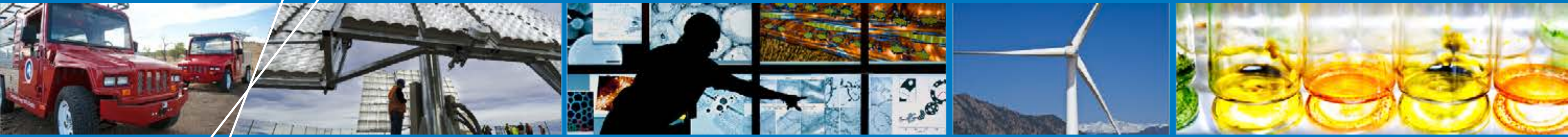
NATIONAL RENEWABLE ENERGY LABORATORY

# H2@Scale Overview



## 2020 DOE Hydrogen and Fuel Cells Program Review

**Bryan Pivovar**

**May 29, 2020**

H2000



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.

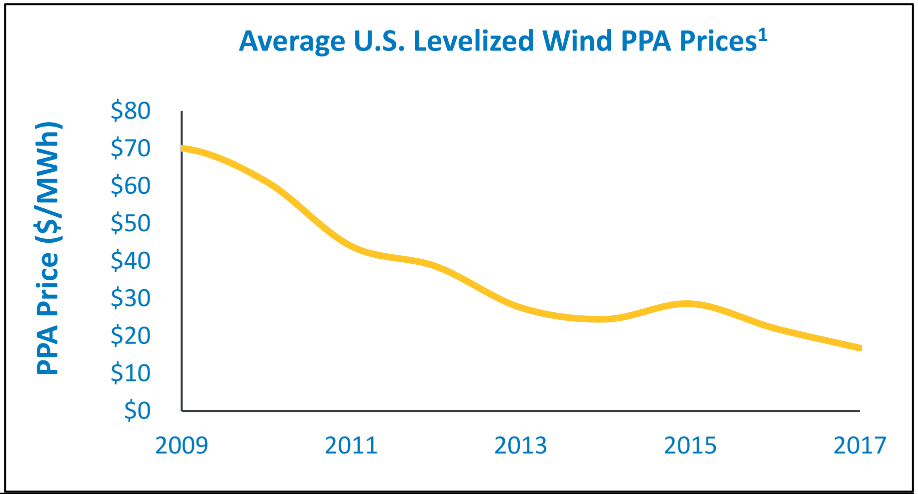
# Overview

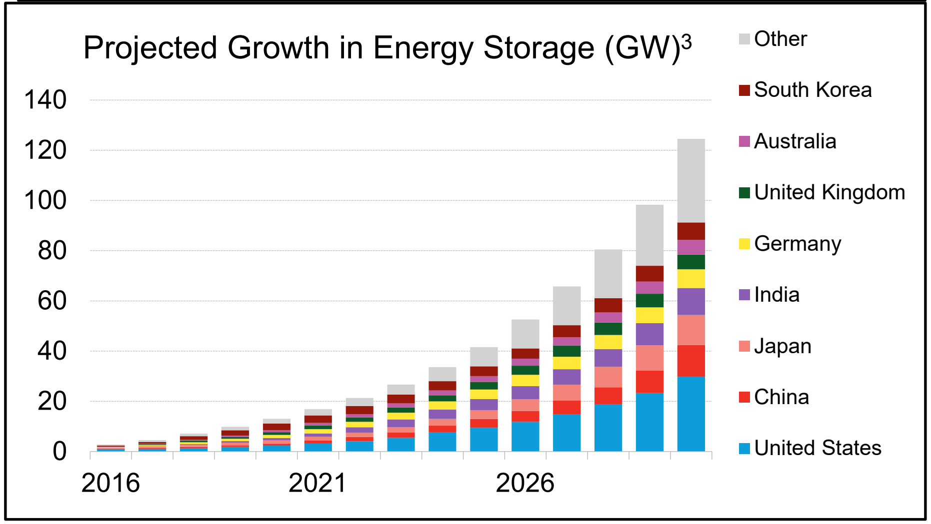
- **Focus of this poster (which is not a currently funded project and not being reviewed – although input is always solicited) is an overview, introduction, and update to the continually evolving H2@Scale program and vision.  Feedback is welcomed and continually solicited.**

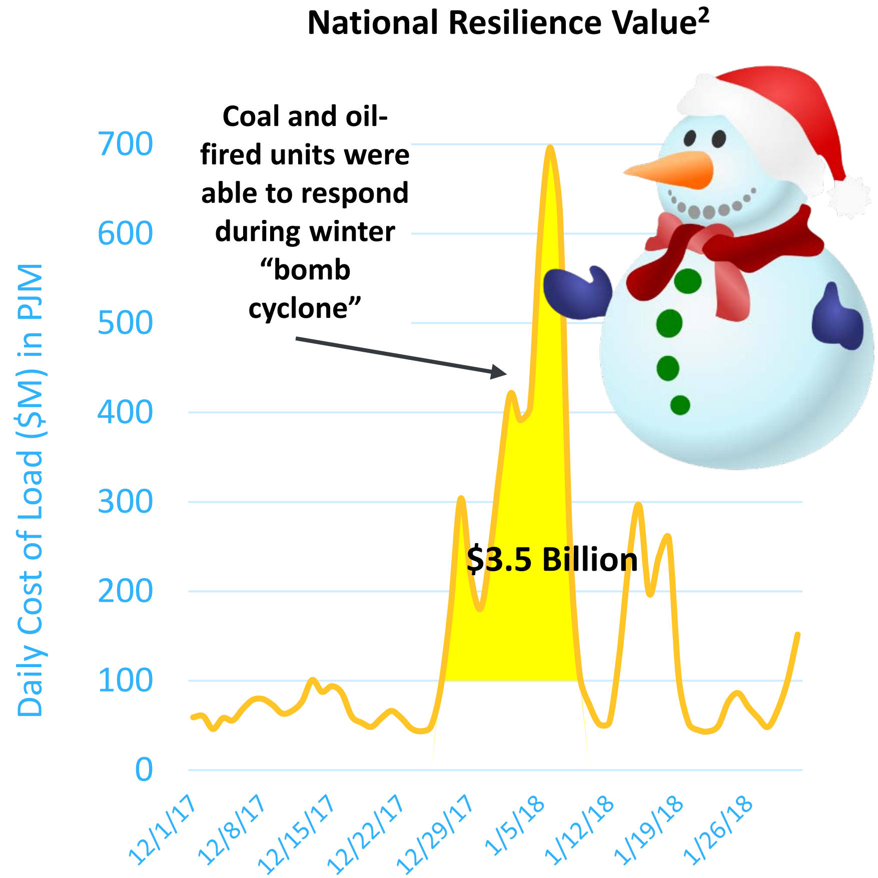
- **H2@Scale detailed projects presented elsewhere**
  - Poster Session
  - Detailed talks
  - Overlap in many other areas

# 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

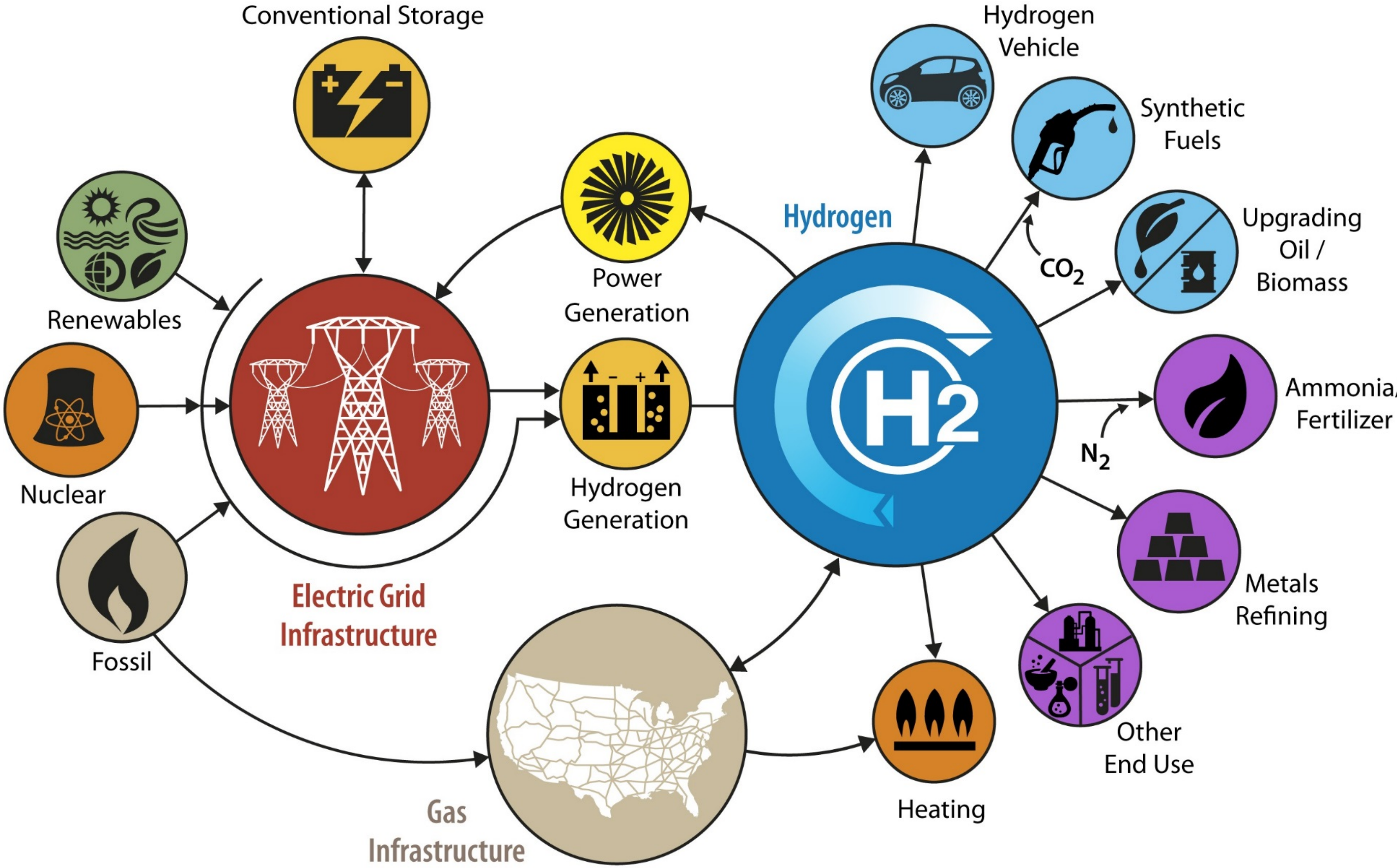
- **Multi-sector requirements**
  - Transportation
  - Industrial
  - Grid

**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

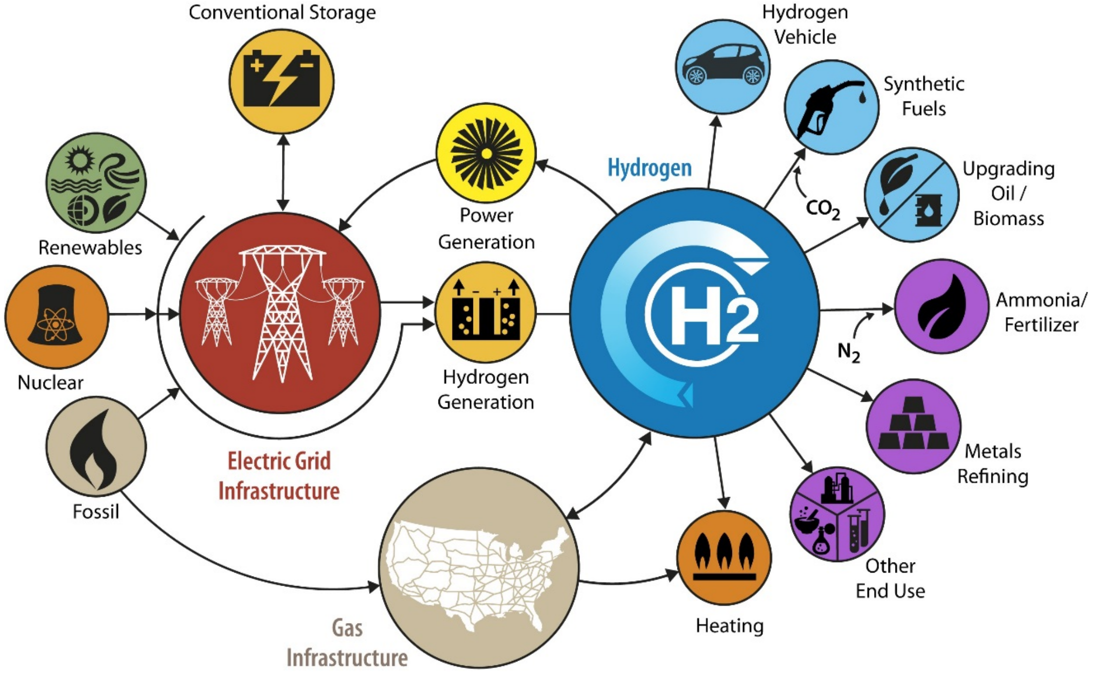
- **Benefits**
  - Economic factors (jobs, GDP)
  - Enhanced Security (energy, manufacturing)
  - Environmental Benefits (air, water)

Getting all 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

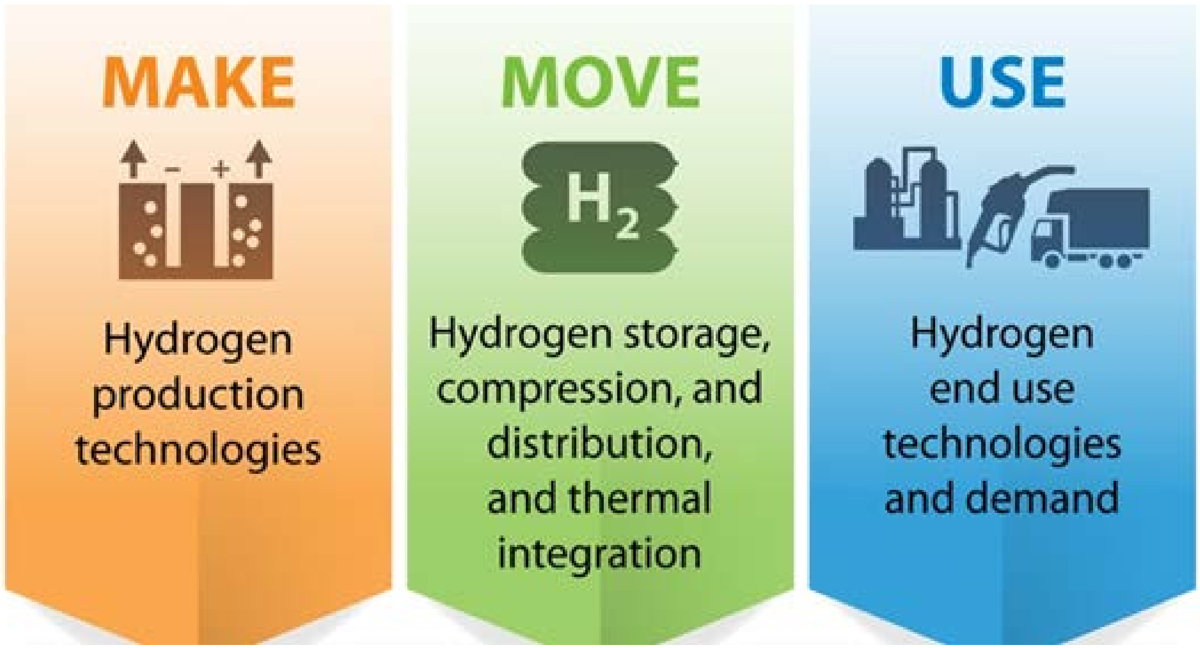
## Demonstration, Deployment & Commercialization

- Private Sector
- Partnerships
  - $H_2$USA
  - CaFCP

H2@Scale℠
U.S. Department of Energy

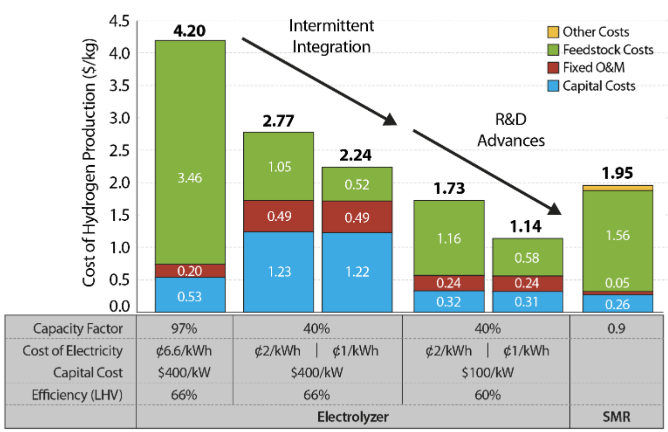
# Improving the economics of H2@Scale

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** |



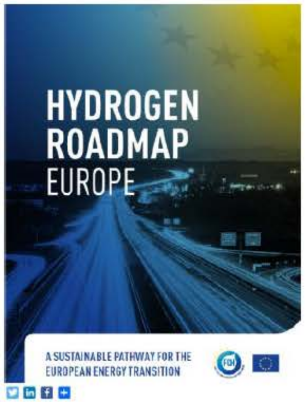

Decreasing cost of $H_2$ production

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.

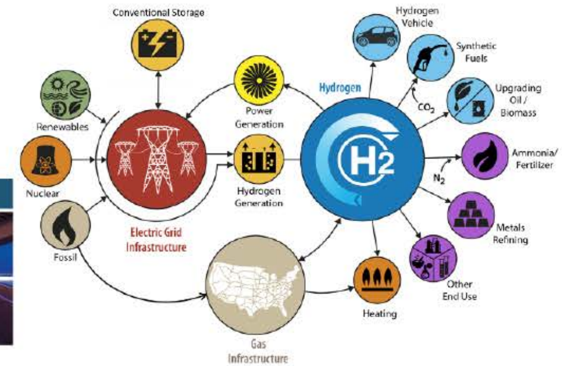
https://www.hydrogen.energy.gov/pdfs/review18/tv045_ruth_2018_o.pdf

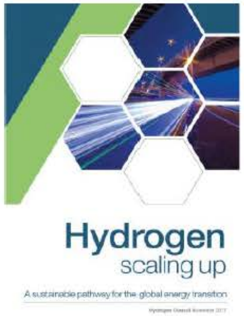
# "Hydrogen – at Scale and Sector Coupling" – A Common Vision Across Multiple Regions in the World

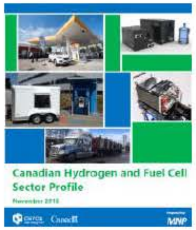




Global Action Agenda released at Hydrogen Energy Ministerial, Tokyo (9/25/2019)
Aspirational Targets:
"10, 10, 10"
10M systems,
10K stations, 10 years





High priority areas include: Global harmonization of codes and standards and addressing gaps, safety
From 10/19 IPHE meeting: Establish common definition of clean hydrogen to facilitate international trade

https://www.hydrogen.energy.gov/pdfs/htac_nov19_01_satyapal.pdf

# US Hydrogen Study/Roadmap

Potential benefits of hydrogen in the US in the ambitious scenario – by the numbers

Hydrogen in the US could ...

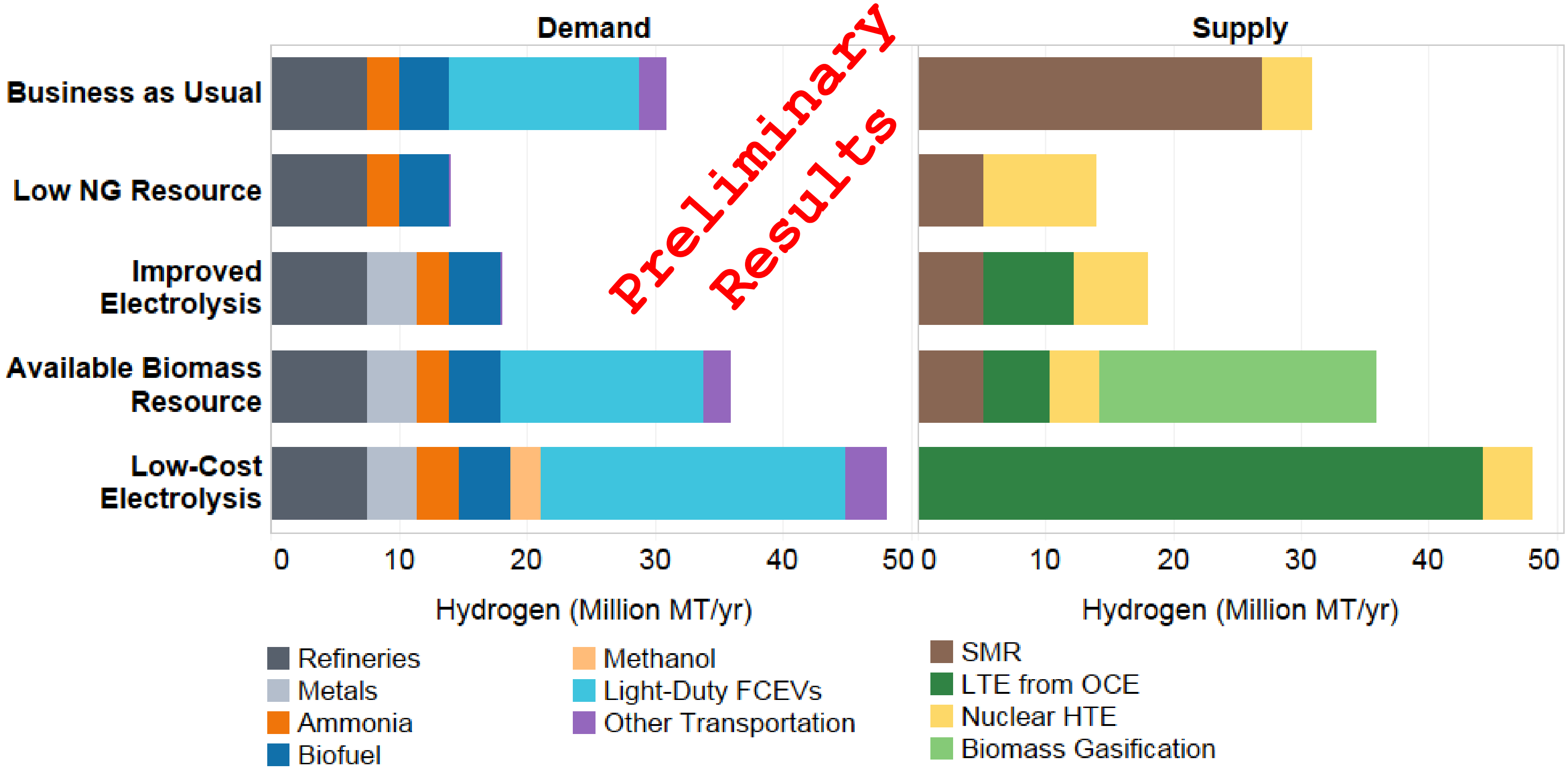

| Strengthen the US economy, supporting up to: | Create a highly competitive source of domestically produced low-emission energy | Provide significant environmental benefits and improve air quality | Benefit the US energy system |
|---|---|---|---|
| ~$140 bn in revenue<br>0.7 m jobs | ~100% domestically produced | Less $CO_2$, $NO_x$, $SO_x$, and particulate emissions in cities | |
| ... in 2030 | | | |
| ~$750 bn in revenue<br>3.4 m jobs | ~100% domestically produced | -16% $CO_2$<br>-36% $NO_x$ | ~14% of final energy demand |
| ... in 2050 | | | |

This report was developed with input from 19 companies and organizations:

- Air Liquide
- American Honda Motor Co., Inc
- Audi
- Chevron
- Cummins Inc.
- Daimler AG: Mercedes-Benz Fuel Cell GmbH/Mercedes-Benz Research & Development North America
- Engie
- Exelon Corporation
- Hyundai Motor Company
- Microsoft
- Nikola Motors
- Nel Hydrogen
- Plug Power
- Power Innovations
- Shell
- Southern California Gas Company
- Southern Company Services, Inc.
- Toyota
- Xcel Energy

http://www.fchea.org/us-hydrogen-study

# H2@Scale Analysis Overview




**Accomplishment:** Developed and Reviewed Economic Potential Results: ***14 - 48 MMT $H_2$ / yr***

https://www.hydrogen.energy.gov/pdfs/review19/sa171_ruth_2019_o.pdf

# H2@Scale Targets Focus R&D (DOE FCTO)

## FCTO Focus: Developing application specific targets: Make, Move, Use, Store

**MAKE**
Increased Clean, Affordable Hydrogen Production

**MOVE**
More Efficient, Affordable Hydrogen Transport

**USE**
Low Cost Value-added Applications across Sectors

**STORE**
Flexible, Low-cost Storage Technologies

| Application | Power (kW) | Cost ($/kW) | Durability (h) | Performance |
|---|---|---|---|---|
| Light-duty vehicles | 80 | 30<br>75*<br>120* | 8,000<br>5,000<br>4,100 | 70% efficiency,<br>$\leq$0.125 $mg_{PGM}/cm^2$<br>~0.35 $mg_{PGM}/cm^2$ |
| Medium and Heavy-duty vehicles | 160 to >360 | 60<br>92* | 30,000<br>--- | 72% efficiency<br>$\leq$0.2 $mg_{PGM}/cm^2$<br>0.4 $mg_{PGM}/cm^2$ |
| Stationary | 1 to 1,000 | 1,000 | 80,000-130,000<br>40,000-80,000 | >50% electrical efficiency |

**Green: target; black: lab-demonstrated tech; blue: on-road/installed tech**
*Projected system cost for 100,000 units/year
**Technical targets under development

### Targets are Application Specific- Examples

- **$H_2$: $4/gge (including production, delivery, bulk storage and dispensing; untaxed)**
- **Fuel Cell System for FCEVs: $30/kW; 8,000 hrs**
- **H2 Onboard Storage for FCEVs $8/kWh, 2.2 kWh/kg, 1.7 kWh/L.**

**By 2025:**

- **$7/gge**
- **$40/kW, 5,000 hrs**
- **$10/kWh (FCEV storage), 1.8 kWh/kg, 1.3 kWh/L**

https://www.hydrogen.energy.gov/pdfs/htac_nov19_01_satyapal.pdf

# FY19 FOA Selections: DOE FCTO 29 Projects $40M & Joint DOE EERE 8 H2-based projects ~$15M

FCTO

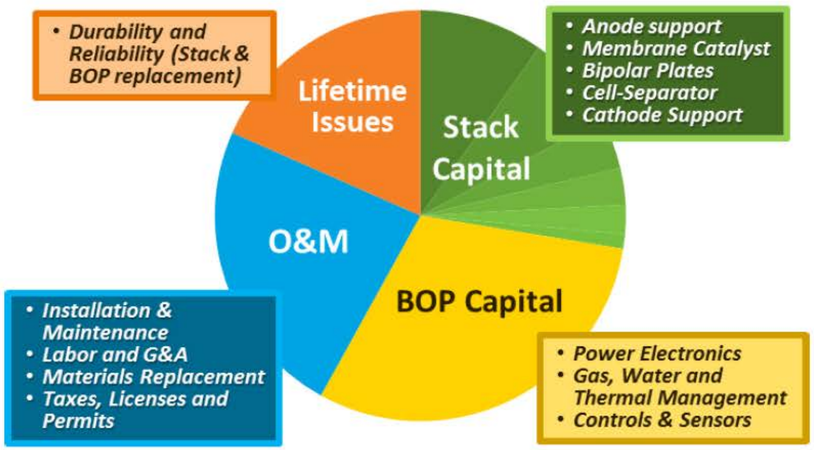
| | Topic Area | Awardee | DOE Share |
|---|---|---|---|
| store | Topic 1A: Novel Hydrogen Carrier Development | Colorado School of Mines | $0.4M |
| | | University of Hawaii | $0.9M |
| | | University of Southern California | $1M |
| | | Washington State University | $1M |
| move | Topic 1B: H-Mat Materials Compatibility Consortium R&D: Hydrogen Effects in Materials for Fueling Infrastructure | Clemson University | $1M |
| | | Colorado School of Mines | $1.4M |
| | | Hy-Performance Materials Testing, LLC | $0.6M |
| | | Massachusetts Institute of Technology | $1M |
| | | The University of Alabama | $1M |
| | | University of Illinois at Urbana-Champaign | $2M |
| make | Topic 2A: Advanced Water Splitting Materials Research (integrated with HydroGEN Consortium) | Georgia Institute of Technology | $1M |
| | | Nexceris, LLC | $1M |
| | | Redox Power Systems, LLC | $1M |
| | | The Chemours Company FC, LLC | $1M |
| | | The University of Toledo | $0.7M |
| | | University of California: Irvine | $1M |
| | | University of California: San Diego | $1M |
| | | University of Florida | $1M |
| | | University of Oregon | $0.5M |
| | | University of South Carolina | $1M |
| | | William Marsh Rice University | $0.8M |
| make | Topic 2B: Affordable Biological Hydrogen Production from Biomass Resources | Oregon State University | $1M |
| use | Topic 2C: Co-production of H2 and Value-add Byproducts | C-Zero, LLC | $1M |
| | | University of Colorado, Boulder | $1M |
| make/use | Topic 2D: Reversible Fuel Cell Development and Validation | FuelCell Energy, Inc | $2M |
| | | Proton Energy Systems, Inc | $2M |
| all | Topic 3: H2@Scale Pilot - Integrated Production, Storage, and Fueling System | Exelon Corporation | $3.6M |
| | | Frontier Energy, Inc. | $5.4M |
| | | Giner ELX, Inc. | $4M |

Joint EERE

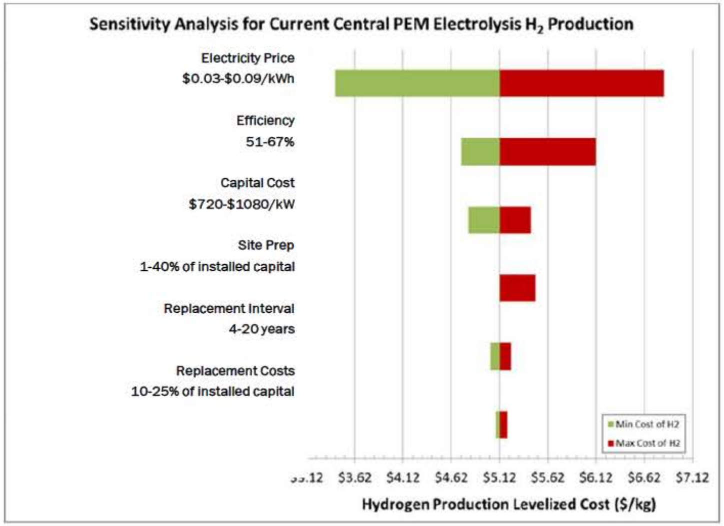
| | Topic Area | Awardee | DOE Share |
|---|---|---|---|
| store | 1a – Advanced Storage for Gaseous Fuels | Northwestern University | $1M |
| | | University of South Florida | $0.8M |
| move | 3 - High Throughput Hydrogen Fueling Technologies for Medium- and Heavy-duty Transportation | Air Products and Chemicals, Inc. | $1.7M |
| | | NEL Hydrogen Inc. | $2M |
| | | Electricore, Inc. | $3M |
| use | 4 – High-durability, Low Platinum Group Metal Membrane Electrode Assemblies (Meas) For Medium- And Heavy-duty Truck Applications | General Motors LLC | $2M |
| | | Nikola Motor Company | $1.7M |
| | | Carnegie Mellon University | $2M |

https://www.hydrogen.energy.gov/pdfs/htac_nov19_01_satyapal.pdf

| Cases | Low Range ($/kg $H_2$) | Baseline Cost ($/kg $H_2$) | High Range ($/kg $H_2$) |
|---|---|---|---|
| Forecourt Current | $4.79 | $5.14 | $5.49 |
| Forecourt Future | $4.08 | $4.23 | $4.37 |
| Central Current | $4.80 | $5.12 | $5.45 |
| Central Future | $4.07 | $4.20 | $4.33 |




Excludes electricity cost




https://www.hydrogen.energy.gov/pdfs/htac_nov19_01_satyapal.pdf

# $H_2$ 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).

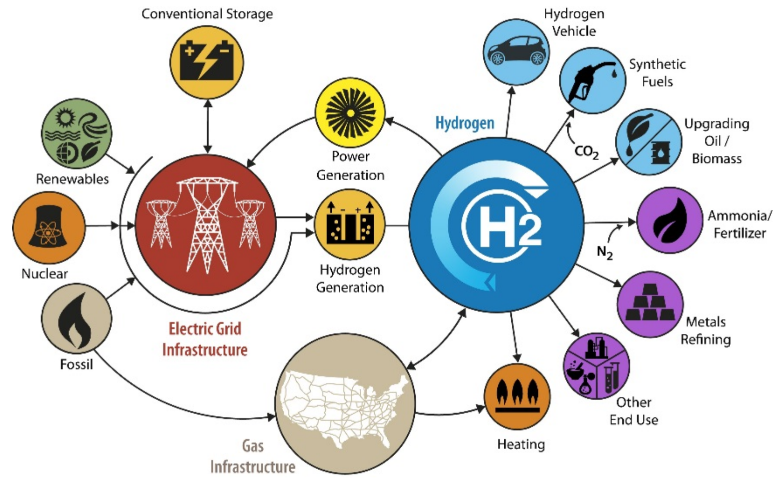
32 steering members and 20 supporting members (Nov 2018).

81 members (Jan 2020).

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

# 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.**

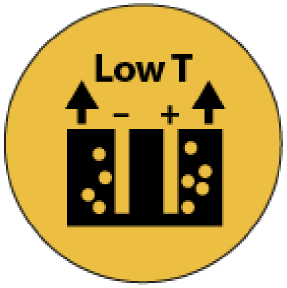
| Rxn | ΔG (kJ/mol) | V cell (V) | # e– |
|---|---|---|---|
| $H_2 + 1/2O_2 \rightarrow H_2O$ | –228.6 | 1.19 | 2 |
| $CH_4 + 2O_2 \rightarrow 2H_2O + CO_2$ | –800.8 | 1.04 | 8 |
| $C + O_2 \rightarrow CO_2$ | –394.4 | 1.02 | 4 |
| $NH_3 + 3/2O_2 \rightarrow 1/2N_2 + 3/2H_2O$ | –326.5 | 1.13 | 3 |
|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

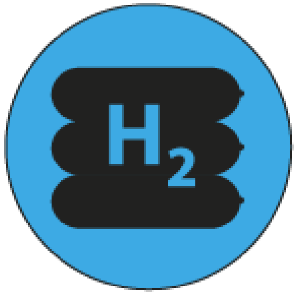
## Low and High Temperature $H_2$ Generation




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

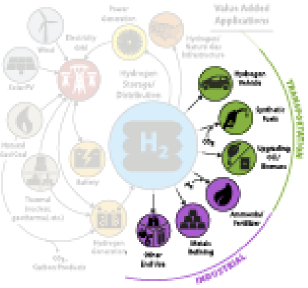

R&D for **thermally integrated, low cost, durable, and variable $H_2$** generation.

## $H_2$ Storage and Distribution




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

## $H_2$ Utilization



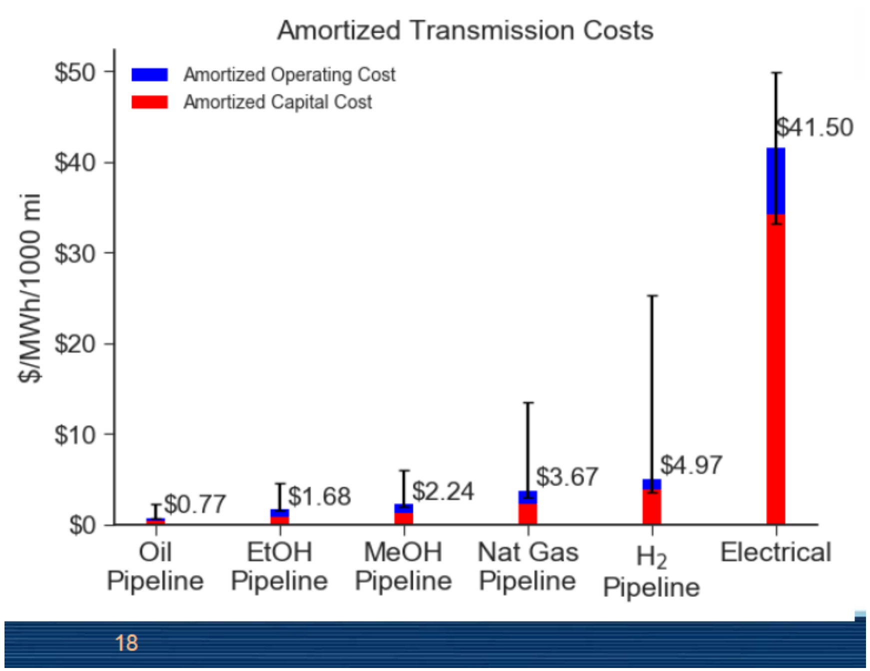
**$H_2$ as game-changing energy carrier,** revolutionizing energy sectors.

**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