

Research & Development Priorities

• Systems analysis
• Systems engineering
• Systems design and demo
Analysis

Analysis Priorities
• Specifying the role of hydrogen in deep decarbonization of the U.S. energy sector
• Understanding of drivers impacting energy sector evolution
• Quantification of hydrogen potential to meet seasonal electricity storage requirements
• Techno-economic analysis
• Life cycle analysis

Specific Analysis Needs
• Role of hydrogen within energy sector
  – Energy sector evolution / capacity expansion analysis to identify key opportunities for hydrogen to support power, gas, industrial, and transportation sectors
  – Grid operations co-optimization with hydrogen providing grid support on short and long time-frames and on regional and national scales
  – Analysis of the hydrogen’s benefits resilience, reliability, and robustness
• Techno-economic analysis to support R&D direction in hydrogen generation, storage & distribution, and end use
• Life cycle analysis to identify opportunities to reduce GHG and criteria pollutant emissions
History/Timeline
H₂ Big Idea Timeline

2014
- 2014 Idea Summit
- Reuben starts
- 1st Big Idea Meeting
- National Lab Working Group Meeting at AMR
- 2015 Idea Summit
- 1st TWG meeting
- Grid-Scale Hybrid Hydrogen Systems presented to TWG
- H₂ Community (11/4)
- ARPA E (11/6)
- OE (9/10)
- Reuben (11/12)

2015
- 2nd Big Idea Mtg
- FY16 Lab Call
- TWG meeting (Aug 4, ORNL)
- TWG update (ORNL, 11/9)
- White Paper (2/22)
- Updated slide deck
- Renewable Power Hollett (10/2)
- CRO Review (3/8)
- CRO Red Team (TBD, ~4/8)
- AMR (6/6)
- Big Idea Summit 3 (April 21-22)
- IPHE (5/20)

2016
- Team face to face (3/24)
- HTAC (4/6)
- Utilities (5/3, 5/19)
Connection to Energy Storage
Storage Needs with Increased RE Penetration

RE Futures Study
Comparison between Energy Storage Options

Battery systems
Power and Energy scale together
More energy storage = more batteries
Marginal cost of storage capacity is $1400/kWh

Hydrogen systems
Power and energy scale separately
More energy storage = more tanks only $140/kWh

Source: Hydrogenics
## Examples – Hydrogen vs. Batteries

### Competitive Analysis vs. Battery Storage

<table>
<thead>
<tr>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>Favorable Total Cost of Ownership</td>
<td>$1.69 $0.68 $0.61 $0.40</td>
<td>$0.68 $0.68 $0.61 $0.40</td>
<td>$1.69 $0.68 $0.61 $0.40</td>
<td>$1.69 $0.68 $0.61 $0.40</td>
</tr>
<tr>
<td>Technical Scalability</td>
<td>$1400 - $850/kWh $1400 - $850/kWh</td>
<td>$1400 - $850/kWh $1400 - $850/kWh</td>
<td>$1400 - $850/kWh $1400 - $850/kWh</td>
<td>$1400 - $850/kWh $1400 - $850/kWh</td>
</tr>
<tr>
<td>Modularity</td>
<td>71% 71% 71% 71%</td>
<td>71% 71% 71% 71%</td>
<td>71% 71% 71% 71%</td>
<td>71% 71% 71% 71%</td>
</tr>
<tr>
<td>Maintenance Requiements</td>
<td>2.6x + 2.6x + 2.6x + 2.6x</td>
<td>2.6x + 2.6x + 2.6x + 2.6x</td>
<td>2.6x + 2.6x + 2.6x + 2.6x</td>
<td>2.6x + 2.6x + 2.6x + 2.6x</td>
</tr>
<tr>
<td>Capital System Cost</td>
<td>35% 35% 35% 35%</td>
<td>35% 35% 35% 35%</td>
<td>35% 35% 35% 35%</td>
<td>35% 35% 35% 35%</td>
</tr>
<tr>
<td>Environmental Attributes/Disposal</td>
<td>$1400 - $850/kWh $1400 - $850/kWh</td>
<td>$1400 - $850/kWh $1400 - $850/kWh</td>
<td>$1400 - $850/kWh $1400 - $850/kWh</td>
<td>$1400 - $850/kWh $1400 - $850/kWh</td>
</tr>
<tr>
<td>Conditioned Footprint</td>
<td>2.6x + 2.6x + 2.6x + 2.6x</td>
<td>2.6x + 2.6x + 2.6x + 2.6x</td>
<td>2.6x + 2.6x + 2.6x + 2.6x</td>
<td>2.6x + 2.6x + 2.6x + 2.6x</td>
</tr>
<tr>
<td>Reliability</td>
<td>35% 35% 35% 35%</td>
<td>35% 35% 35% 35%</td>
<td>35% 35% 35% 35%</td>
<td>35% 35% 35% 35%</td>
</tr>
<tr>
<td>Expected Lifetime of Electrochemical Core</td>
<td>2.6x + 2.6x + 2.6x + 2.6x</td>
<td>2.6x + 2.6x + 2.6x + 2.6x</td>
<td>2.6x + 2.6x + 2.6x + 2.6x</td>
<td>2.6x + 2.6x + 2.6x + 2.6x</td>
</tr>
</tbody>
</table>

**Good = □; Concern = △; Not Good = ✗**

### Hydrogen vs. LiOH Battery Solution

<table>
<thead>
<tr>
<th>Factor</th>
<th>Battery System</th>
<th>Difference</th>
<th>Hydrogen System</th>
</tr>
</thead>
<tbody>
<tr>
<td>Net Energy Cost Cost</td>
<td>$1.69</td>
<td>2.5X +</td>
<td>$0.68</td>
</tr>
<tr>
<td>Incremental Storage Cost</td>
<td>$1400 - $850/kWh</td>
<td>10x +</td>
<td>$50-140/ kWh</td>
</tr>
<tr>
<td>% of Time Full</td>
<td>71%</td>
<td>1.6x +</td>
<td>43%</td>
</tr>
<tr>
<td>Wind Energy Wasted (1)</td>
<td>7.9/12.3 (64%)</td>
<td>2.6x +</td>
<td>2.8/10.9 (25%)</td>
</tr>
<tr>
<td>Capital Cost</td>
<td>69M$</td>
<td>2.5x +</td>
<td>28M</td>
</tr>
<tr>
<td>Total Life Cycle Cost</td>
<td>91M$</td>
<td>2.6x +</td>
<td>36.5M$</td>
</tr>
<tr>
<td>Net System Efficiency</td>
<td>35%</td>
<td>8% +</td>
<td>39%</td>
</tr>
<tr>
<td>Environmental Impact</td>
<td>D</td>
<td>+</td>
<td>O</td>
</tr>
</tbody>
</table>

Source: Hydrogenics
Energy Storage

Many Jobs, Many Solutions

Capacity, Not Efficiency a Larger Driver for Renewable Storage
Energy Storage Preliminary Analysis

Only Long-Term H$_2$ Storage competes in single day cycling

But multi-day energy storage will likely be necessary in a high renewables penetration scenario, if there is more value placed on otherwise curtailed renewable resources due to:

- Higher Renewable Portfolio Standards
- Carbon Dioxide Emission Controls

### Figure 1. Price of on-Peak electricity for various below-ground H$_2$ & CAES storage and battery storage options with one-day storage and 10% "free" (stranded) energy for a 10MW output over 4 hours (40MWh/day) & NG = $5/MBTU (for CAES) [All battery & CAES costs are based on the lower EPRI estimates.]

<table>
<thead>
<tr>
<th>Storage Type</th>
<th>Li-ion</th>
<th>NaS</th>
<th>Zn/Air</th>
<th>Fe/Cr</th>
<th>Zn/Br</th>
<th>Adv PbA</th>
<th>CAES-Below</th>
<th>H$_2$ Storage - Long-Term</th>
<th>H$_2$ Storage - Medium-Term</th>
<th>H$_2$ Storage - Near-Term</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity cost from storage (cents/kWh)</td>
<td>30.2</td>
<td>43.4</td>
<td>25.2</td>
<td>29.5</td>
<td>31.5</td>
<td>36.2</td>
<td>19.5</td>
<td>33.7</td>
<td>46.6</td>
<td>83.6</td>
</tr>
</tbody>
</table>

Need to understand when there is economic value for longer storage times under high penetration renewables scenarios

Source: Sandy Thomas
Energy “Storage”

Storage will need to compete with flexible generation on economics and probably emissions. Efficiency challenges exist, but when considering renewable electrons, it is economics, not efficiency, that is the critical metric.

Hydrogen goes beyond other technologies by providing a sink for grid electrons rather than a just a capacitor.

Carbon emitting options. Including the social cost of carbon will increase reported values.

Limited geographical locations available. May not be available in some regions due to water stress.

Non-energy values (e.g., ancillary services, capacity) are not included in these analyses but are likely to benefit storage as compared to combustion turbines (see Denholm, et al “The Relative Economic Merits of Storage and Combustion Turbines for Meeting Peak Capacity Requirements under Increased Penetrations of Solar Photovoltaics” (2015).

ATB: Annual Technology Baseline; CF: Capacity Factor; H2FC: Hydrogen Fuel Cell; CAES: Compressed Air Energy Storage
Safety Perceptions/Concerns
Hydrogen Safety

What is the first thing you think of when “Hydrogen Safety” is mentioned?

The flames observed are actually the burning aluminum powder, and lacquer applied to the canvas skin to mitigate against lightning strikes, not the hydrogen inside the airship. 1

1 The Freedom Element, Living with Hydrogen, Dr. A. Bain, Blue Note Publications, Cocoa Beach, FL, USA, 2004.

Fuel Flamability Comparison

<table>
<thead>
<tr>
<th></th>
<th>Hydrogen</th>
<th>Gasoline Vapors</th>
<th>Natural Gas</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flammability Limits (in air)</td>
<td>4-74%</td>
<td>1.4-7.6%</td>
<td>5.3-15%</td>
</tr>
<tr>
<td>Explosion Limits (in air)</td>
<td>18.3-59.0%</td>
<td>1.1-3.3%</td>
<td>5.7-14.0%</td>
</tr>
<tr>
<td>Ignition Energy (MJ)</td>
<td>0.02</td>
<td>0.2</td>
<td>0.29</td>
</tr>
<tr>
<td>Flame Temp. in air (°C)</td>
<td>2045</td>
<td>2197</td>
<td>1875</td>
</tr>
<tr>
<td>Stoichiometric Mixture (most easily ignited)</td>
<td>29%</td>
<td>2%</td>
<td>9%</td>
</tr>
</tbody>
</table>

“Hydrogen safety concerns are not cause for alarm; they simply are different than those we are accustomed to with gasoline or natural gas.”

AirProducts and Chemicals, Inc.

Fuel Leak Simulation
Punctured tank and ignition with equivalent energy release
# H₂ Safety

## Hydrogen Risk Assessment Models (HyRAM)
Developed a tool to enable integrated probabilistic and deterministic modeling (Quantitative Risk Assessment) for end users.

## LH₂ Reduced Separation Distances
Use of performance-based design to reduce separation distance and overall station footprint. Published report on ongoing research and research gaps in liquid hydrogen models ([http://prod.sandia.gov/techlib/access-control.cgi/2014/1418776.pdf](http://prod.sandia.gov/techlib/access-control.cgi/2014/1418776.pdf))

## Materials Compatibility
Testing of hydrogen compatibility of materials. Use of austenitic stainless steel provides life-time cost reductions (High fatigue stress can be achieved with cycles to failure >10,000 cycles). Development of high-pressure hydrogen materials testing protocol. ([www.sandia.gov/matlsTechRef/](http://www.sandia.gov/matlsTechRef/))

## Fuel Quality
- Developing a concept inline hydrogen analyzer to continuously monitor impurities and alert the user to any fuel quality issues at the station.
- Investigating effect of performance at low Pt (toward DOE target) loadings.
Connection to Grid
Future Electric Grid

Specific Grid Integration Technology Needs

- **Affordability**
  - Modest capital investment for production and storage
  - Renewable hydrogen source for marketplace revenue

- **Flexibility**
  - Scalable, deployable, multiple renewable hydrogen markets

- **Reliability**
  - Stable, sufficient power source
  - Inherently integrated element of grid

- **Resilience**
  - Distributed production and storage systems—large storage options

- **Sustainability**
  - Enable stable grid with abundant renewables-demand/response

- **Security**
  - Enable domestic, renewable energy resource

Research & Development Priorities

- Systems analysis
- Systems engineering
- Systems design and demo
Grid Support

• **How does H\textsubscript{2} impact Reliability, Resiliency, Security?**
  – We’re not sure and need your help, but there are specific features that are likely to have impact, there is also the ability to control (improve) impacts

• **Ancillary services (including fast dynamic response)**

• **Large scale potential**
  – Scalability
  – Flexibility (sighting and integration)
  – Energy storage
Resiliency

- Blackouts cost economy $billions annually.
- \( \text{H}_2 \) can provide resiliency (how is \( \text{H}_2 \) impact quantified, validated, and/or monetized?)
Grid Support

- Ancillary services (response time/duration)
Exceptional Energy Storage Capability and Real Time Dynamic Response

Note: IESO signal test completed June 2011 – AGC (Automatic Generation Control)
H₂ Storage Potential

- Current natural gas system
  - 305,000 miles of transmission pipelines
  - 400 underground natural gas storage facilities
  - 3.9 Bcf underground storage working gas capacity
- If transitioned to H₂ equates to...
  - 38 billion kg of H₂

H₂ storage capacity
~2 months energy needs potentially available
Does this reflect resiliency or security?

Source: www.eia.gov/pub/oil_gas/natural_gas/analysis_publications/ngpipeline/index.html
Scalability/Flexibility

• Distributed options vs. centralized options
  – From sub-MW to GW scale
  – Coupling with local generation (wind, PV, CSP, NE)
  – Electricity transmission vs. hydrogen distribution
  – On-site consumption or conversion
Cross-DOE-Office Connections
### Cross-Office Collaborations

#### R&D Focus

<table>
<thead>
<tr>
<th><strong>Low T H₂ Production</strong></th>
<th><strong>Research Activities</strong></th>
<th><strong>DOE Programs</strong></th>
<th><strong>Impact</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>• Reduce precious metal loadings on electrolyzer electrodes</td>
<td>ARPA-E BES SETO Wind OE FCTO</td>
<td>✓ Increase the value of renewable electrons</td>
</tr>
<tr>
<td></td>
<td>• Low-cost, durable high-conductivity membranes</td>
<td></td>
<td>✓ Enable high penetration of renewables on the grid</td>
</tr>
<tr>
<td></td>
<td>• Low-cost, corrosion resistant, thin film protective coatings</td>
<td></td>
<td>✓ Improve efficiency and stability of electrochemical and photoelectrochemical technologies</td>
</tr>
<tr>
<td></td>
<td>• Develop durable systems for intermittent operation</td>
<td></td>
<td>✓ Decrease the cost of H₂ at high volume by 5X</td>
</tr>
<tr>
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<td>• Develop transformational technologies for water splitting from renewable feedstock</td>
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<td>• Materials discovery and development for high T electrolyzers (e.g. SOEC)</td>
<td>NE BES SETO FCTO</td>
<td>✓ Reduce electricity consumption of electrolysis by leveraging waste heat</td>
</tr>
<tr>
<td></td>
<td>• Component durability in intermittent heat sources</td>
<td></td>
<td>✓ New materials discovery</td>
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<tr>
<td></td>
<td>• Develop transformational high-temperature redox materials and reactor components for hydrogen generation</td>
<td></td>
<td>✓ Improve thermochemical/concentrated solar system design and components including materials, heliostat, and power electronics</td>
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<th><strong>H₂ Storage and Distribution</strong></th>
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<td></td>
<td>• Polymer and steel compatibility with H₂</td>
<td>NNSA BES ARPA-E AMO FE FCTO</td>
<td>✓ Develop physics-based understanding of hydrogen embrittlement</td>
</tr>
<tr>
<td></td>
<td>• Advanced liquefaction and refrigeration</td>
<td></td>
<td>✓ Improve hydrogen liquefaction efficiency by &gt; 60%</td>
</tr>
<tr>
<td></td>
<td>• Materials for harsh environments</td>
<td></td>
<td>✓ Improve reliability and efficiency of gas compression</td>
</tr>
<tr>
<td></td>
<td>• Reduce moving parts, and improve efficiency of pipeline and forecourt compressors</td>
<td></td>
<td>✓ Lower cost of high-pressure pipelines</td>
</tr>
<tr>
<td></td>
<td>• Use of fiber reinforced composite polymers in pipelines</td>
<td></td>
<td>✓ Enable over 2X reduction in cost of hydrogen delivery and dispensing</td>
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</table>
### Cross-Office Collaborations

#### R&D Focus

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</table>
| **Ammonia** | • Modular Plants  
• Catalyst R&D  
• Process intensification  
• Ammonia Fuel Cells | ARPA-E  
AMO  
FCTO  
FE  
SC | ✓ Decrease cost of NH₃ production >25%  
✓ Improve process efficiency  
✓ Improve NH₃ handling safety |
| **Refineries** | • Electrolysis and refinery heat integration  
• H₂ and O₂ combustion  
• Integrated coke gasification  
• NE &RE energy utilization | FE  
FCTO  
AMO SC  
NE & RE | ✓ >75% GHG footprint reduction  
✓ Facilitate heavy crude refining  
✓ Coke by-product management  
✓ Expand markets for RE & NE |
| **Chemicals** | • Catalyst R&D for H₂-dependent chemicals  
• CO₂ reduction chemistry  
• Process intensification  
• Hybrid electricity/chemicals | ARPA-E  
AMO SC  
NE & RE  
FCTO | ✓ Sustainable chemicals production  
✓ Pathway to CO₂ utilization  
✓ Domestic workforce with competitive manufacturing |
| **Biofuels** | • Modular plants for distributed production  
• H₂ (and O₂) incorporation in bio-refineries | BETO  
VTO SC  
NE & RE  
FCTO | ✓ Increase biofuels potential production >30%  
✓ 100% zero-emissions biofuels  
✓ Expand markets for local RE |
| **Metals & Glass Refining** | • Direct reduction of iron process development  
• Metals annealing/tempering  
• Materials codification | ARPA-E  
AMO SC | ✓ 10x increase in U.S. steel production with associated heavy manufacturing  
✓ >5% impact on world GHG |
| **Combustion Processes** | • Flame chemistry and heat transfer studies  
• Burner and turbine testing | ARPA-E  
AMO  
FE SC | ✓ Movement toward Zero-emissions process heating  
✓ Clean power generation |
| **H₂ Heat Pumps** | • Low temperature heat use  
• Industrial and residential energy efficiency studies  
• Power systems integration | ARPA-E  
AMO  
BTO  
FE SC | ✓ 5% efficiency improvement for manufacturing industries  
✓ 10% efficiency improvement for power generation turbines  
✓ >50% cooling water reduction |
QTR Connections
QTR Feedback

• Major challenges:
  Reduce the cost of producing and delivering H₂ from renewable/low-carbon sources for FCEV and other uses (capex, O&M, feedstock, infrastructure, safety, permitting, codes/standards)

• Factors driving change in the technologies:
  – FCEVs are driving requirements (e.g. high P tanks)
  – Need to reduce cost of 700 bar refueling stations for near-term FCEV roll-out

• Where the technology R&D needs to go:
  – Materials innovations to improve efficiencies, performance, durability and cost, and address safety (e.g. embrittlement, high pressure issues)
  – System-level innovations including renewable integration schemes, tri-generation (co-produce power, heat and H₂), energy storage balance-of-plant improvements, etc.
  – Cost reductions in H₂ compression, storage and dispensing components
  – Continued resource assessments to identify regional solutions to cost-competitive H₂

H₂ offers important long-term value as a clean energy carrier

Renewable energy integration options with hydrogen
QTR - Hydrogen Analysis and Research Goals

- Reduce the cost of H₂ from renewable and low-carbon domestic resources to achieve a delivered & dispensed cost of <$4/gge (Note: 1 kg H₂ ~ 1 gge)

Pathways:
- Electrolysis, high temperature thermochemical (solar/nuclear), biomass gasification/bio-derived liquids, coal gasification with CCS, biological & photoelectrochemical

- Need R&D in materials and components to improve efficiency, performance, durability, and reduce capital and operating costs for all pathways
  - For many pathways, feedstock cost is a key driver of H₂ cost

- Need strong techno-economic and regional resource analysis

- Opportunities for energy storage (e.g. curtailed wind for electrolyzing water)