NREL
NATIONAL RENEWABLE ENERGY LABORATORY

H2@Scale Overview

2020 DOE Hydrogen and Fuel Cells Program Review

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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.

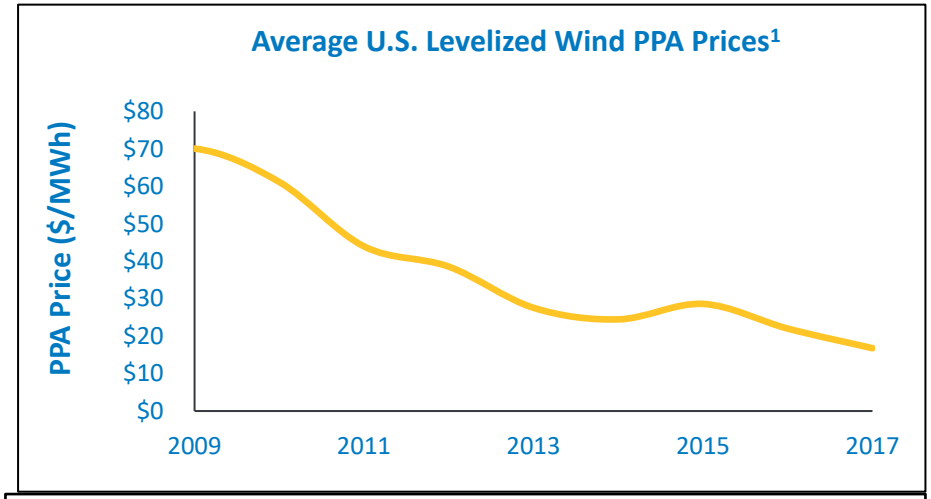
Overview

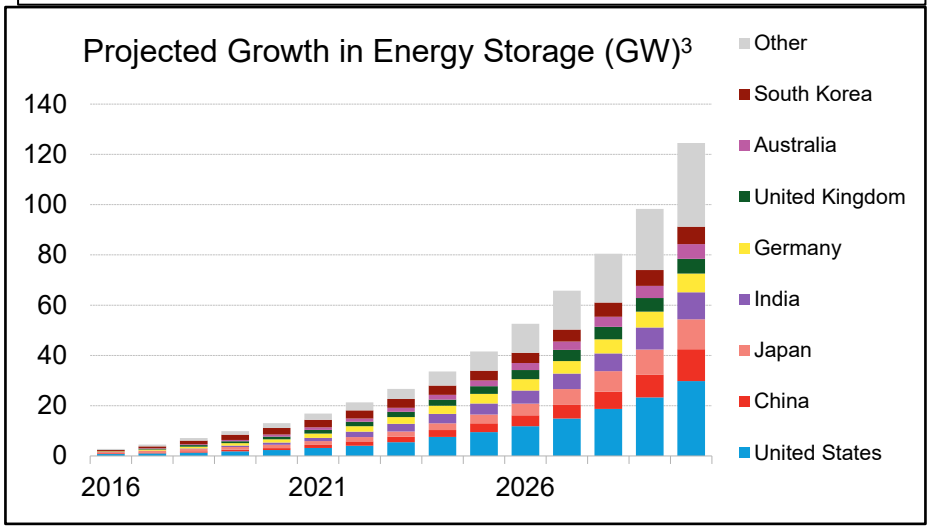
- **Focus of this poster (which is not a currently funded project and not being reviewed – although input is always solicited) is an overview, introduction, and update to the continually evolving H2@Scale program and vision. Feedback is welcomed and continually solicited.**

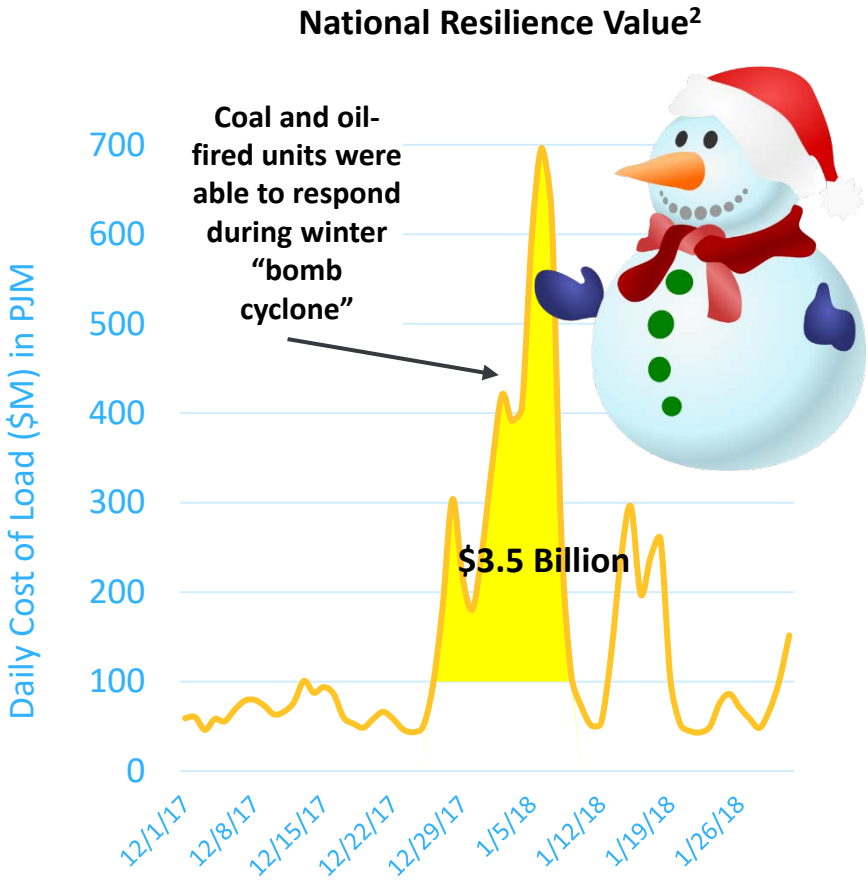
- **H2@Scale detailed projects presented elsewhere**
  - Poster Session
  - Detailed talks
  - Overlap in many other areas

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

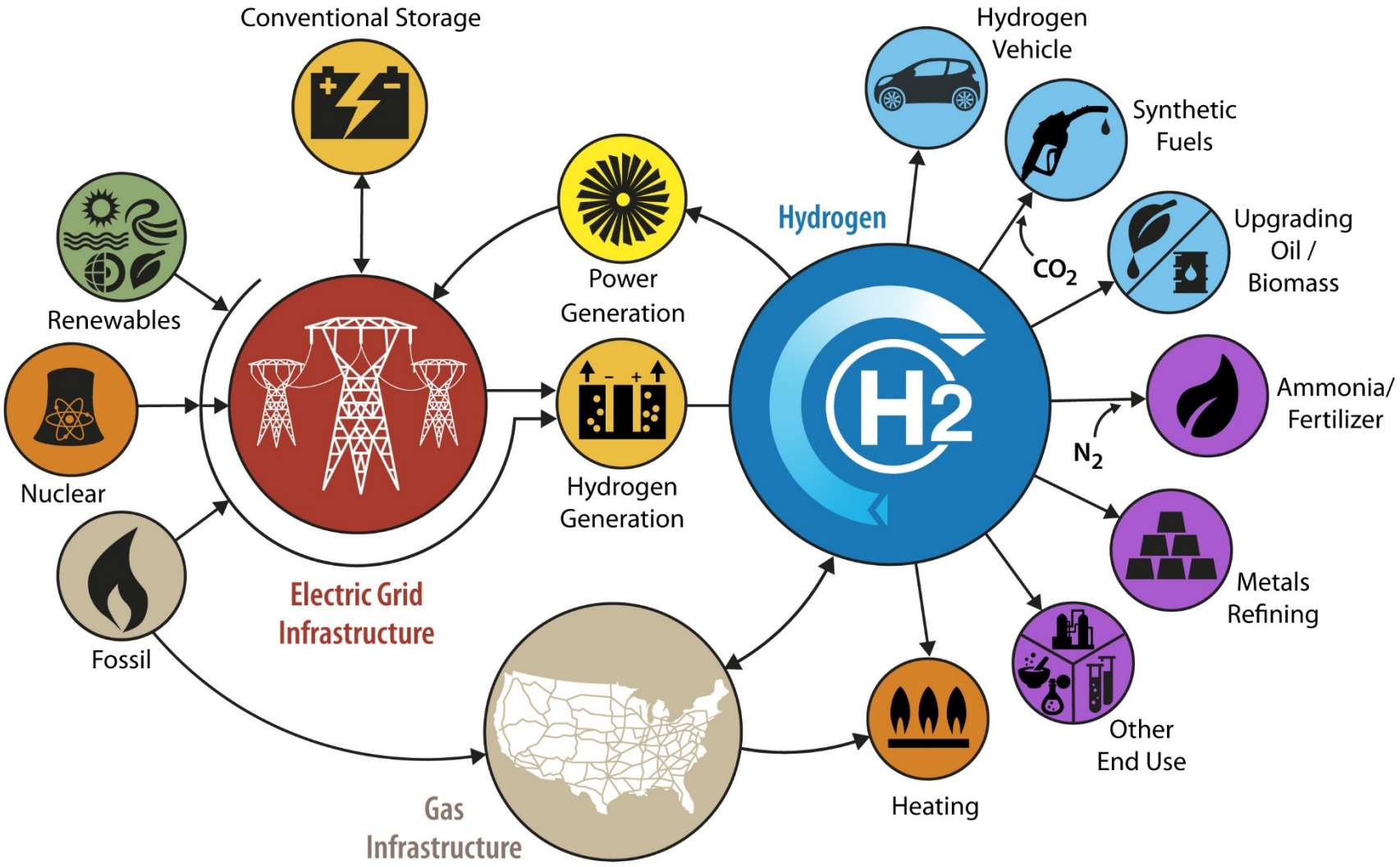
- **Multi-sector requirements**
  - Transportation
  - Industrial
  - Grid

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

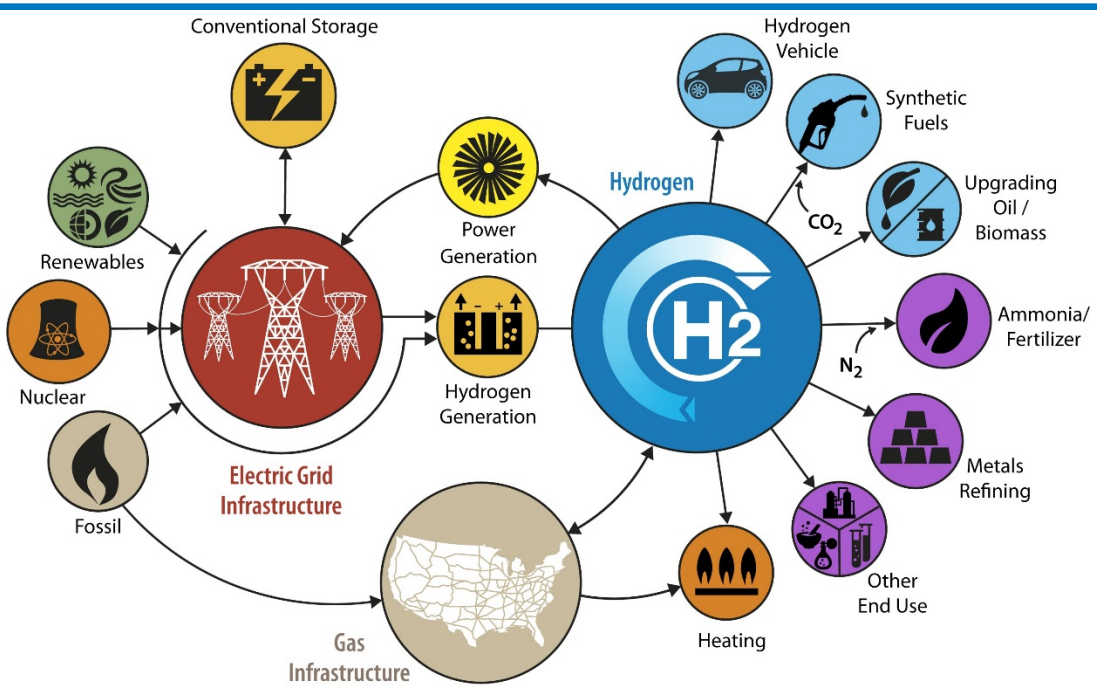
- **Benefits**
  - Economic factors (jobs, GDP)
  - Enhanced Security (energy, manufacturing)
  - Environmental Benefits (air, water)

Getting all these benefits in a single energy system significantly enhances value proposition.

Stakeholder Groups - Engagement

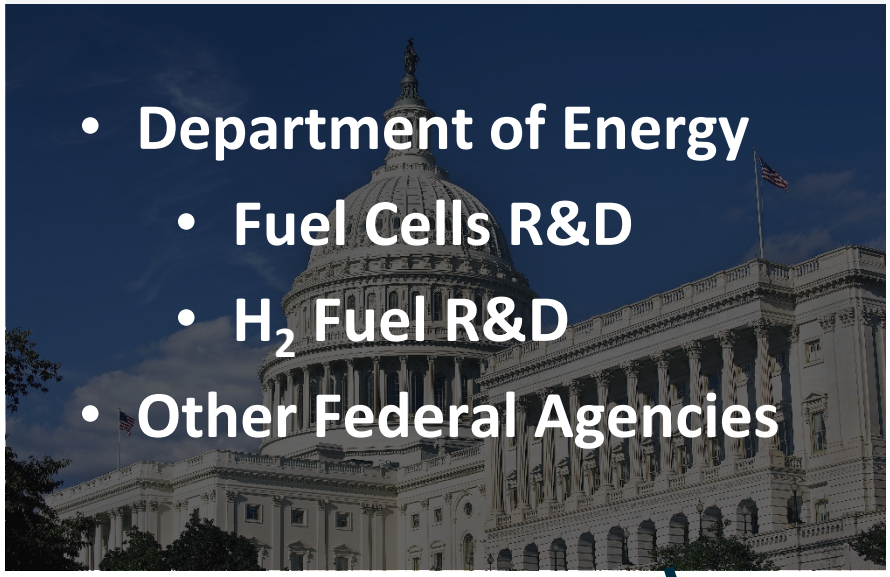
- Nuclear
- Wind
- Solar
- Fossil
- Grid/Utilities
- Regulators
- Electrolysis
- Industrial Gas
- Auto OEMs/supply chain
- Fuels Production (Big Oil)
- Metals/Steel
- Ammonia

- Analysis
- Investors



Technology Development Roles

Early- Stage R&D



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

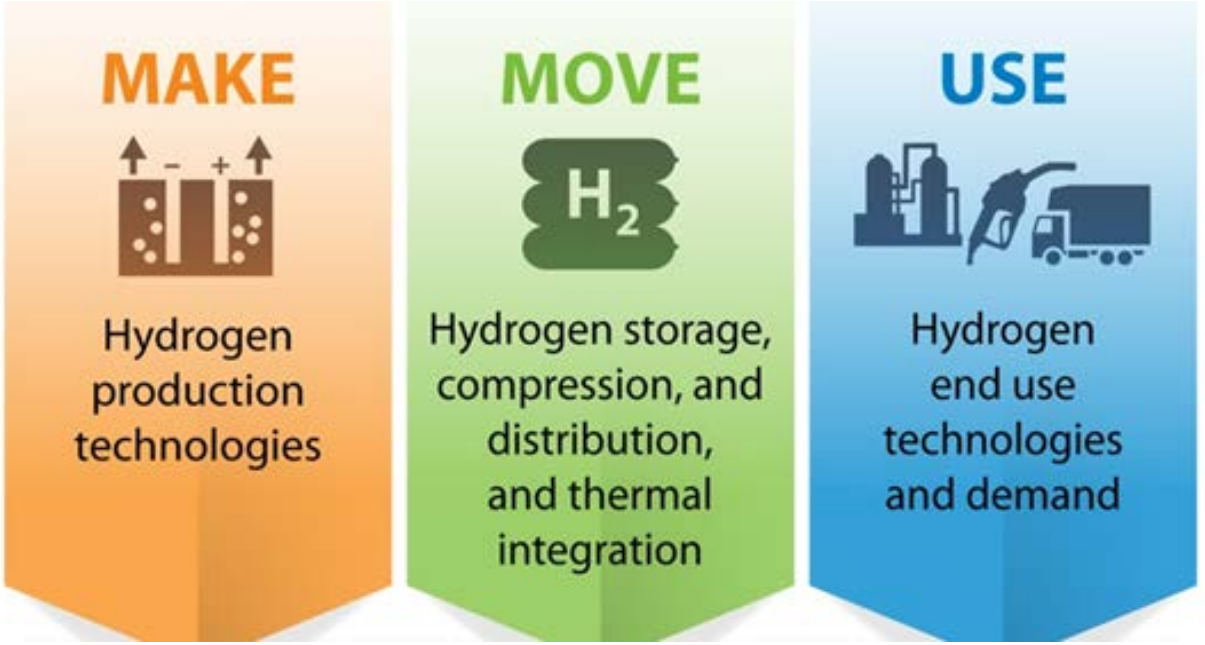
Demonstration, Deployment & Commercialization

- Private Sector
- Partnerships
  - H_2USA
  - CaFCP

H2@Scale℠
U.S. Department of Energy

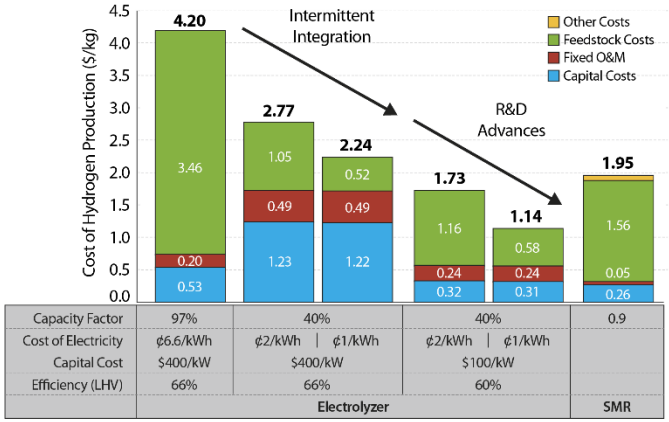
Improving the economics of H2@Scale

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

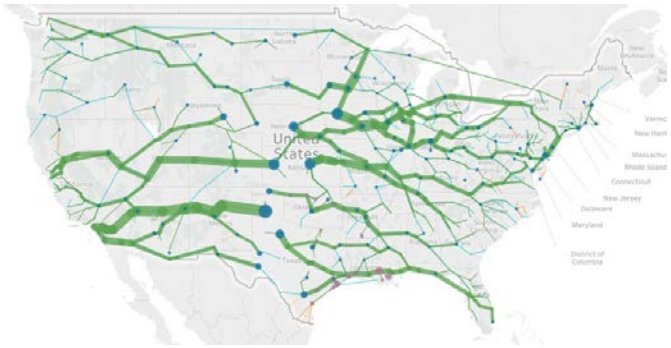


Preliminary

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

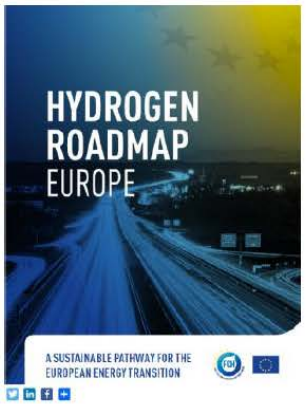


Optimizing H_2 storage and distribution

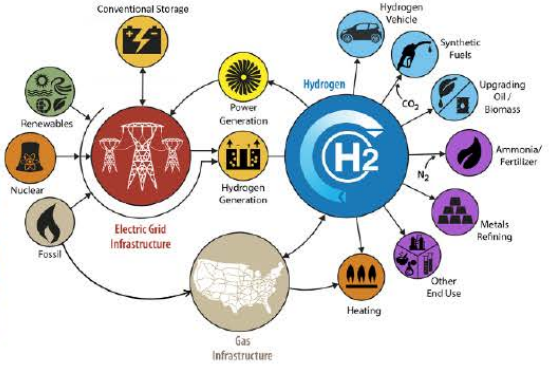
Leveraging of national laboratories' early-stage R&D capabilities needed to develop affordable technologies for production, delivery, and end use applications.

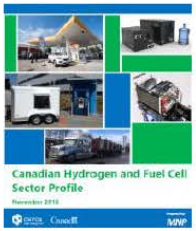
https://www.hydrogen.energy.gov/pdfs/review18/tv045_ruth_2018_o.pdf

“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	~100% domestically produced	Less CO_2, NO_x, SO_x, and particulate emissions in cities	
0.7 m jobs			

… in 2030

~$750 bn in revenue	~100% domestically produced	-16% CO_2	~14% of final energy demand
3.4 m jobs		-36% NO_x	

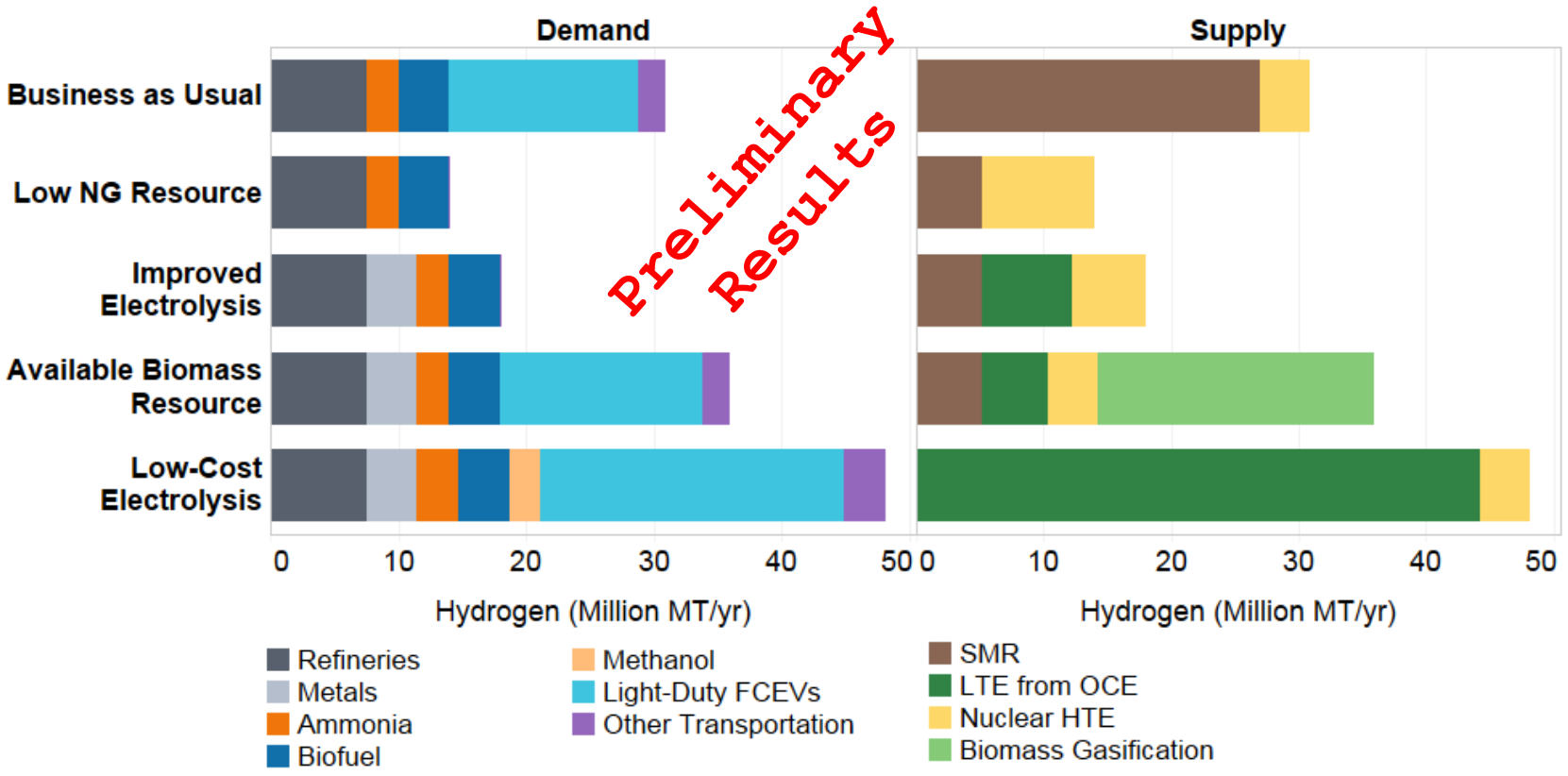
… in 2050

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

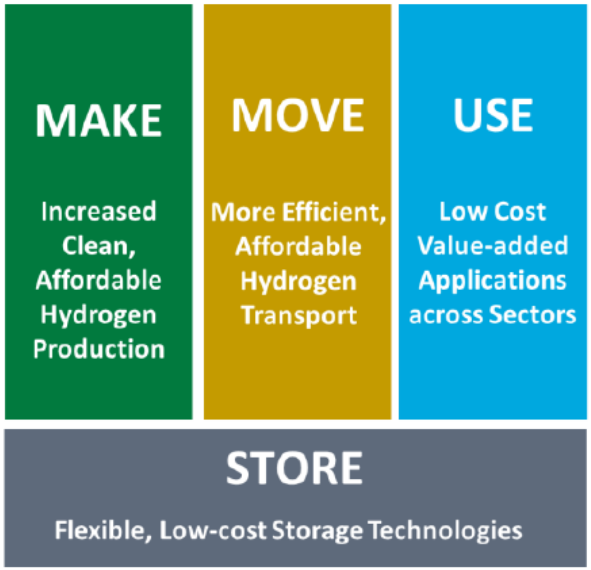


Accomplishment: Developed and Reviewed Economic Potential Results: ***14 - 48 MMT H_2 / yr***

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



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

store

move

make

make use

make/use

all

Topic Area	Awardee	DOE Share
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
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
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
Topic 2B: Affordable Biological Hydrogen Production from Biomass Resources	Oregon State University	$1M
Topic 2C: Co-production of H2 and Value-add Byproducts	C-Zero, LLC	$1M
	University of Colorado, Boulder	$1M
Topic 2D: Reversible Fuel Cell Development and Validation	FuelCell Energy, Inc	$2M
	Proton Energy Systems, Inc	$2M
Topic 3: H2@Scale Pilot - Integrated Production, Storage, and Fueling System	Exelon Corporation	$3.6M
	Frontier Energy, Inc.	$5.4M
	Giner ELX, Inc.	$4M

FCTO

store

move

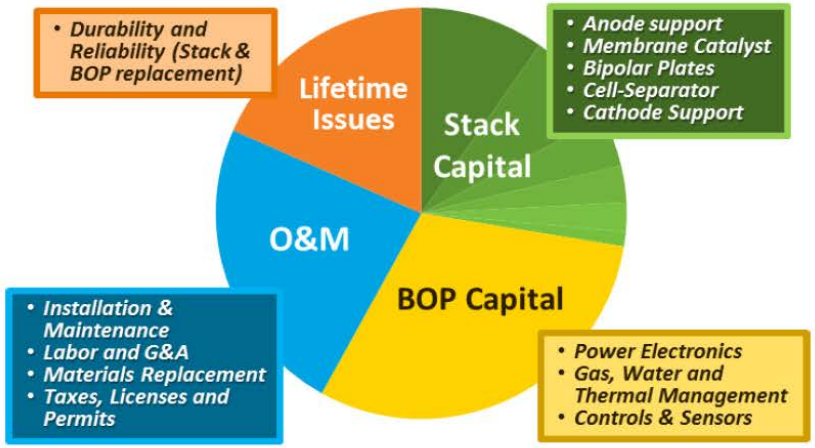
use

Topic Area	Awardee	DOE Share
1a – Advanced Storage for Gaseous Fuels	Northwestern University	$1M
	University of South Florida	$0.8M
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
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

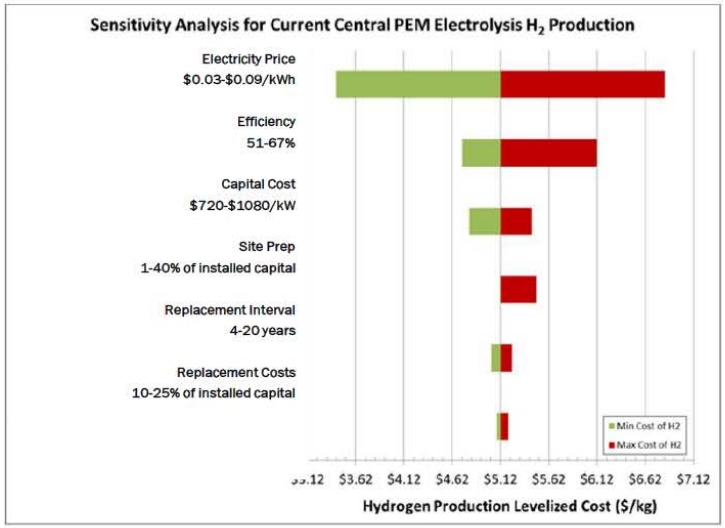
Joint EERE

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).

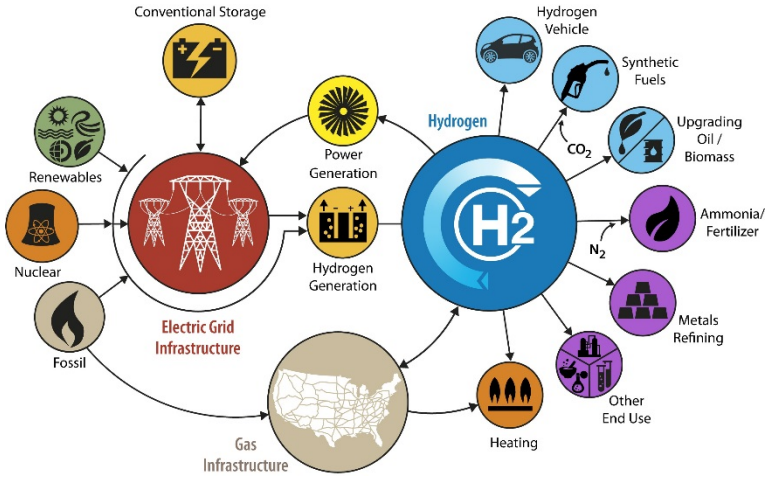
32 steering members and 20 supporting members (Nov 2018).

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.

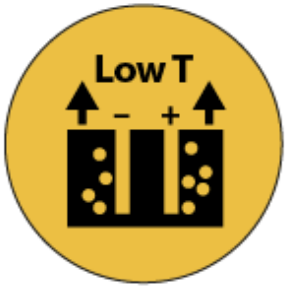
Rxn	ΔG (kJ/mol)	V cell (V)	# e–
$H_2 + 1/2O_2 \rightarrow H_2O$	–228.6	1.19	2
$CH_4 + 2O_2 \rightarrow 2H_2O+CO_2$	–800.8	1.04	8
$C + O_2 \rightarrow CO_2$	–394.4	1.02	4
$NH_3 + 3/2O_2 \rightarrow 1/2N_2 + 3/2H_2O$	–326.5	1.13	3
$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$	–113.6	0.15	8
$N_2 + H_2 \rightarrow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

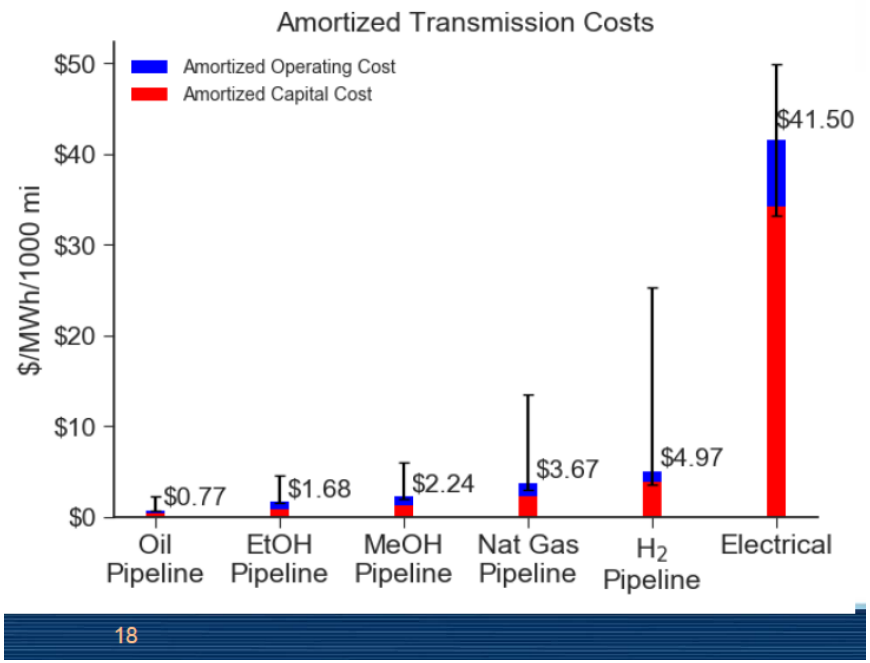
H_2 as game-changing energy carrier, revolutionizing energy sectors.

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