U.S. DEPARTMENT OF ENERGY

Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

DOE H_2 Carrier Workshop – Novel Pathways for Optimized Hydrogen Transport & Stationary Storage

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Acknowledgements and many thanks to:

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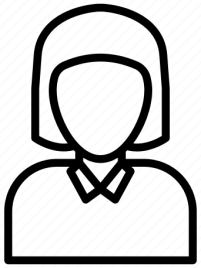

Stacey Young

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Presenters and Expert Panel Members:

- Rajesh Ahluwalia – Argonne National Laboratory
- Tom Autrey – Pacific Northwest National Laboratory
- Daisuke Kurosaki – Chiyoda Corp.
- Rafael Schmidt – Hydrogenius LOHC Technologies GmbH
- Mike Perry – United Technologies Research Center
- Guido Pez –Lehigh University (retired Air Products)
- Genevieve Saur – National Renewable Energy Laboratory

Meeting Facilitators and Note Takers:

- Elizabeth Connelly
- Eric Parker
- James Vickers
- Michael Hahn

H_2 and Fuel Cells Technologies Office

Early R&D Focus

Applied research, development and innovation in hydrogen and fuel cell technologies leading to:

- Energy security
- Energy resiliency
- Strong domestic economy

Early R&D Areas

Fuel Cells

- PGM- free catalysts
- Durable MEAs
- Electrode performance

Hydrogen Fuel

- Production Pathways
- Advanced materials for storage

Infrastructure R&D

- Safety
- Manufacturing
- Delivery components
- Others

PGM = Platinum group metals

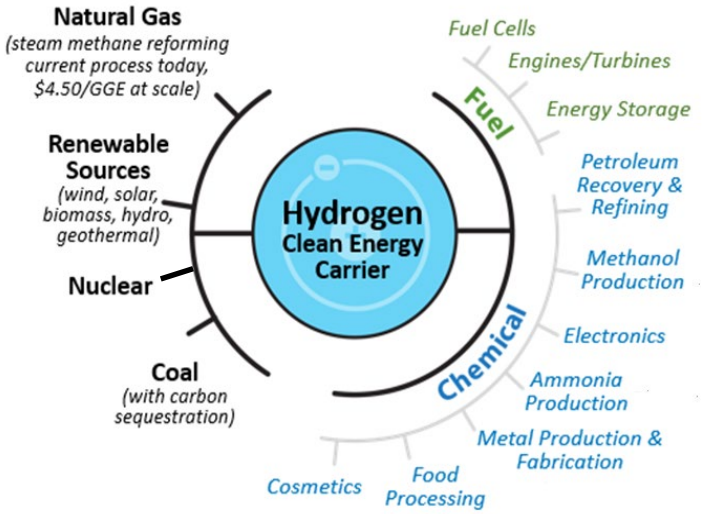
MEA = Membrane Electrode Assembly

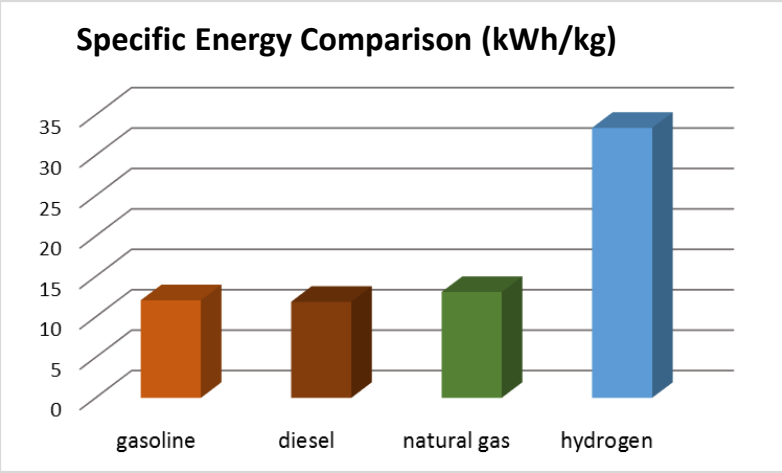
Enabling

H2@Scale
U.S. Department of Energy

Why hydrogen and fuel cells?

Can be produced from numerous feedstocks and has ~3x more energy per mass compared to other fuels





Are pollution free, reliable, resilient, and can be 2X as efficient as traditional technologies for a range of applications

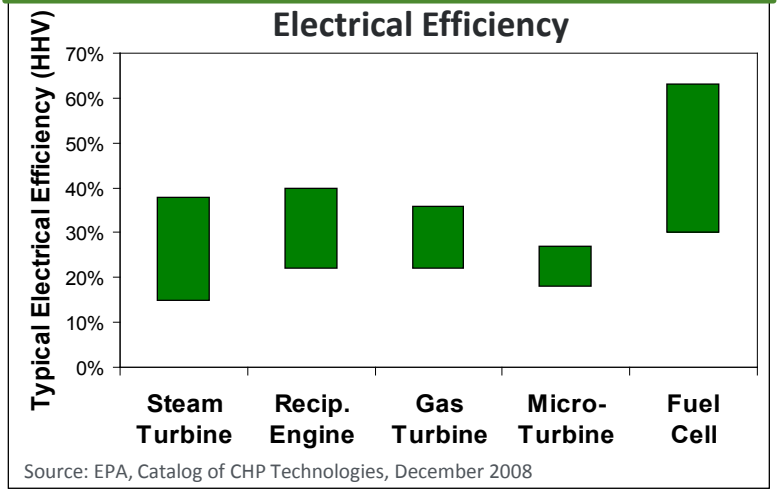
Transportation

60 MPG Fuel Cell **vs.** <30 MPG Gasoline Engine

~6 MPDG Fuel Cell **vs.** ~4 MPDG Diesel Engine

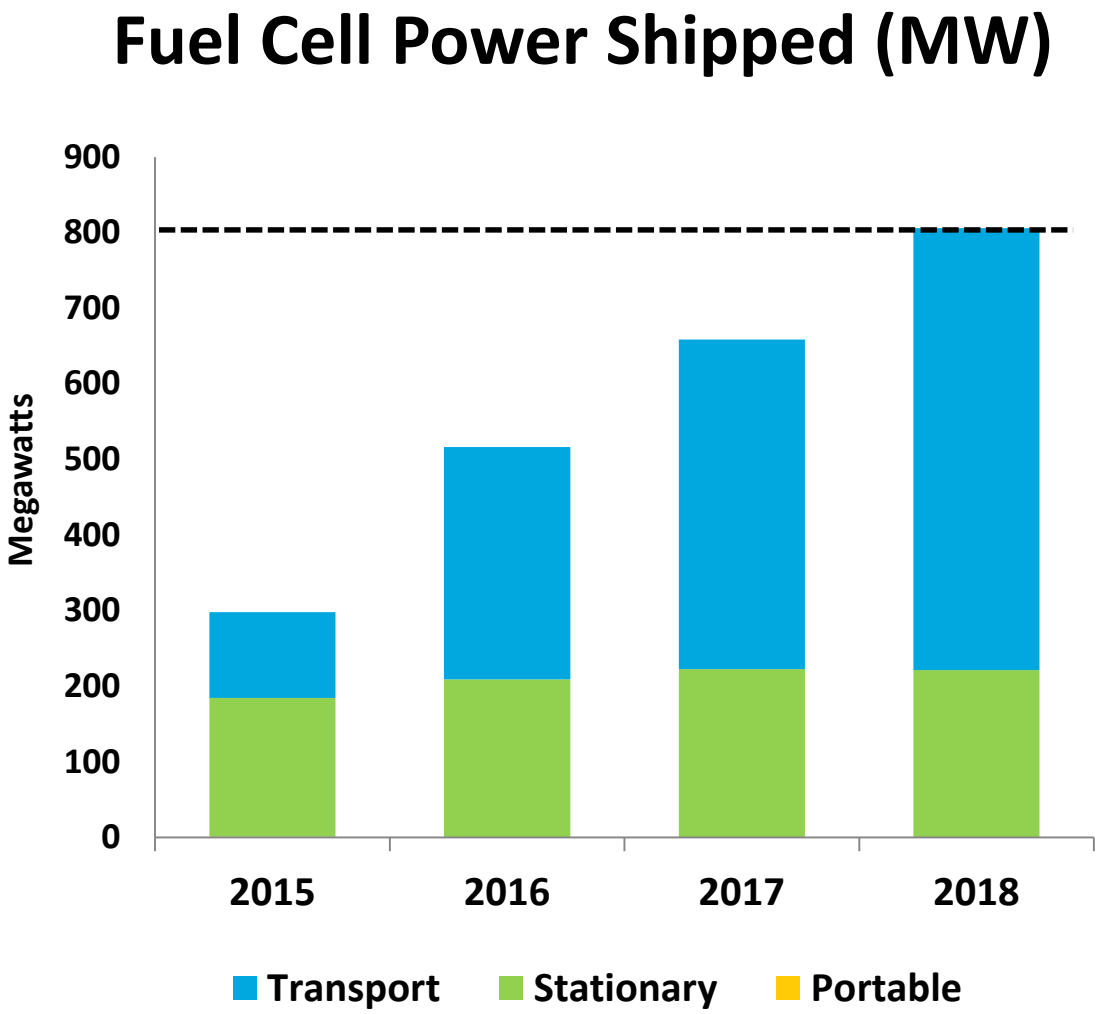
Stationary

Range of electrical efficiencies for distributed power generation technologies



Source: EPA, Catalog of CHP Technologies, December 2008

Growth in Global Fuel Cell Power Shipments



800 MW
fuel cell power
shipped worldwide

68,500
fuel cell units
shipped worldwide

Approximately
$2.3 Billion
fuel cell revenue*

* Revenue from publicly available

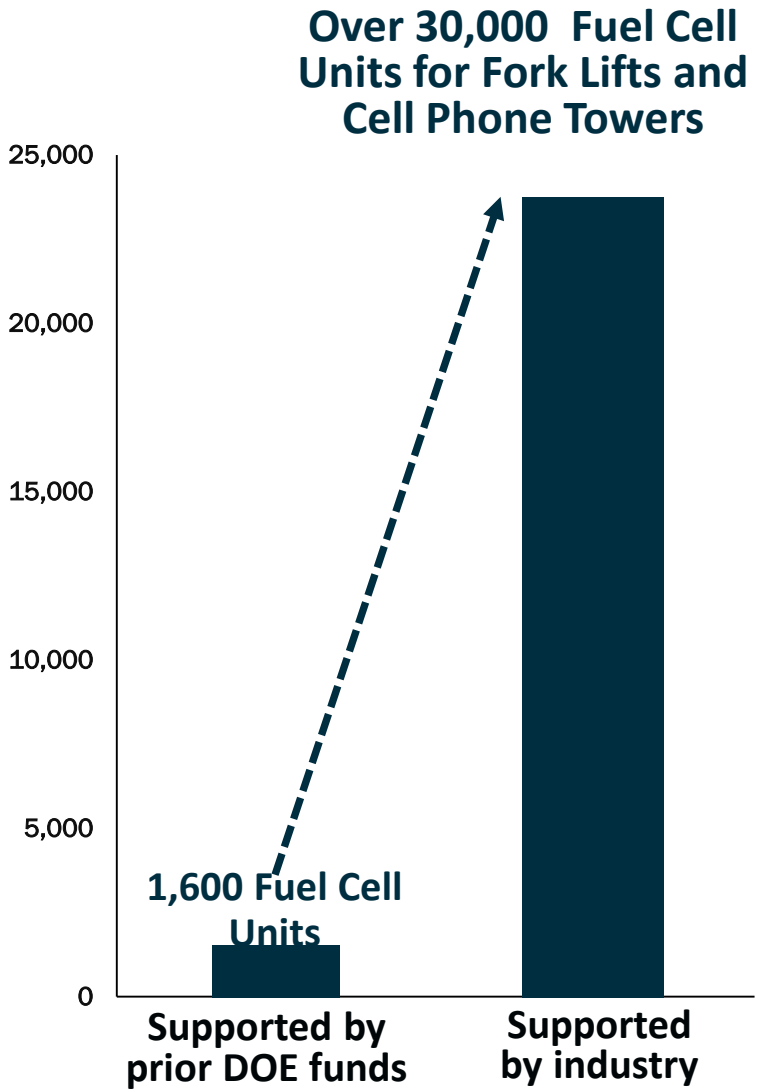
Source: DOE and E4Tech

Market Success: H_2-FC Powered Material Handling

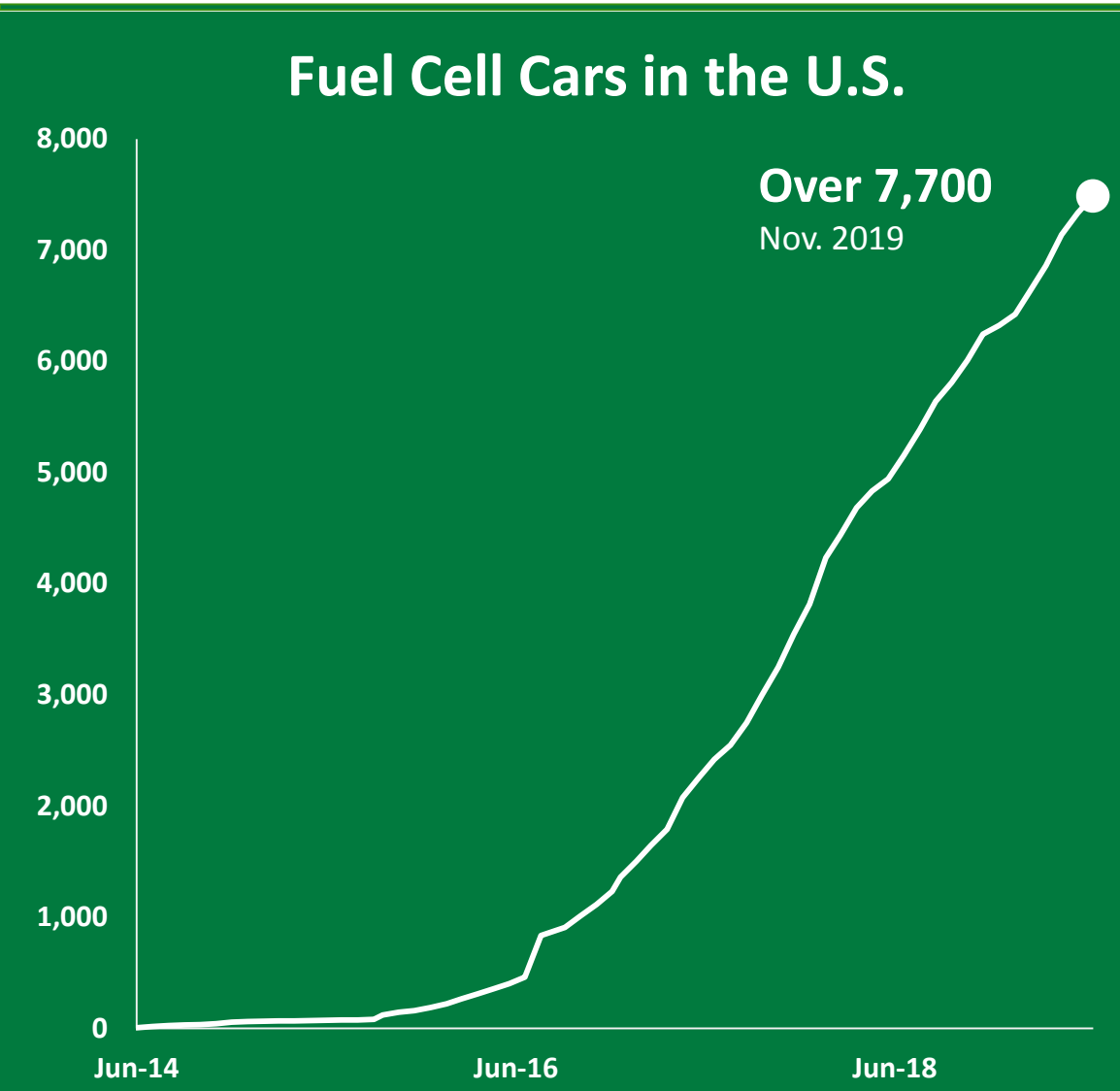
BMW plant in Greer, South Carolina

Over 30,000 fuel cell forklifts deployed or on order

Millions hydrogen refuelings performed to date



Commercial Fuel Cell Passenger Vehicles in the U.S.

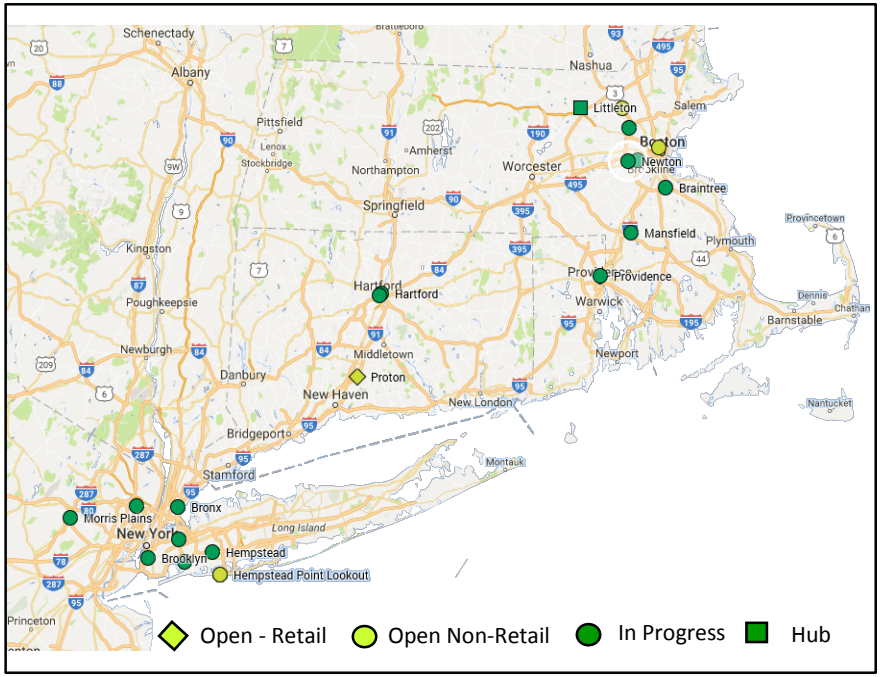


H_2 stations now open in selected U.S. regions

California

~ 42 retail stations open

Funding for 200

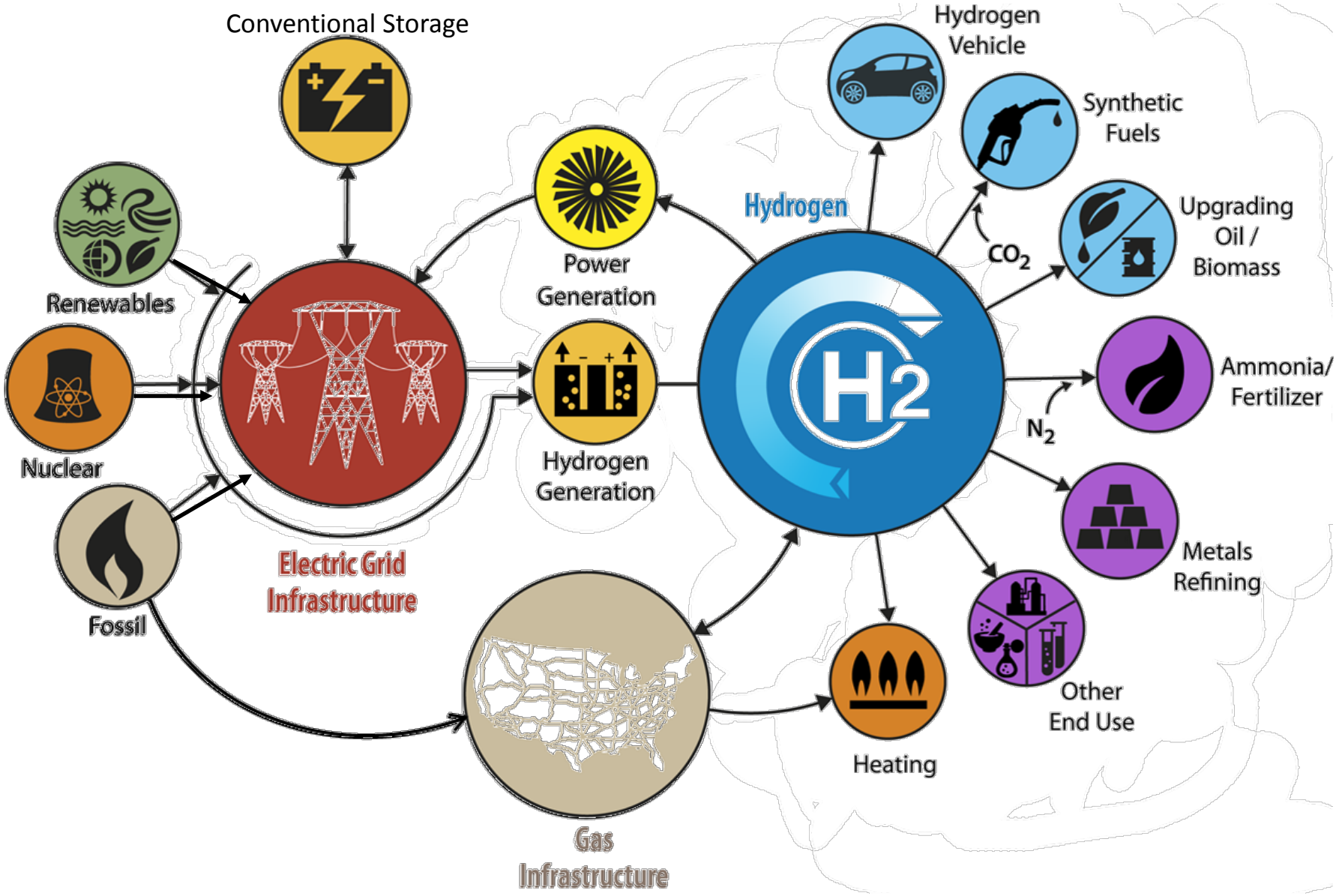


Northeast

Approx. 12 to 25 stations planned

Others with interest: Hawaii, Ohio, Texas, Colorado, South Carolina, and others

H_2@scale: Enabling affordable, reliable, clean, secure energy across sectors



Improving the economics of H2@Scale

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

MAKE

Hydrogen production technologies

MOVE

H_2

Hydrogen storage, compression, and distribution, and thermal integration

USE

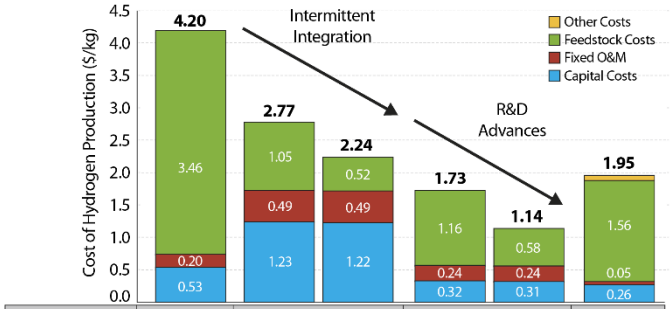
Hydrogen end use technologies and demand

STORE

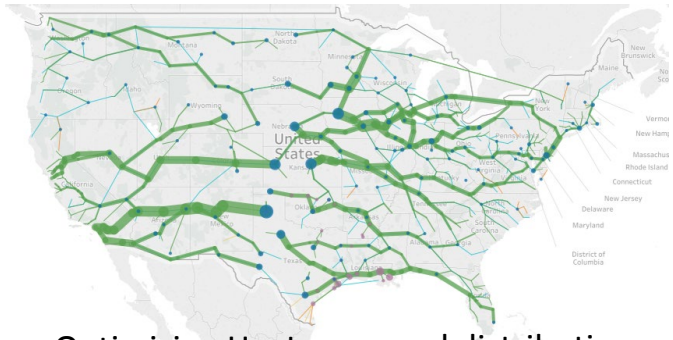
Improved Bulk Storage Technologies

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

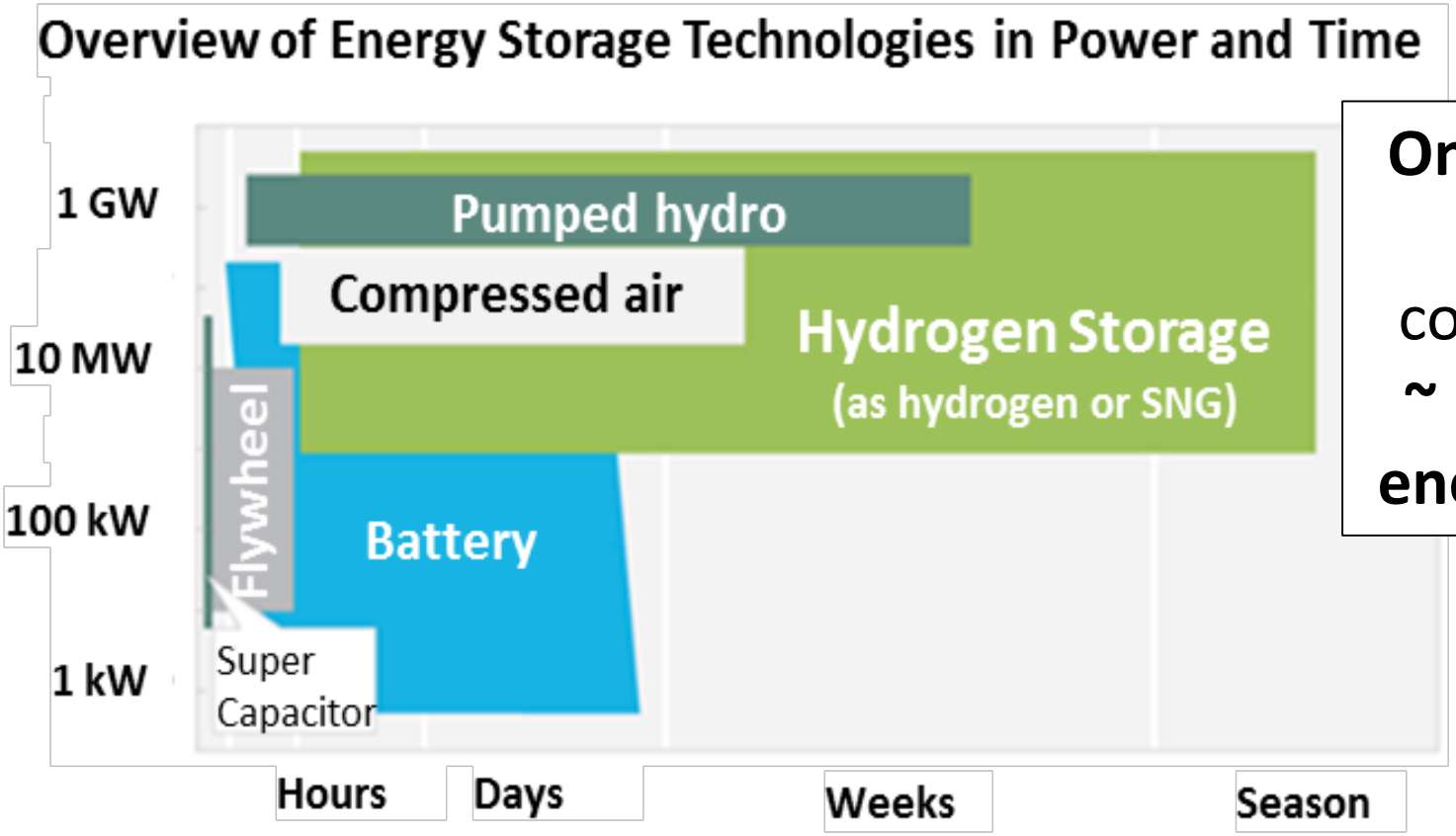
End uses of hydrogen: value proposition

Use	Potential H_2 Consumption (MMT / yr)	Purpose	Petroleum Reduction (bbl/yr)	NG Reduction (mmBtu/yr)
Refineries	8	*Crack heavy crudes, desulfurization*	900,000	1,332,000,000
Ammonia	5	*Feedstock*	500,000	833,000,000
Metals	5	*Direct Reduction of Iron*		365,000,000
Natural Gas System	7	*Combustion*	700,000	923,000,000
Biofuels§	4	*Upgrade biomass*	77,500,000	-26,000,000*
Light Duty Vehicles	28	*190M fuel cell electric vehicles*	1,017,600,000	629,000,000
Other Transport	3	*Medium/heavy- duty fuel cell vehicles*	113,400,000	51,000,000
Total	60		1.2 Billion bbl	4.1 Quads

~17% of U.S. petroleum consumption in 2016

~14% of U.S. natural gas consumption in 2016

Hydrogen can Provide Long Duration Energy Storage



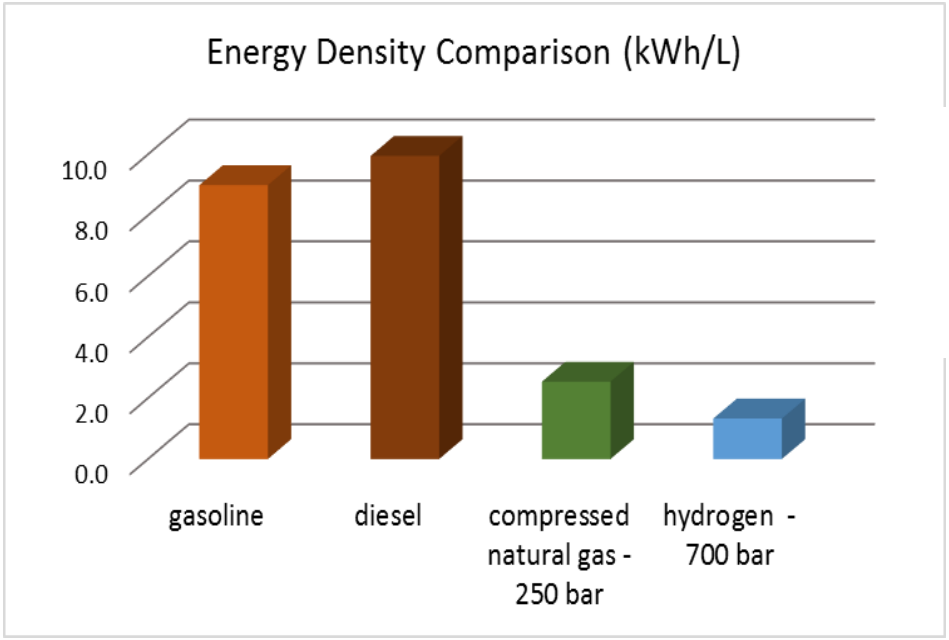
One hydrogen cavern could provide **~ 100 GWh** of **energy storage**

Image: Hydrogen Council

Hydrogen can be used to monetize surplus electricity from the grid, or remote, off-grid energy feedstock (e.g. solar, wind) for days to months.

Challenges for hydrogen as an energy carrier

Very Low Energy Density



Even when compressed to high pressures, H_2 has low energy by volume compared than most other fuels!

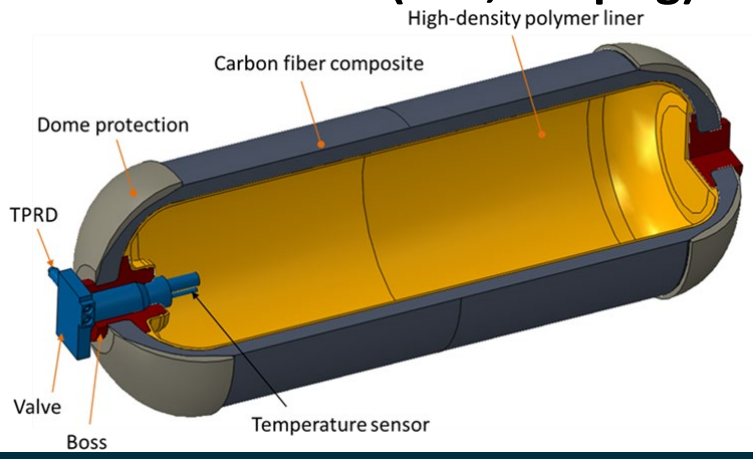
H_2 fuel tanks onboard vehicles are larger than typical gasoline tanks

… even with efficiency of the fuel cell is considered

Gasoline

Hydrogen @ 700 bar

Hydrogen is currently stored in Composite Overwrapped Pressure Vessels at 700 bar (~10,000 psig)



Hydrogen is a low-density gas under all practical conditions on earth

Today's H_2 Transport Options

Compressed H_2

Steel jumbo tube trailers: **~300 kg** payload

Composite tube trailers: **~700-1000 kg** payload

Liquefied H_2

Liquid H_2 tanker trailers: **~4500 kg** payload

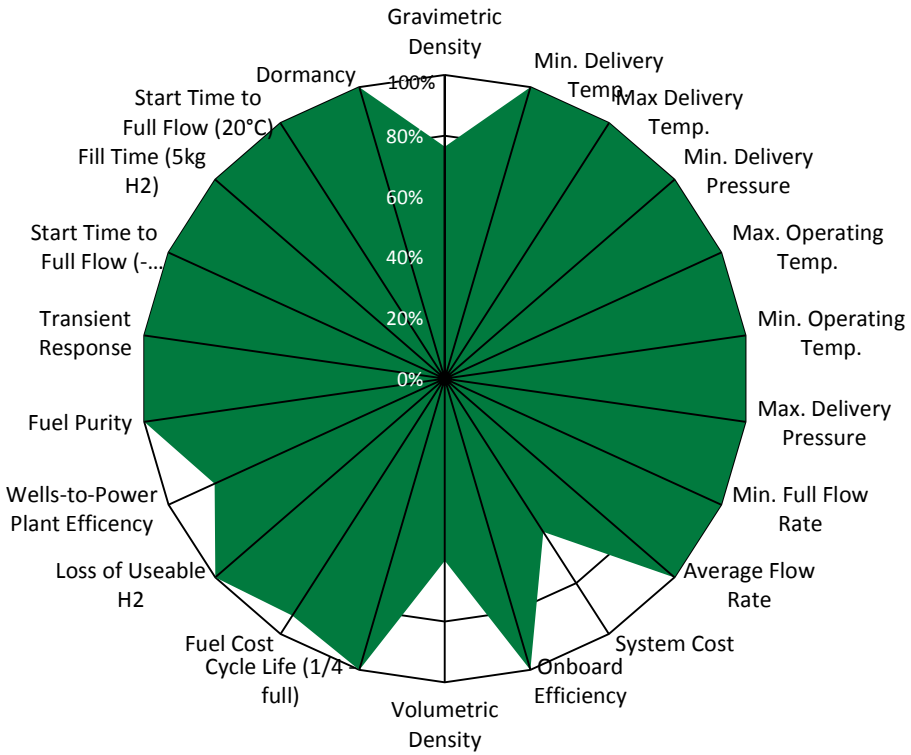
H_2 Carriers

Hydrogen Carriers: **>>1000 kg** payload? (*and at what cost?*)

Onboard H_2 Storage R&D Targets and Status

Storage Targets	Gravimetric kWh/kg (kg H_2/kg system)	Volumetric kWh/L (kg H_2/L system)	Costs [1] $/kWh ($/kg H_2)
2020	1.5 (0.045)	1.0 (0.030)	$10 ($333)
2025	1.8 (0.055)	1.3 (0.040)	$9 ($300)
Ultimate	2.2 (0.065)	1.7 (0.050)	$8 ($266)
Current Status [2]			
700 bar compressed (5.6 kg H_2, Type IV, Single Tank)	1.5 (0.044)	0.8 (0.025)	$16 ($523)

700 Bar Compressed Status[2] vs. 2025 Targets



[1] Projected at 100,000 units/year

[2] FCTO Data Record #19***xxx***, 9/23/2019: ***FCTO website – Data Records – to be released soon***

The full set of H_2 storage targets can be found on the Program's website:

https://energy.gov/eere/fuelcells/downloads/doe-targets-onboard-hydrogen-storage-systems-light-duty-vehicles

Questions to consider during the workshop

- Analysis so far has focused on cost comparison with liquid and gaseous H_2 transport, what are other potential advantages of H_2 carriers:
  - Use of existing infrastructure
    - Petroleum pipelines
    - Underground storage tanks
    - Liquid tankers
    - Existing production facilities
  - Reducing current burdens
    - Setback distances for installations
    - Direct generation of pressurized hydrogen
- What applications for H_2 carriers should be targeted
- Key R&D needed to develop and demonstrate H_2 carriers

Thank You

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energy.gov/eere/fuelcells