Overview

• Focus of this is an overview, introduction, and update to the continually evolving H2@Scale program and vision.

• H2@Scale: Enabling Affordable, Reliable, Clean, and Secure Energy Across Sectors

• H2@Scale detailed projects presented elsewhere
  – Remainder of Session 3
  – Poster Session (Thursday night, H2@Scale CRADA)
  – Overlap in many other areas
Key Drivers for Evolving Energy System

- Increasing low-cost, renewable variable electricity
- Rapid growth in energy storage
- Competitive Manufacturing
- Energy System Security/Resilience

**Average U.S. Levelized Wind PPA Prices**

- **Average PPA Price ($/MWh)**
  - 2009: $80
  - 2011: $60
  - 2013: $40
  - 2015: $20
  - 2017: $0

**Projected Growth in Energy Storage (GW)**

- South Korea
- Australia
- United Kingdom
- Germany
- India
- Japan
- China
- United States

**National Resilience Value**

- Coal and oil-fired units were able to respond during winter “bomb cyclone”
- $3.5 Billion

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Energy System Challenge

• Multi-sector requirements
  o Transportation
  o Industrial
  o Grid

How do we supply all these services in the best way?
What constitutes “a pace and scale that matters” for our efforts to transform clean energy systems?

Note: % VRE in 2015

% Variable Renewable Energy

(percentage of annual energy)

System Size (GW)

Actual Operating System

Modeled System

Lanai

Alaska Village

Maui

Denmark*

Ireland

CA 50%

WWSIS

ERGIS

Germany*

Cont. USA

CA*

DOE 2050 Goals

35% Wind (404 GW)

19% PV (632 GW)

Aggressive Growth in Renewables

1400 GW wind

900 GW Solar

Extremely Difficult

Much harder

Relatively Easy

Credit:
B. Kroposki, NREL

WWSIS = Western Wind and Solar Integration study
ERGIS = Eastern Renewable Generation Integration Study
REF = Renewable Electricity Futures Study

* Part of a larger synchronous AC power system

Note: % VRE in 2015
• Dwight D. Eisenhower

"If you can't solve a problem, enlarge it"
Conceptual H2@Scale Energy System*

*Illustrative example, not comprehensive
H2@Scale Vision

• **Attributes**
  - Cross-sectoral and temporal energy impact
  - Clean, efficient end use (and generation)

• **Benefits**
  - Economic factors (jobs, GDP)
  - Enhanced Security (energy, manufacturing)
  - Environmental Benefits (air, water)

All these benefits in a **single**, energy system.
Stakeholder Groups - Engagement

- Nuclear
- Wind
- Solar
- Fossil
- Grid/Utilities
- Regulators
- Electrolysis
- Industrial Gas
- Auto OEMs/supply chain
- Fuels Production (Big Oil)
- Metals/Steel
- Ammonia

- Analysis
- Investors
Technology Development Roles

Early-Stage R&D

- U.S. Department of Energy
- Fuel Cells R&D
- H₂ Fuel R&D

Demonstration, Deployment & Commercialization

- Private Sector
- Partnerships
- Other Agencies
- States
Improving the economics of H2@Scale

Early-stage research is required to evolve and de-risk the technologies.

Leveraging of national laboratories’ early-stage R&D capabilities needed to develop affordable technologies for production, delivery, and end use applications.

Optimizing H₂ storage and distribution

H2@Scale CRADA Call Selections

First round of Selections Include 24 Applications from:

H$_2$ Station Risk Analysis
- Air Liquide
- California Energy Commission
- Connecticut Center for Advanced Technology
- PDC Machines
- Quong & Associates, Inc.

Hydrogen Production R&D
- Honda
- C4-MCP, Inc.
- GinerELX
- GTA, Inc.

Hydrogen Integration
- Electric Power Research Institute
- Exelon
- Southern Company / Terrestrial Energy
- Nikola Motor
- Pacific Gas & Electric
- TerraPower

Component R&D
- California Go-Biz Office
- Frontier Energy
- HyET
- Honda
- NanoSonic
- RIX
- Tatsuno

Selections and subsequent working group assignments are subject to negotiation.
H$_2$ today is different

- **Hydrogen Council**

  - Launched in January 2017 its members include leading companies with over $10 billion in investments along the hydrogen value chain, including transportation, industry, and energy exploration, production, and distribution.

  - Engagement – remarkable evolution over the years I’ve been involved with H2@Scale.
Real-world H2@Scale Examples

~5,000 Fuel Cell Vehicles and 35 commercial H₂ fueling stations open in CA.

1,000 kg/day hydrogen stations to be deployed in 14-28 locations for fuel cell trucks (2018; Nikola, Nel)
Real-world H2@Scale Examples

750,000 tonne/year ammonia plant using by-product hydrogen opens in Freeport, TX (2018; Yara, BSF)

Integration of 1.5-MW of electrolysis with wind and tidal power in Orkney, Scotland (2018; BIG HIT project)
Real-world H2@Scale Examples

Integration of 10-MW of electrolysis with Rheinland Refinery Complex (Germany) (2018; Shell)

Integration of 6 MW of electrolysis with wind energy and natural gas pipelines (2015; Mainz, EnergiePark Mainz)
Next Steps

- **FY17-FY18**
  - Development of H2@Scale goals
  - Development of draft H2@Scale Roadmap identifying and prioritizing RD&D needs
  - Analysis to assess potential supply and demand of H2@Scale under future market scenarios
  - Pathway to H₂ at the Gigaton-scale Workshop
  - H2@Scale Workshops/Working Group meetings

- **June 13-15, 2018: Annual Merit Review**
  - Presentations to follow
  - Poster Session June 14, 2018, 6pm

- **August 1-2, 2018: Kick-off of H2@Scale Consortium Working Groups at workshop in Chicago, IL**
Summary/Key Points

• H2@Scale has become firmly established as an R&D priority for DOE and various stakeholders.
• The view of $H_2$ amongst different stakeholder groups is changing rapidly, with unprecedented efforts around $H_2$.
• Constancy of purpose
• Consistency and clarity of message

Our country and children are counting on us.
Technical Backup Slides
Role of $\text{H}_2$ in storing chemical energy

Representing the reactions this way, allows for the comparison of bond energy on a per electron basis (V cell). Notably, HH bonds have the most energy per electron (1.19 V), followed by NH bonds (1.13 V), CH bonds (1.04 V), and CC bonds (1.02 V). It is slightly exothermic (downhill) going from H2 plus CO2 to hydrocarbons (including the Sabatier process, fifth reaction, for methane generation or Fischer-Tropsch chemistry for liquid fuels or other multiple carbon, hydrocarbon products) or going from H2 plus N2 to ammonia (Haber-Bosch process, sixth reaction). Through these established, large-scale industrial processes (Sabatier, Fischer-Tropsch and Haber-Bosch), H2 can serve as the energy-containing intermediate leading to fuels or products, with enough energy to drive processes, but not so much excess energy that product formation “wastes” an excessive amount of the input energy.

<table>
<thead>
<tr>
<th>Rxn</th>
<th>$\Delta G$ (kJ/mol)</th>
<th>V cell (V)</th>
<th># e–</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{H}_2 + 1/2\text{O}_2 \rightarrow \text{H}_2\text{O}$</td>
<td>-228.6</td>
<td>1.19</td>
<td>2</td>
</tr>
<tr>
<td>$\text{CH}_4 + 2\text{O}_2 \rightarrow 2\text{H}_2\text{O} + \text{CO}_2$</td>
<td>-800.8</td>
<td>1.04</td>
<td>8</td>
</tr>
<tr>
<td>$\text{C} + \text{O}_2 \rightarrow \text{CO}_2$</td>
<td>-394.4</td>
<td>1.02</td>
<td>4</td>
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<tr>
<td>$\text{NH}_3 + 3/2\text{O}_2 \rightarrow 1/2\text{N}_2 + 3/2\text{H}_2\text{O}$</td>
<td>-326.5</td>
<td>1.13</td>
<td>3</td>
</tr>
<tr>
<td>$\text{CO}_2 + 4\text{H}_2 \rightarrow \text{CH}_4 + 2\text{H}_2\text{O}$</td>
<td>-113.6</td>
<td>0.15</td>
<td>8</td>
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<tr>
<td>$\text{N}_2 + \text{H}_2 \rightarrow \text{NH}_3$</td>
<td>-16.4</td>
<td>0.06</td>
<td>3</td>
</tr>
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What is needed to achieve H₂@Scale?

Low and High Temperature H₂ Generation

- R&D for **low cost, durable, and intermittent H₂ generation.**

- R&D for **thermally integrated, low cost, durable, and variable H₂ generation.**

H₂ Storage and Distribution

- R&D for **safe, reliable, and economic storage and distribution systems.**

H₂ Utilization

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

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<tr>
<th>Analysis</th>
<th>Foundational Science</th>
<th>Future Electrical Grid</th>
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