H2@Scale Overview

2018 DOE Hydrogen and Fuel Cells Program Review

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H2000

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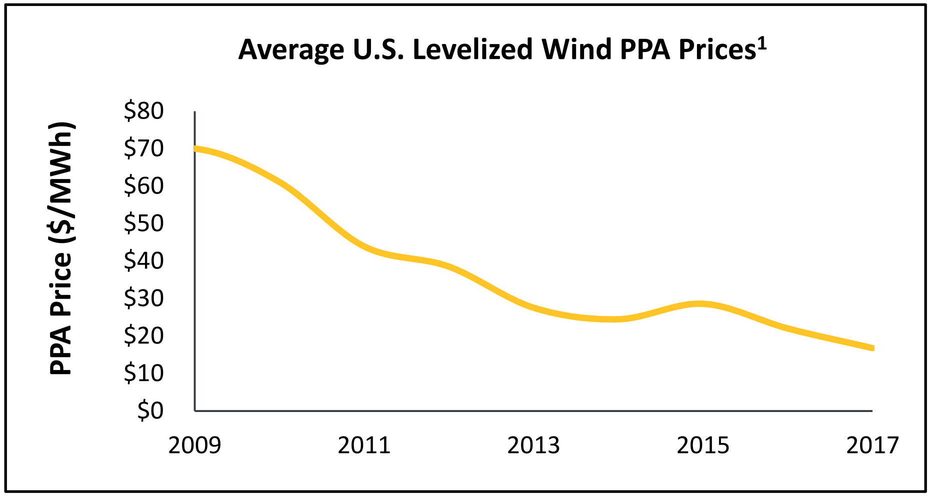
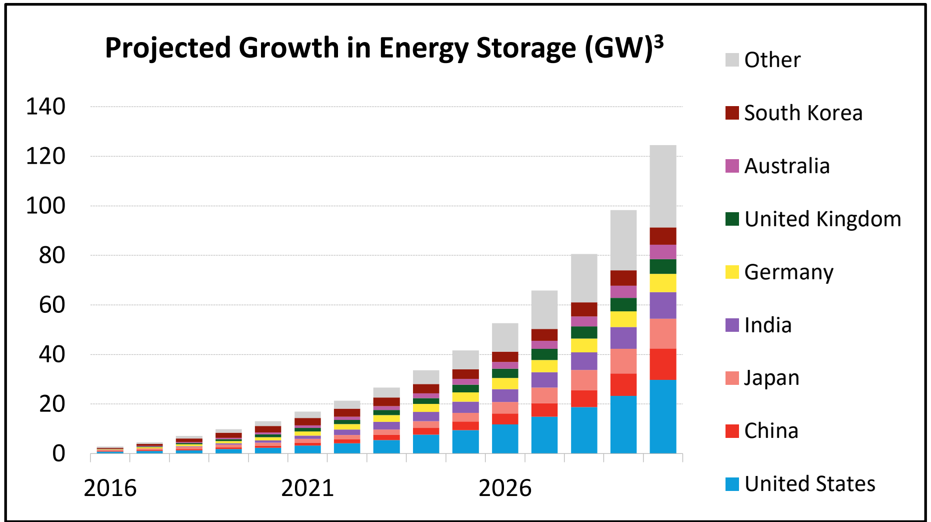
Overview

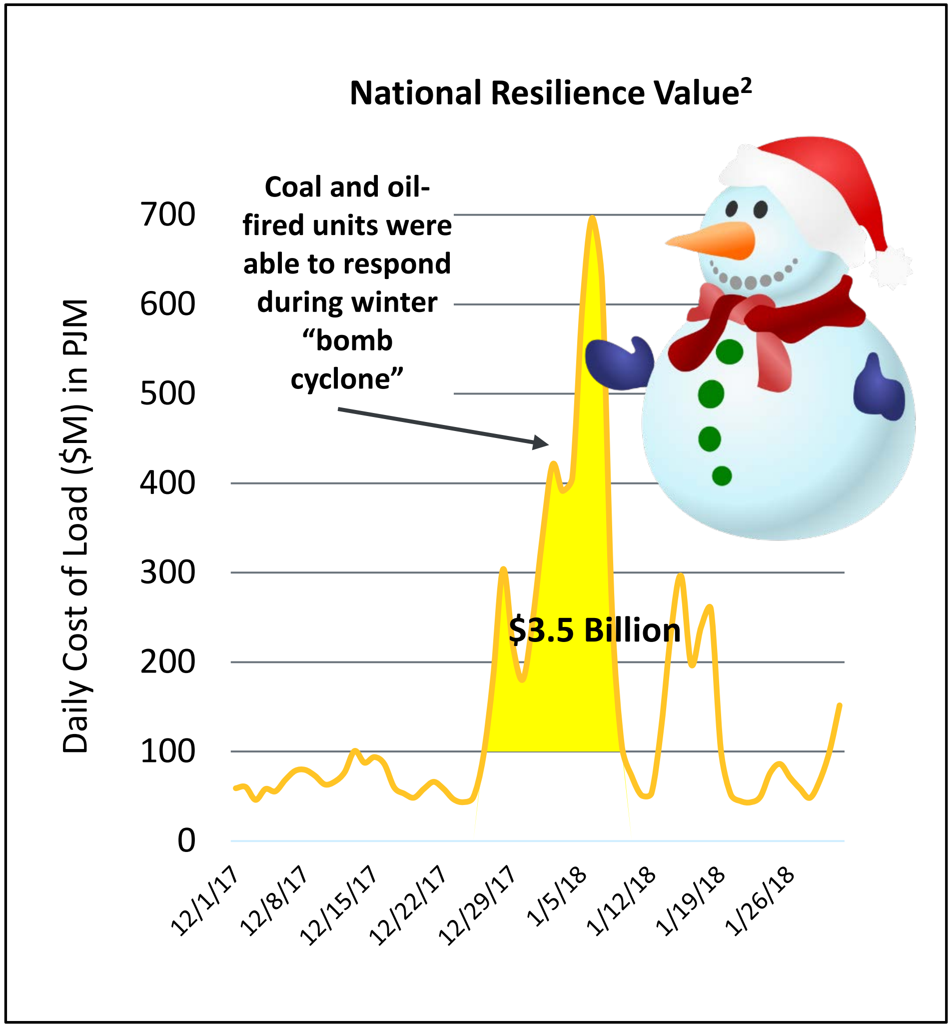
- **Focus of this is an overview, introduction, and update to the continually evolving H2@Scale program and vision.**
- **H2@Scale: Enabling Affordable, Reliable, Clean, and Secure Energy Across Sectors**
- **H2@Scale detailed projects presented elsewhere**
  - Remainder of Session 3
  - Poster Session (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**







1. Lawrence Berkeley National Laboratory, https://emp.lbl.gov/wind-technologies-market-report
2. National Energy Technology Laboratory, https://www.netl.doe.gov/energy-analyses/temp/ReliabilityandtheOncomingWaveofRetiringBaseloadUnitsVolumeITheCriticalRoleofThermalUnits_031318.pdf

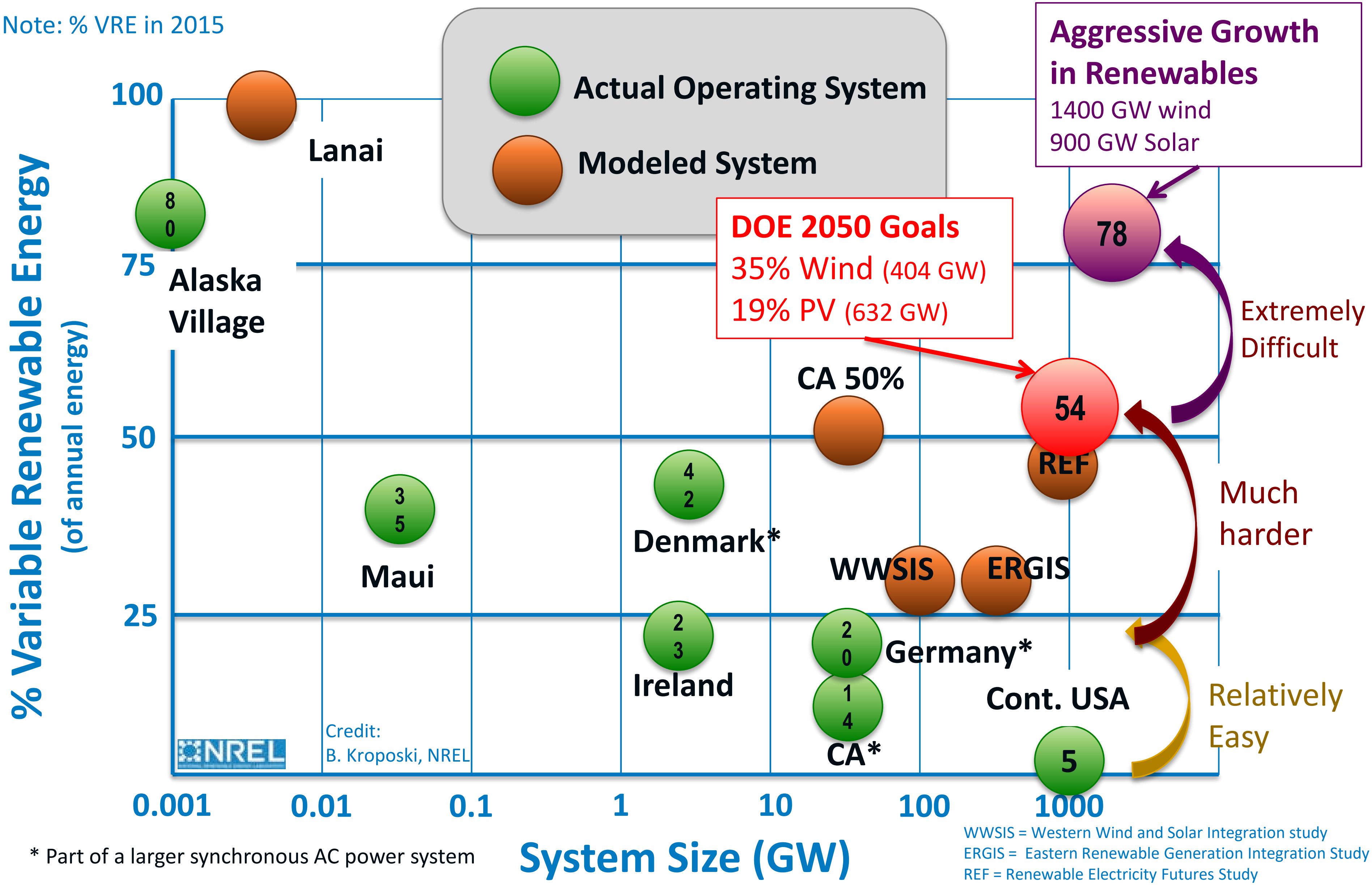
3. Source: Sekine, Yayoi. "2017 Global Energy Storage Forecast". Bloomberg New Energy Finance.

Energy System Challenge

- **Multi-sector requirements**
  - Transportation
  - Industrial
  - 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?

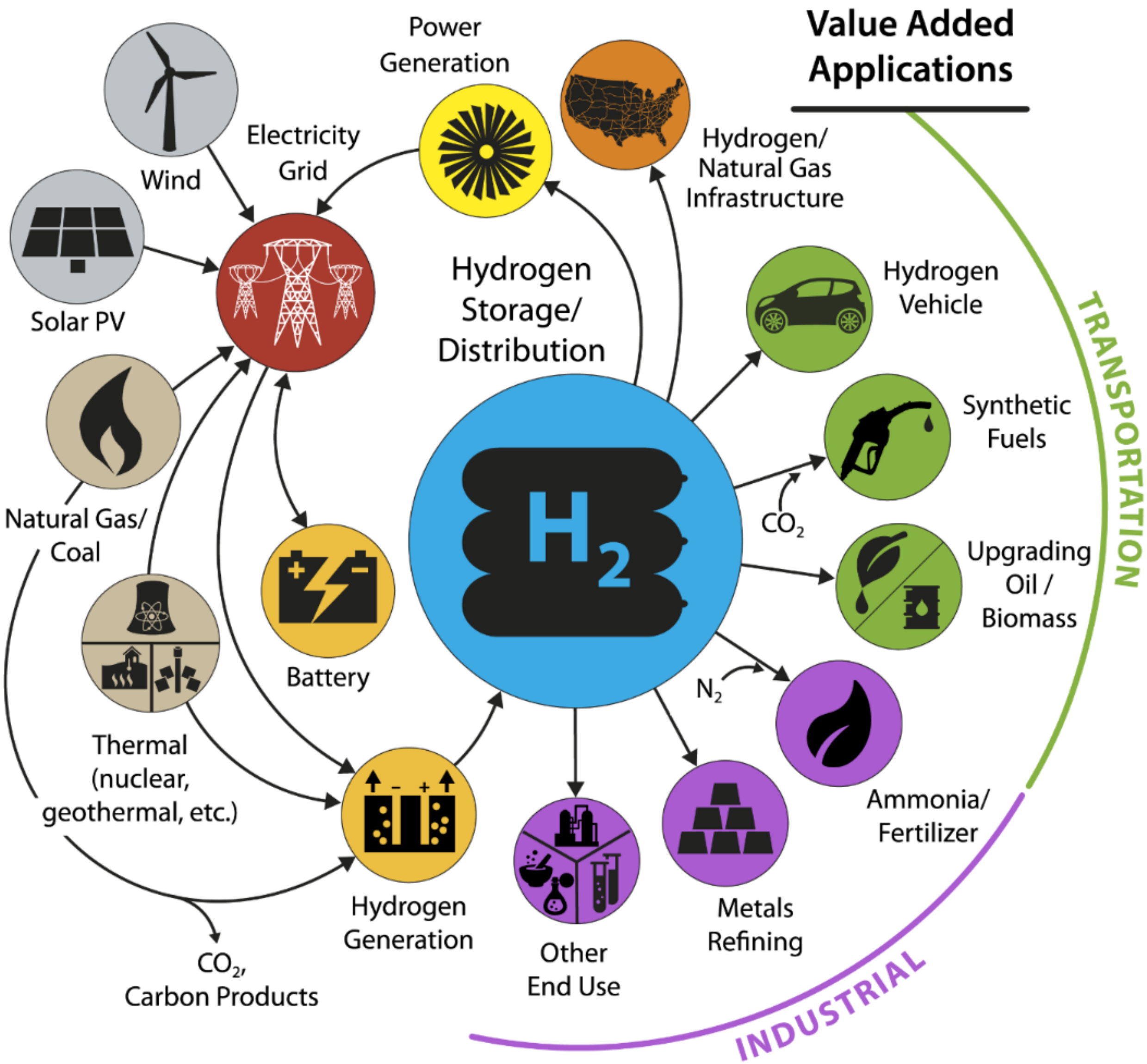


* Part of a larger synchronous AC power system

- **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)

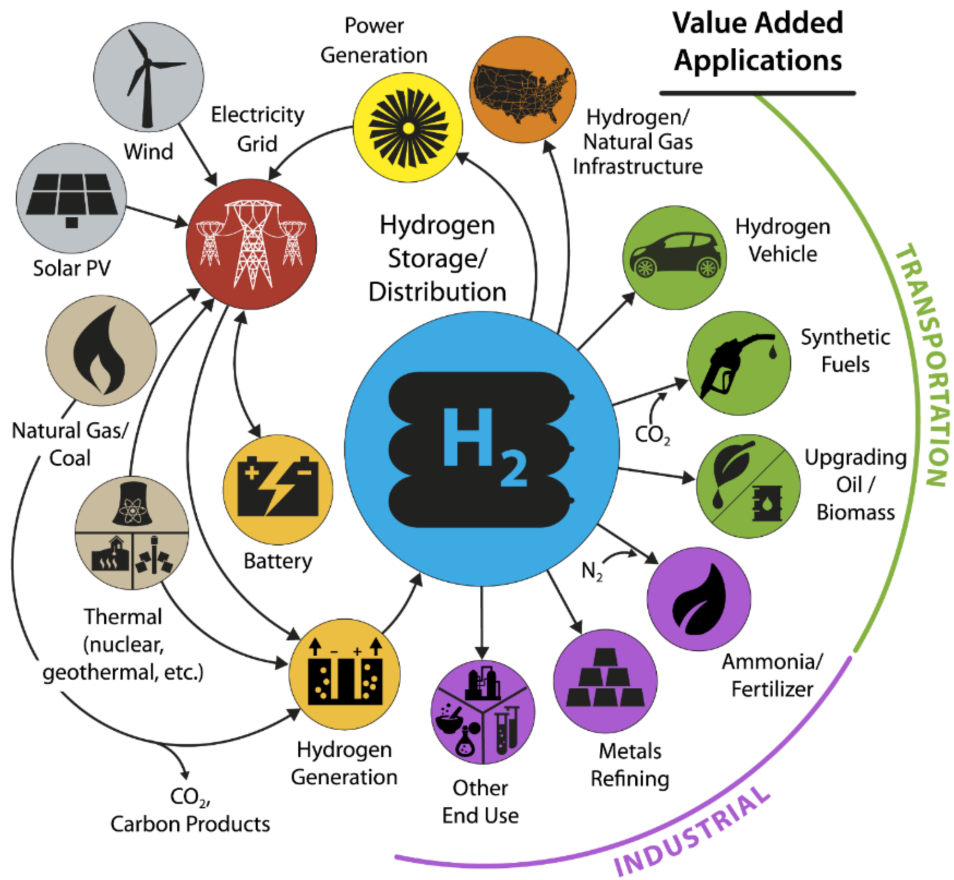
- **Benefits**
  - Economic factors (jobs, GDP)
  - Enhanced Security (energy, manufacturing)
  - Environmental Benefits (air, water)

All these benefits in a **single**, energy system.

Stakeholder Groups - Engagement

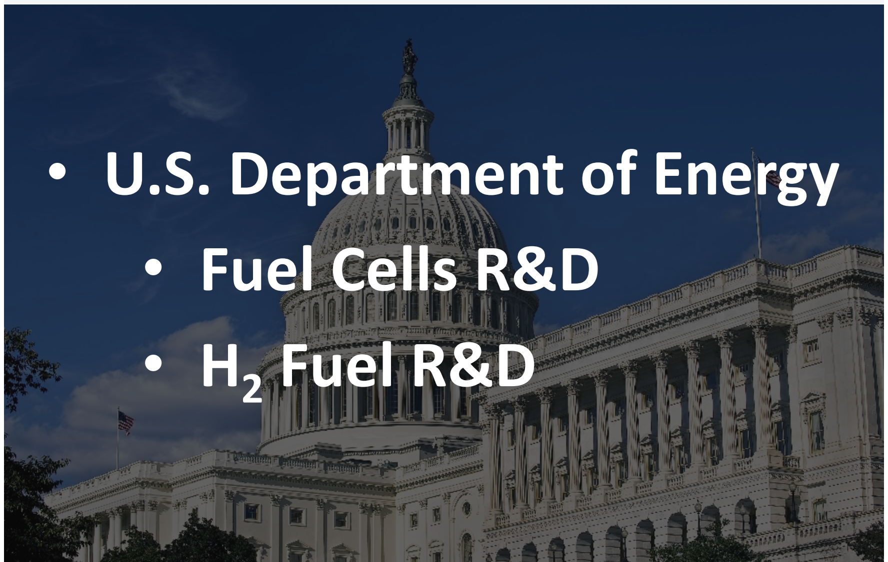
- Nuclear
- Wind
- Solar
- Fossil
- Grid/Utilities
- Regulators
- Electrolysis
- Industrial Gas
- Auto OEMs/supply chain
- Fuels Production (Big Oil)
- Metals/Steel
- Ammonia

- Analysis
- Investors



Technology Development Roles

Early- Stage R&D



- U.S. Department of Energy
  - Fuel Cells R&D
  - H_2 Fuel R&D

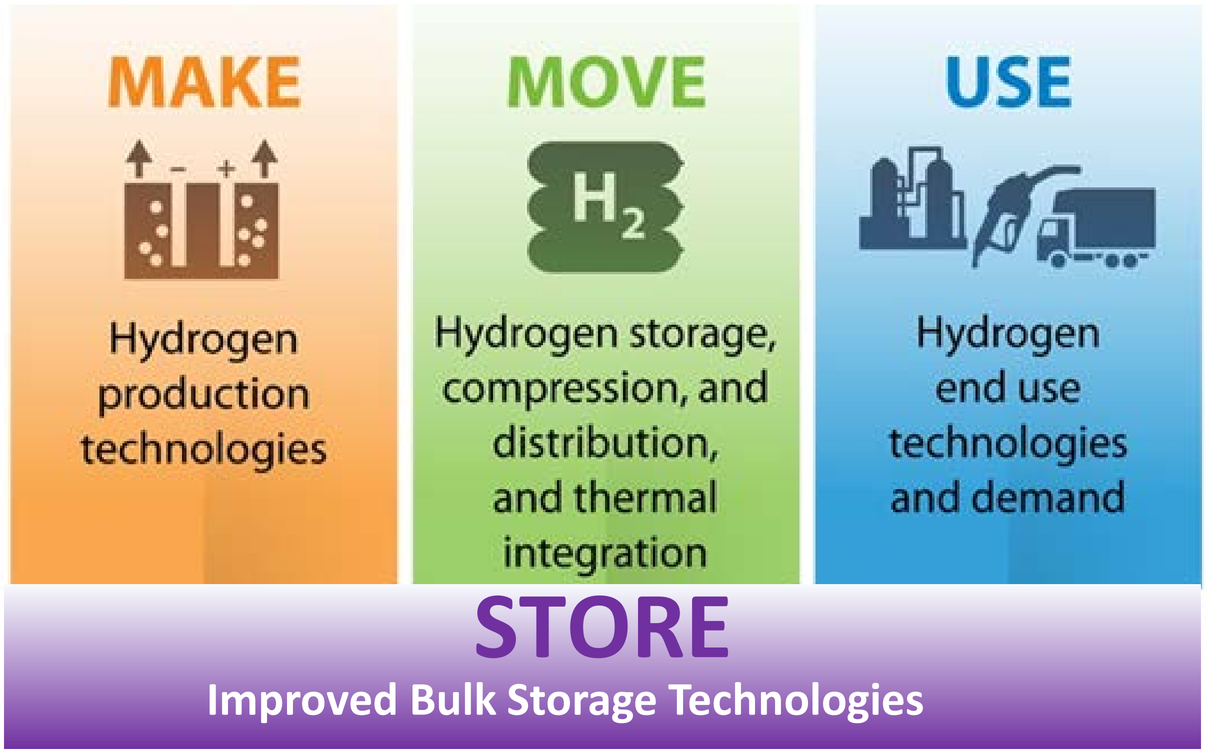
Demonstration, Deployment & Commercialization

- Private Sector
- Partnerships
  - Other Agencies
  - States

H2@Scale℠ U.S. Department of Energy

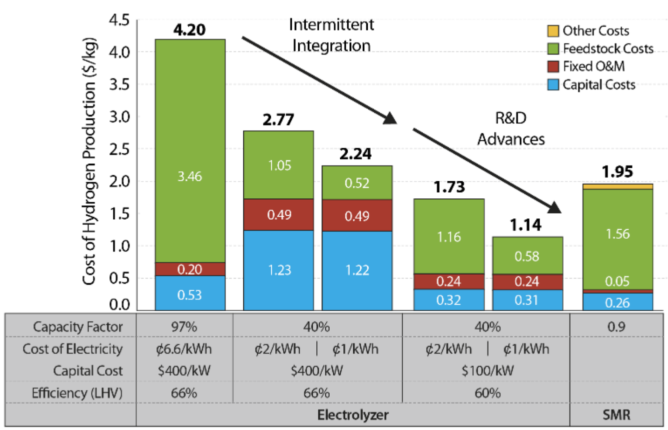
Improving the economics of H2@Scale

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



Preliminary

Use	Potential MMT/yr
Refineries & CPI	8
Metals	6
Ammonia	5
Methanol	1
Biofuels	1
Natural Gas	7
Light Duty Vehicles	28
Other Transport	3
Electricity Storage	28
Total	**87**



Decreasing cost of H_2 production

Optimizing H_2 storage and distribution

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

https://www.hydrogen.energy.gov/pdfs/review18/tv045_ruth_2018_o.pdf

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

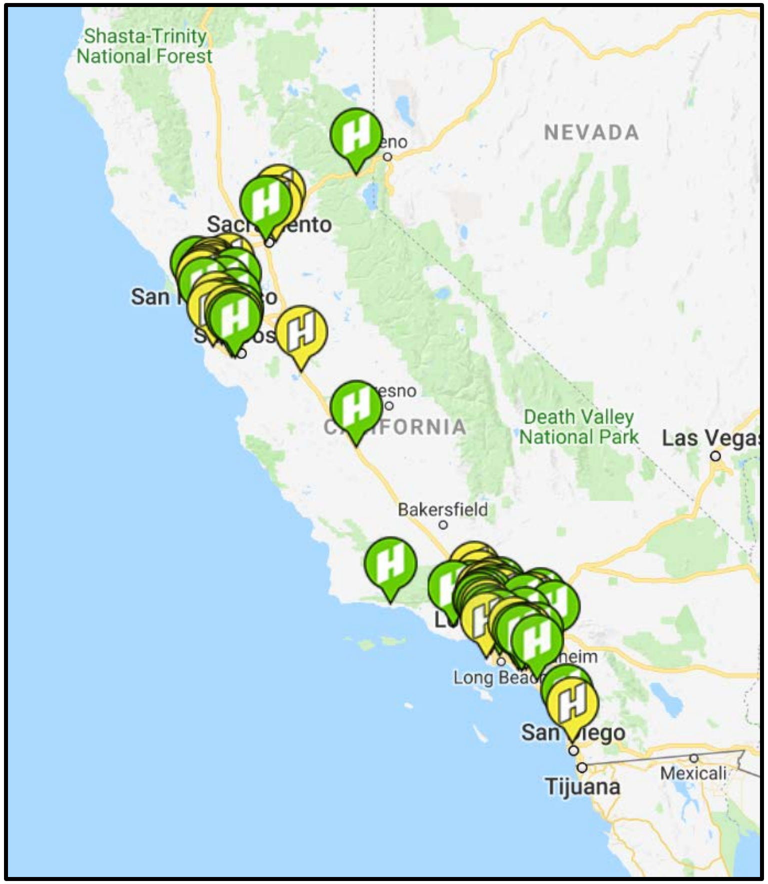
- **Hydrogen Council**

> ***Potential Impacts from Hydrogen Council Roadmap Study. By 2050:***
> - *$2.5 trillion in global revenues*
> - *30 million jobs*
> - *400 million cars, 15-20 million trucks*
> - *18% of total global energy demand*

  - 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

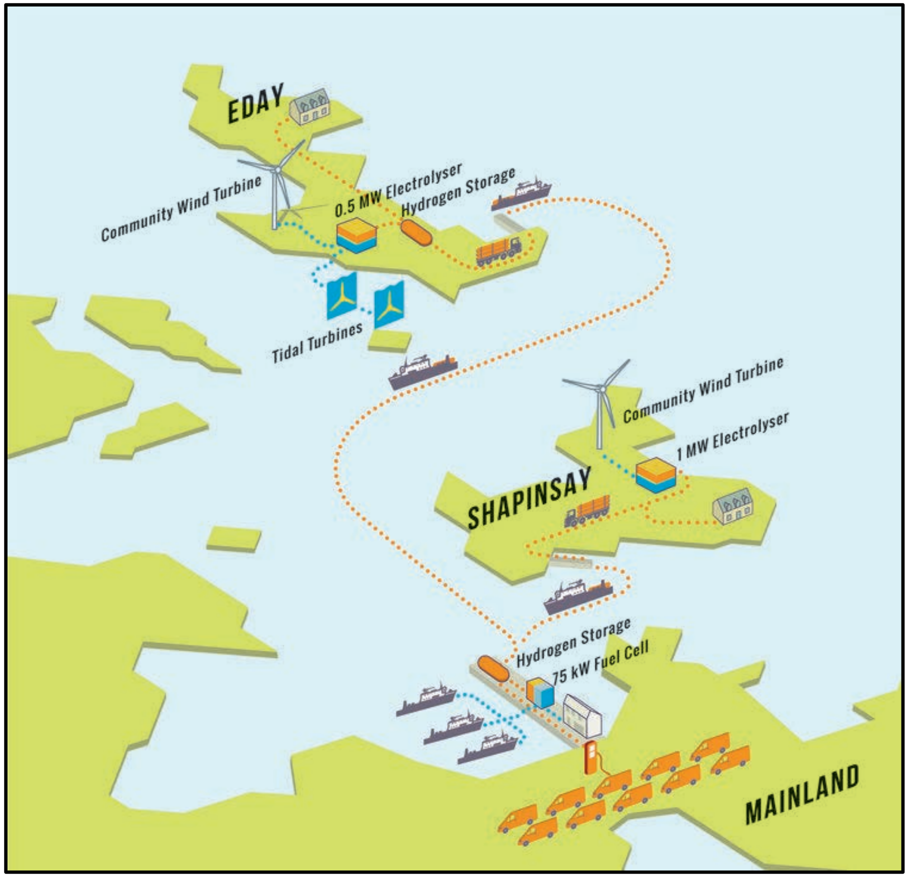


~5,000 Fuel Cell Vehicles and 35 commercial H_2 fueling stations open in CA.

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)



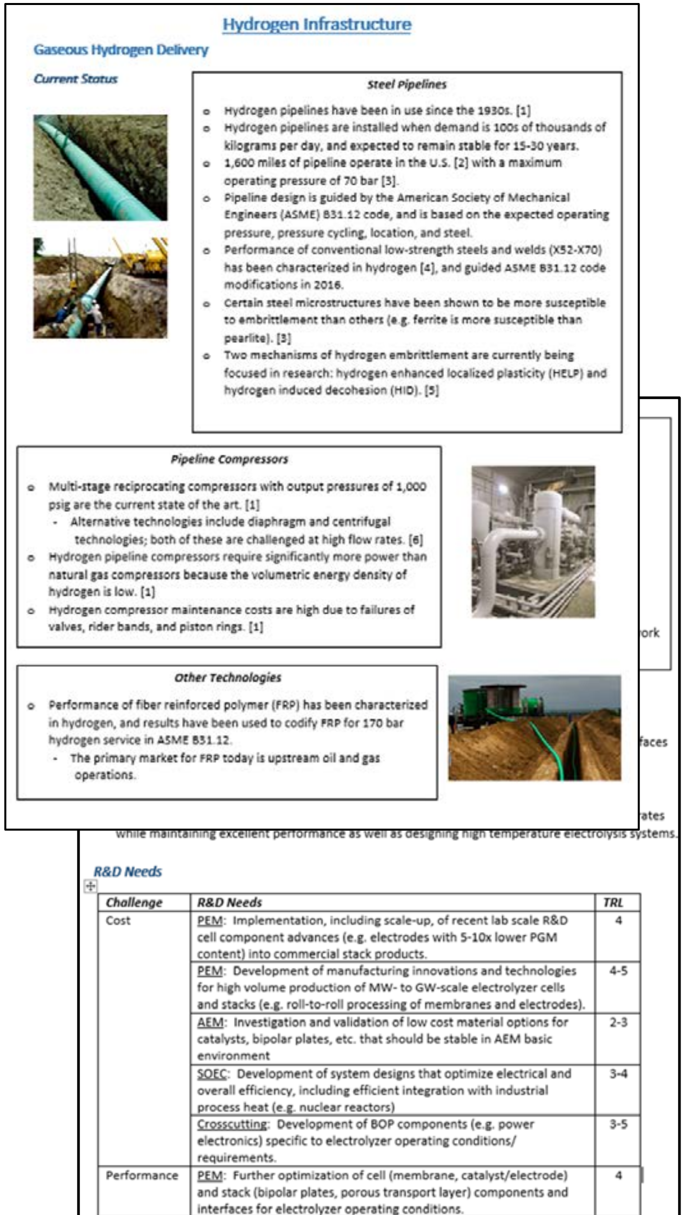
Integration of 1.5-MW of electrolysis with wind and tidal power in Orkney, Scotland
(2018; BIG HIT project)

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



Hydrogen Infrastructure

Gaseous Hydrogen Delivery

Current Status

Steel Pipelines

- Hydrogen pipelines have been in use since the 1930s. [1]
- Hydrogen pipelines are installed when demand is 100s of thousands of kilograms per day, and expected to remain stable for 15-30 years.
- 1,600 miles of pipeline operate in the U.S. [2] with a maximum operating pressure of 70 bar [3].
- Pipeline design is guided by the American Society of Mechanical Engineers (ASME) B31.12 code, and is based on the expected operating pressure, pressure cycling, location, and steel.
- Performance of conventional low-strength steels and welds (X52-X70) has been characterized in hydrogen [4], and guided ASME B31.12 code modifications in 2016.
- Certain steel microstructures have been shown to be more susceptible to embrittlement than others (e.g. ferrite is more susceptible than pearlite). [3]
- Two mechanisms of hydrogen embrittlement are currently being focused in research: hydrogen enhanced localized plasticity (HELP) and hydrogen induced decohesion (HID). [5]

Pipeline Compressors

- Multi-stage reciprocating compressors with output pressures of 1,000 psig are the current state of the art. [1]
  - Alternative technologies include diaphragm and centrifugal technologies; both of these are challenged at high flow rates. [6]
- Hydrogen pipeline compressors require significantly more power than natural gas compressors because the volumetric energy density of hydrogen is low. [1]
- Hydrogen compressor maintenance costs are high due to failures of valves, rider bands, and piston rings. [1]

Other Technologies

- Performance of fiber reinforced polymer (FRP) has been characterized in hydrogen, and results have been used to codify FRP for 170 bar hydrogen service in ASME B31.12.
  - The primary market for FRP today is upstream oil and gas operations.

while maintaining excellent performance as well as designing high temperature electrolysis systems.

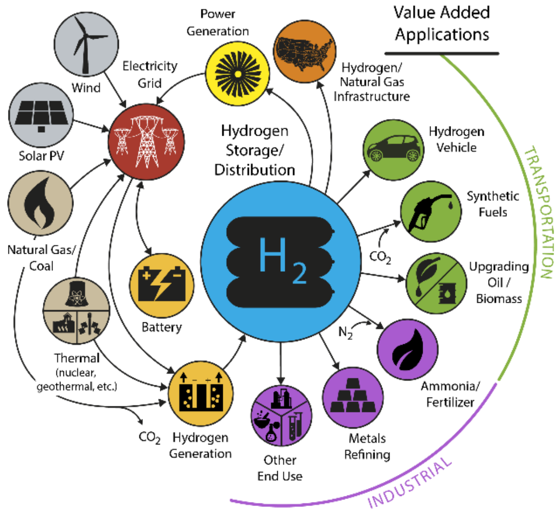
R&D Needs

Challenge	R&D Needs	TRL
Cost	PEM: Implementation, including scale-up, of recent lab scale R&D cell component advances (e.g. electrodes with 5-10x lower PGM content) into commercial stack products.	4
	PEM: Development of manufacturing innovations and technologies for high volume production of MW- to GW-scale electrolyzer cells and stacks (e.g. roll-to-roll processing of membranes and electrodes).	4-5
	AEM: Investigation and validation of low cost material options for catalysts, bipolar plates, etc. that should be stable in AEM basic environment	2-3
	SOEC: Development of system designs that optimize electrical and overall efficiency, including efficient integration with industrial process heat (e.g. nuclear reactors)	3-4
	Crosscutting: Development of BOP components (e.g. power electronics) specific to electrolyzer operating conditions/ requirements.	3-5
Performance	PEM: Further optimization of cell (membrane, catalyst/electrode) and stack (bipolar plates, porous transport layer) components and interfaces for electrolyzer operating conditions.	4

- **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 H_2 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 H_2 in storing chemical energy

Table I. The Gibbs free energy change (ΔG), cell voltage (V cell), and number of electrons generated for select chemical bond energy storing gas-phase reactions.

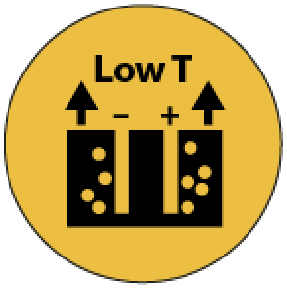
Rxn	ΔG (kJ/mol)	V cell (V)	# e–
$H_2 + 1/2O_2 \rightarrow H_2O$	–228.6	1.19	2
$CH_4 + 2O_2 \rightarrow 2H_2O + CO_2$	–800.8	1.04	8
$C + O_2 \rightarrow CO_2$	–394.4	1.02	4
$NH_3 + 3/2O_2 \rightarrow 1/2N_2 + 3/2H_2O$	–326.5	1.13	3
$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$	–113.6	0.15	8
$N_2 + H_2 \rightarrow NH_3$	–16.4	0.06	3

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.

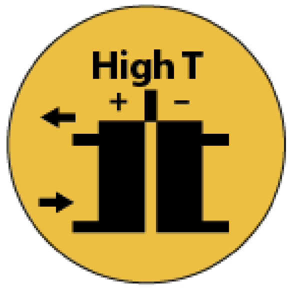
Hydrogen at Scale (H2@Scale): Key to a Clean, Economic, and Sustainable Energy System, Bryan Pivovar, Neha Rustagi, Sunita Satyapal, Electrochem. Soc. Interface Spring 2018 27(1): 47-52; doi:10.1149/2.F04181if

What is needed to achieve H_2@Scale?

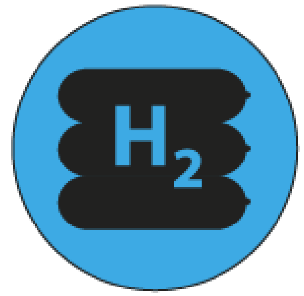
Low and High Temperature H_2 Generation		H_2 Storage and Distribution	H_2 Utilization



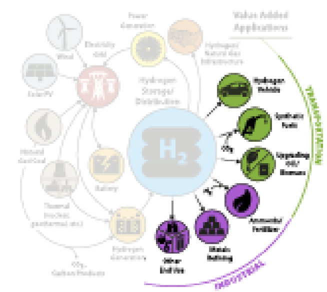
R&D for **low cost, durable, and intermittent H_2** generation.



R&D for **thermally integrated, low cost, durable, and variable H_2** generation.



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



H_2 as game-changing energy carrier, revolutionizing energy sectors.

Analysis

Foundational Science

Future Electrical Grid