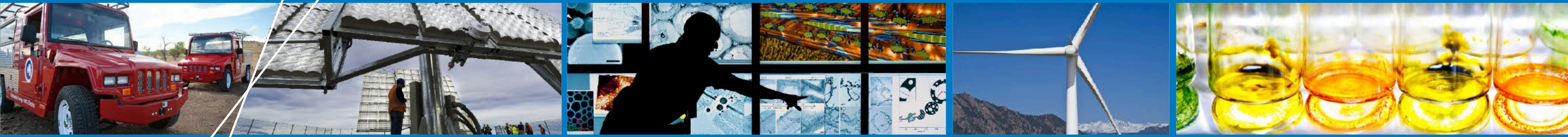
H2@Scale Overview



2019 DOE Hydrogen and Fuel Cells Program Review

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April 30, 2019

H2000

This presentation does not contain any proprietary, confidential, or otherwise restricted information

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

Overview

- **Focus of this poster (which is not a currently funded project and not being reviewed – although input is always solicited) is an overview, introduction, and update to the continually evolving H2@Scale program and vision. Feedback is welcomed and continually solicited.**

- **H2@Scale detailed projects presented elsewhere**
  - Poster Session
  - Detailed talks
  - Overlap in many other areas

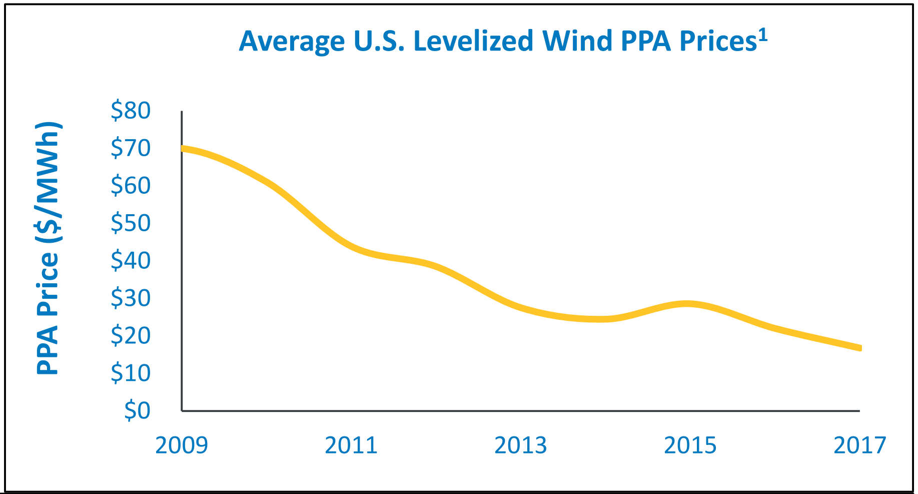
Key Drivers for Evolving Energy System

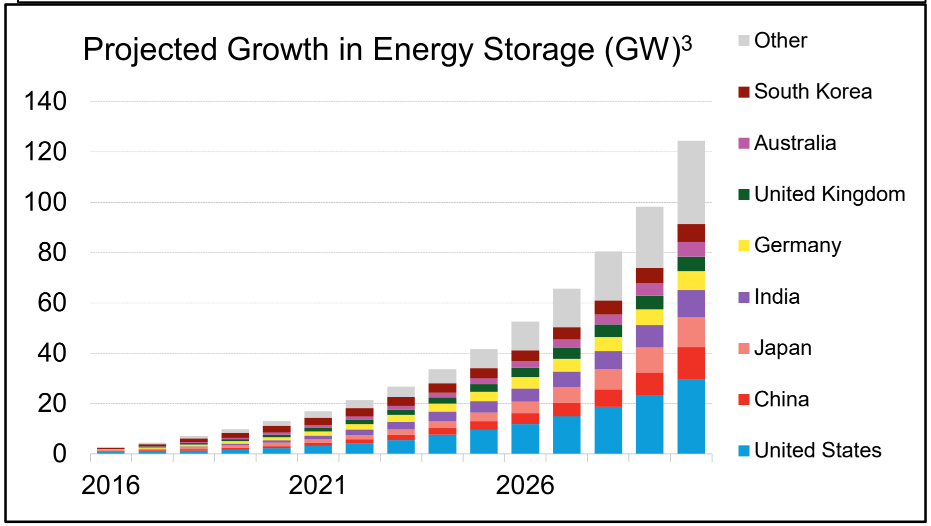
Increasing low-cost, renewable variable electricity

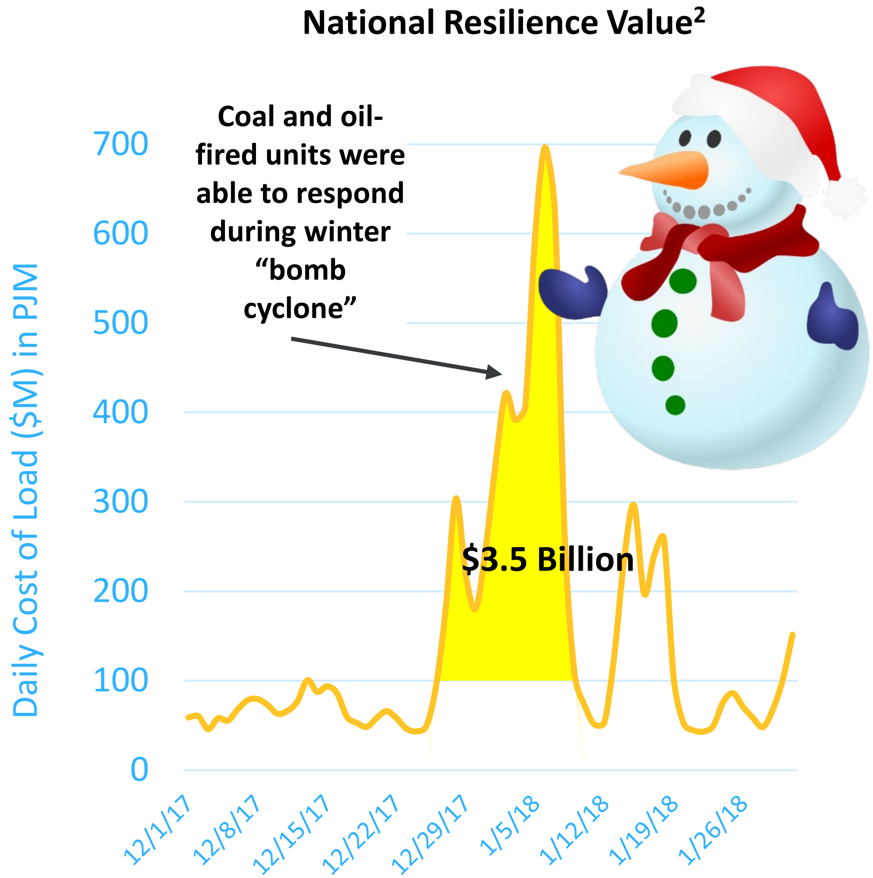
Rapid growth in energy storage

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

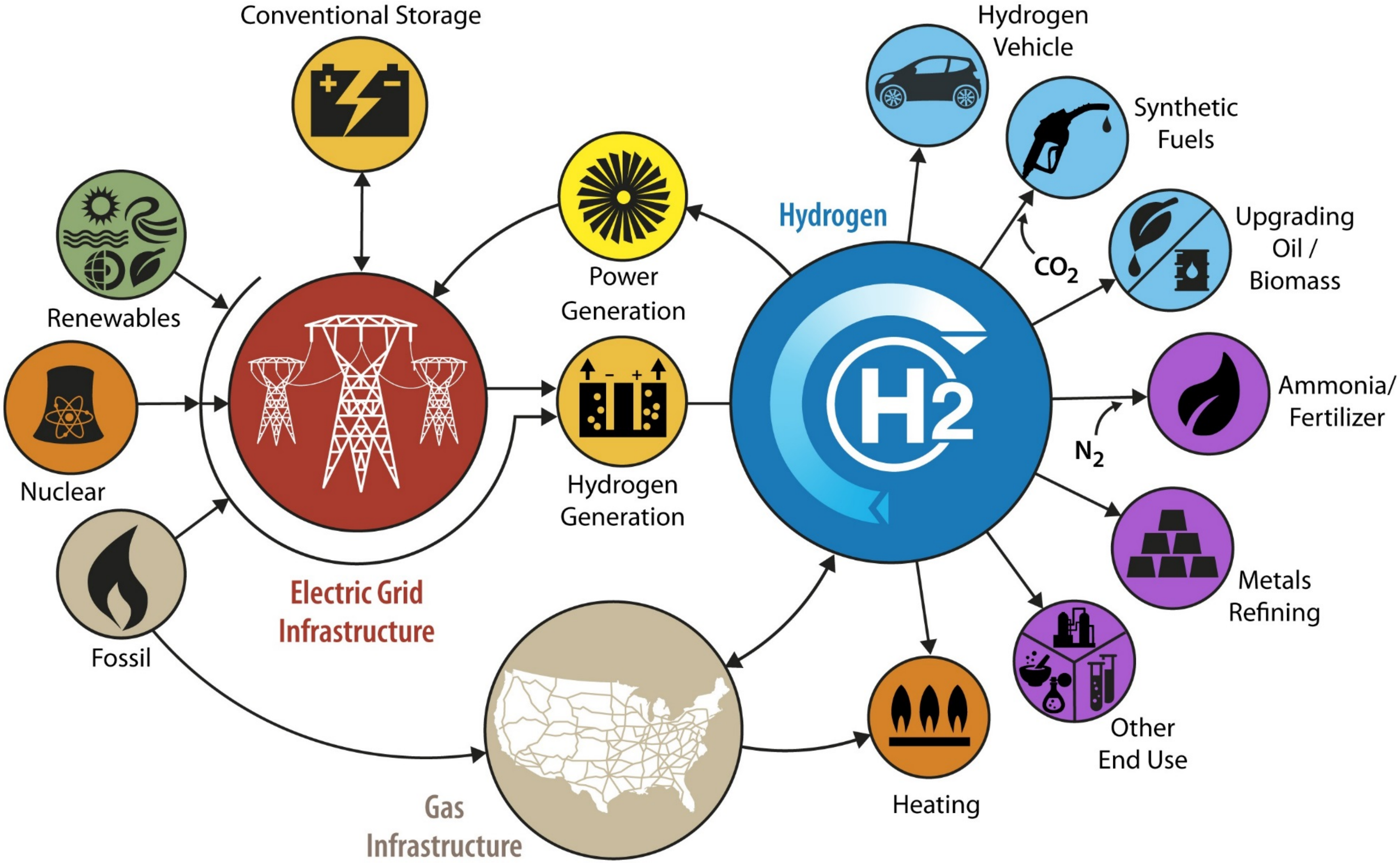
- **Multi-sector requirements**
  - Transportation
  - Industrial
  - Grid

How do we supply all these services in the best way?

- **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

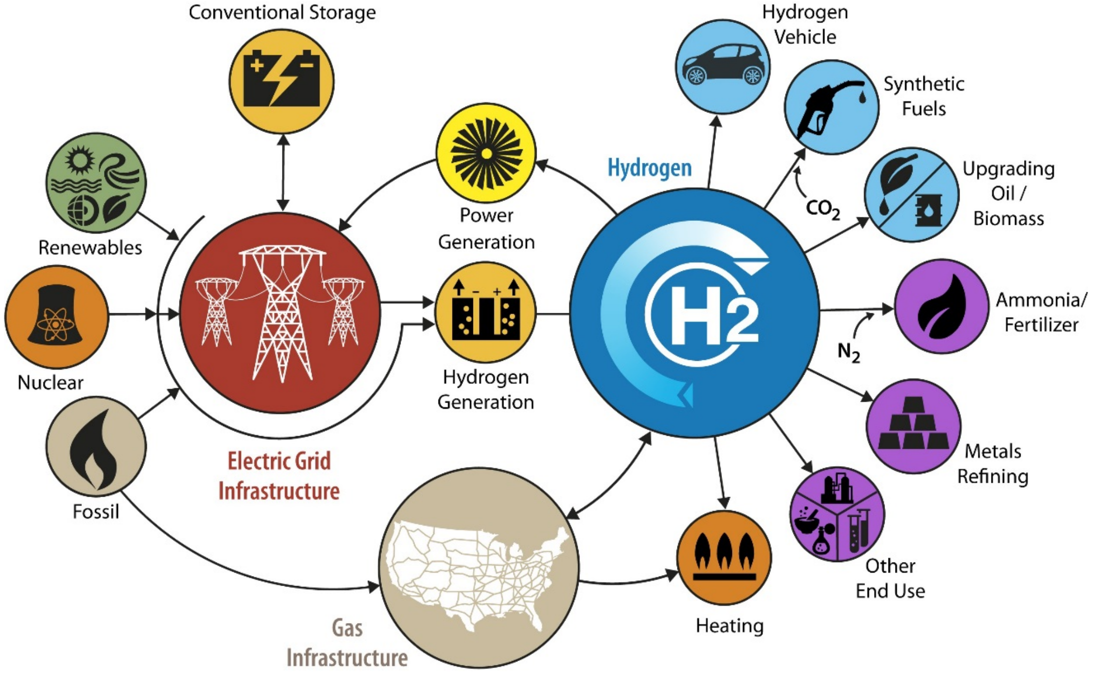
- **Benefits**
  - Economic factors (jobs, GDP)
  - Enhanced Security (energy, manufacturing)
  - Environmental Benefits (air, water)

Getting <u>all</u> these benefits in a single energy system significantly enhances value proposition.

Stakeholder Groups - Engagement

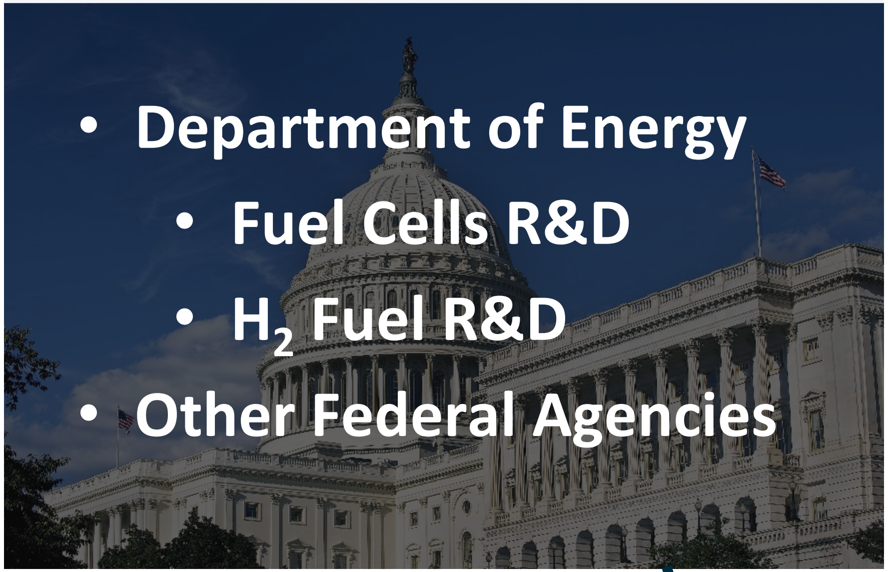
- Nuclear
- Wind
- Solar
- Fossil
- Grid/Utilities
- Regulators
- Electrolysis
- Industrial Gas
- Auto OEMs/supply chain
- Fuels Production (Big Oil)
- Metals/Steel
- Ammonia

- Analysis
- Investors



Technology Development Roles

Early- Stage R&D



- Department of Energy
  - Fuel Cells R&D
  - H_2 Fuel R&D
- Other Federal Agencies

Demonstration, Deployment & Commercialization

- Private Sector
- Partnerships
  - H_2USA
  - CaFCP

H2@Scale[SM]
U.S. Department of Energy

Improving the economics of H2@Scale

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

MAKE
Increased Low Cost Hydrogen Production

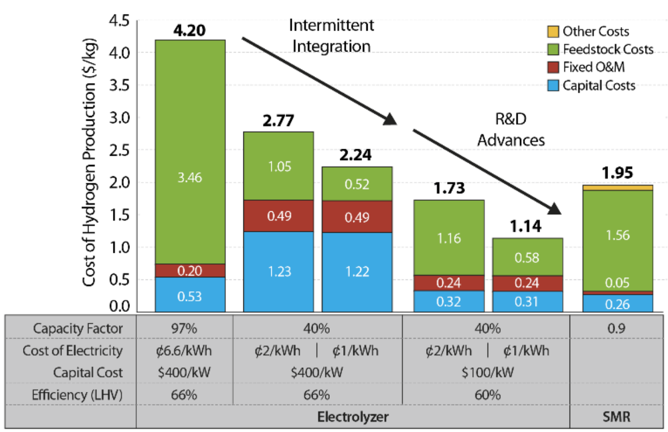
MOVE
More Efficient Hydrogen Transmission

USE
Low Cost Value-added Applications

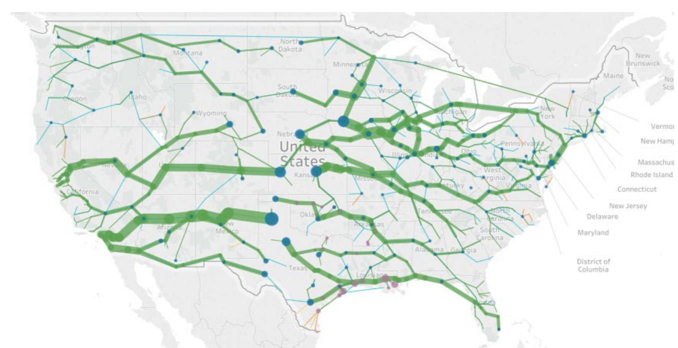
STORE
Improved Bulk Storage Technologies

Preliminary

Use	Potential MMT/yr
Refineries & CPI	8
Metals	12
Ammonia	4
Methanol	4
Biofuels	14
Natural Gas	10
Light Duty Vehicles	57
Other Transport	29
Electricity Storage	28
Total	**166**



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

Over 20 projects selected:

Hydrogen Integration

- Electric Power Research Institute
- Exelon
- Southern Company / Terrestrial Energy
- Pacific Gas & Electric
- TerraPower

Distribution Component R&D

- California Go-Biz Office
- Frontier Energy
- HyET
- Honda
- NanoSonic
- RIX
- Tatsuno
- Shell

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.

Argonne NATIONAL LABORATORY · INL Idaho National Laboratory · BERKELEY LAB · NREL NATIONAL RENEWABLE ENERGY LABORATORY · Pacific Northwest NATIONAL LABORATORY · Sandia National Laboratories · SRNL SAVANNAH RIVER NATIONAL LABORATORY OPERATED BY SAVANNAH RIVER NUCLEAR SOLUTIONS

H_2 today is different and changing fast

- **H_2 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.

> ***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*

13 members (Jan 2017).

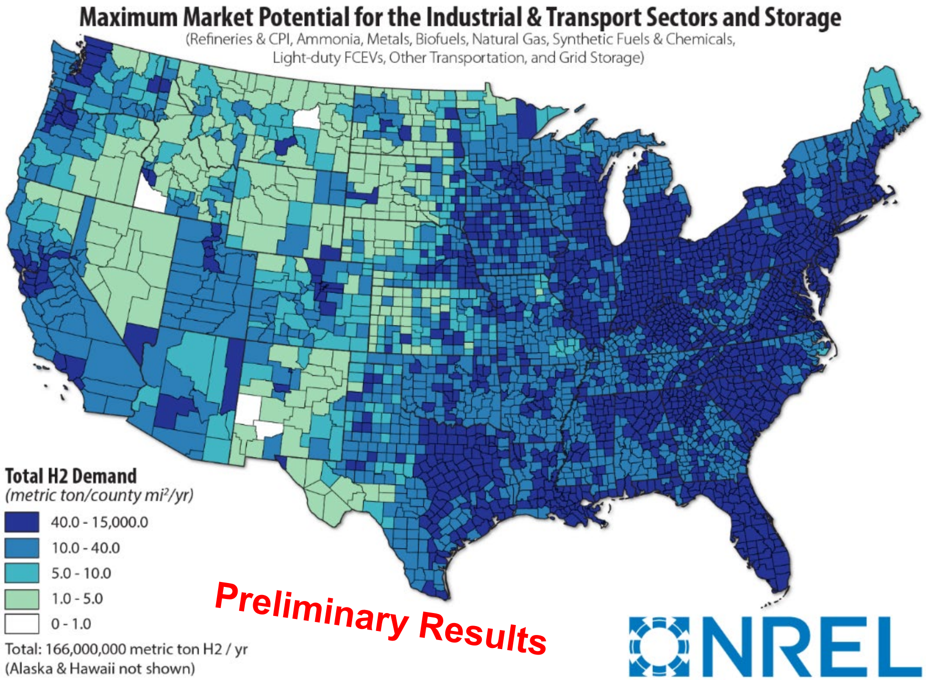
32 steering members and 20 supporting members (Nov 2018).

*Steering members shown, additional supporting members
www.hydrogencouncil.com

Significant growth in short time reflects developing appreciation for hydrogen's role

Estimated Technical Potential Hydrogen Demand

Demand	Technical potential (MMT* / year)
Refineries & CPI§	8
Metals	12
Ammonia	4
Methanol	4
Biofuels	14
Natural Gas	10
Light Duty Vehicles	57
Other Transport	29
Electricity Storage	28
Total	**166**



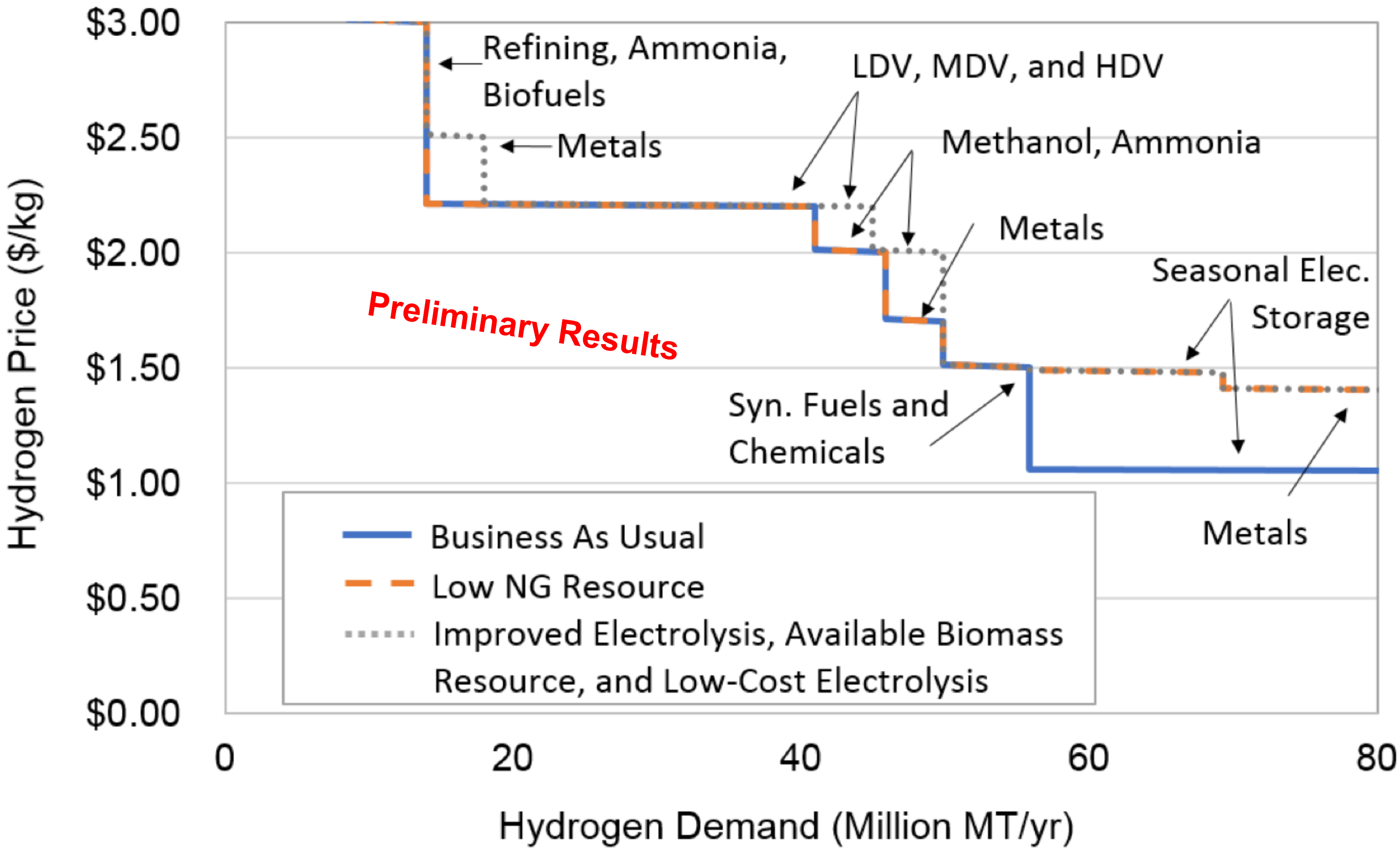
Technical Potential Demand: 166 MMT/yr

Current U.S. market: ≈ 13 MMT/yr
Including captive generation for ammonia and refining

* MMT: Million metric tonnes
§ CPI: Chemical Processing Industry not including metals, ammonia, methanol, or biofuels
Light duty vehicle calculation basis: 190,000,000 light-duty FCEVs from http://www.nap.edu/catalog/18264/transitions-to-alternative-vehicles-and-fuels

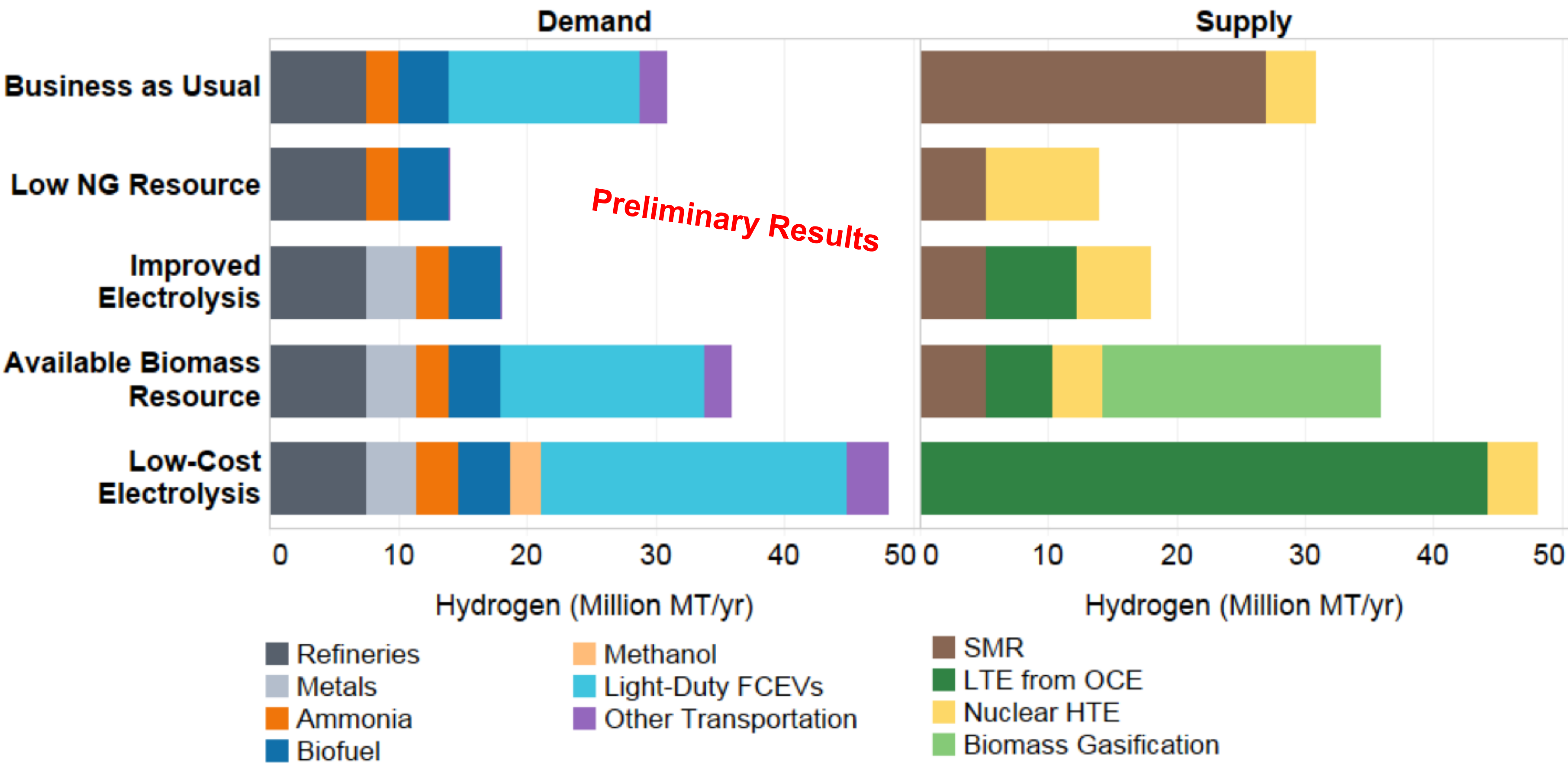
Developed Demand Curves

Estimated market size and willingness to pay for 10 applications on a national basis – range is >$3/kg for refining and ammonia to ≤$1/kg for injection into the natural gas system and some seasonal electricity storage.



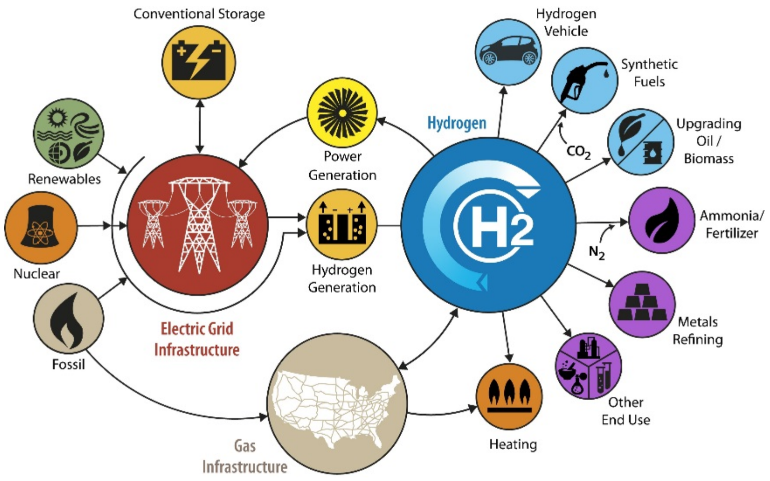
Estimated Economic Potential of H2@Scale for Five Scenarios

Estimated hydrogen market size: 14-48 MMT/yr with AEO Low Oil & Gas Resource Scenario natural gas prices.



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.
- The rate of changes and projects investigated our accelerating.



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.

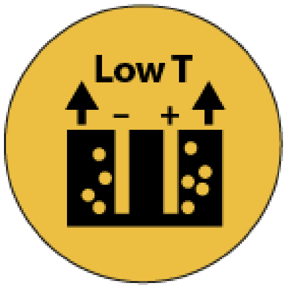
Rxn	ΔG (kJ/mol)	V cell (V)	# e–
$H_2 + 1/2O_2 \rightarrow H_2O$	–228.6	1.19	2
$CH_4 + 2O_2 \rightarrow 2H_2O + CO_2$	–800.8	1.04	8
$C + O_2 \rightarrow CO_2$	–394.4	1.02	4
$NH_3 + 3/2O_2 \rightarrow 1/2N_2 + 3/2H_2O$	–326.5	1.13	3
$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$	–113.6	0.15	8
$N_2 + H_2 \rightarrow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

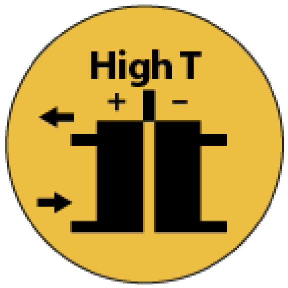
Hydrogen at Scale (H2@Scale): Key to a Clean, Economic, and Sustainable Energy System, Bryan Pivovar, Neha Rustagi, Sunita Satyapal, Electrochem. Soc. Interface Spring 2018 27(1): 47-52; doi:10.1149/2.F04181if

What is needed to achieve H_2@Scale?

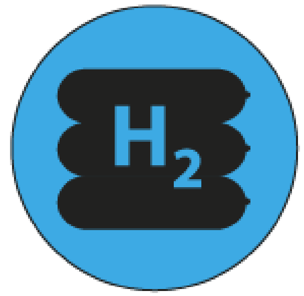
Low and High Temperature H_2 Generation		H_2 Storage and Distribution	H_2 Utilization



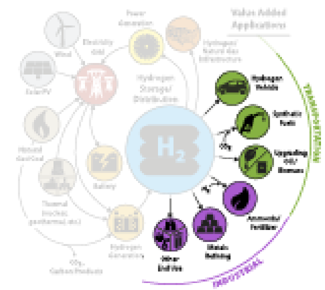
R&D for **low cost, durable, and intermittent H_2** generation.



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



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



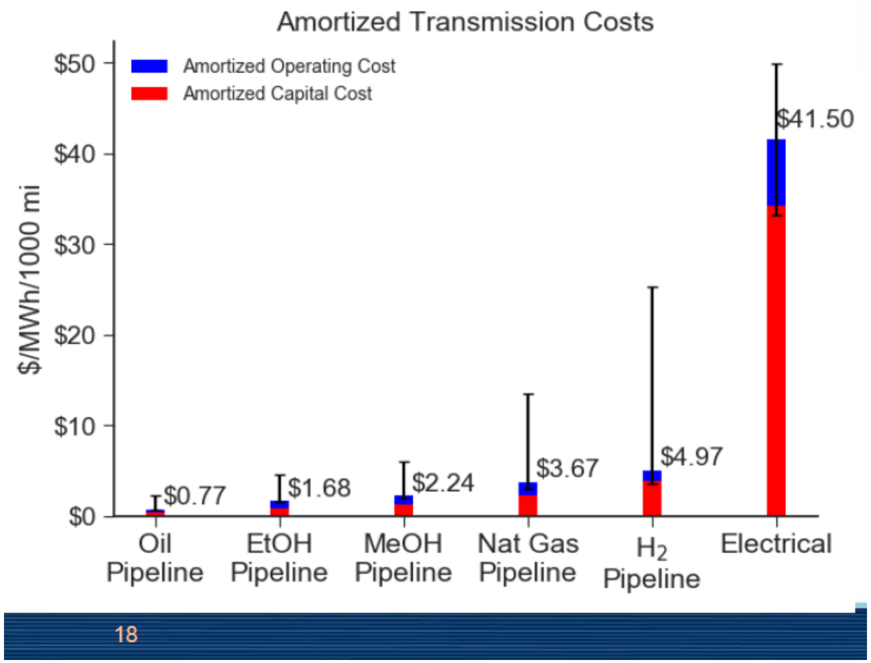
H_2 as game-changing energy carrier, revolutionizing energy sectors.

Analysis

Foundational Science

Future Electrical Grid

Energy Vectoring Costs



The costs of energy transmission are also being investigated.

https://www.hydrogen.energy.gov/pdfs/review18/pd102_james_2018_p.pdf