U.S. DEPARTMENT OF ENERGY

Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

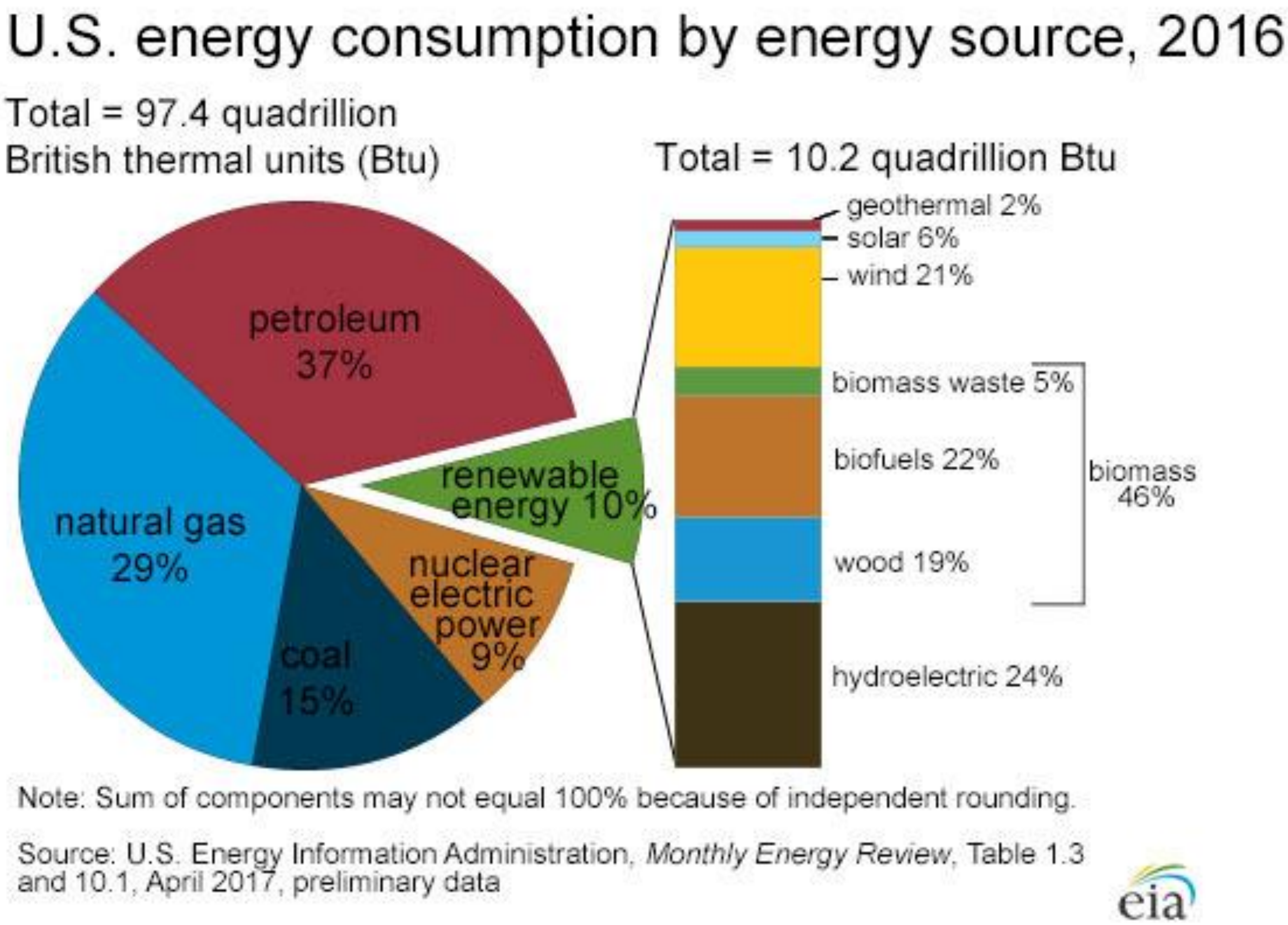
Hydrogen and Fuel Cells: Progress and Opportunities

Sunita Satyapal, Director – Fuel Cell Technologies Office

6th International Forum on Clean Energy

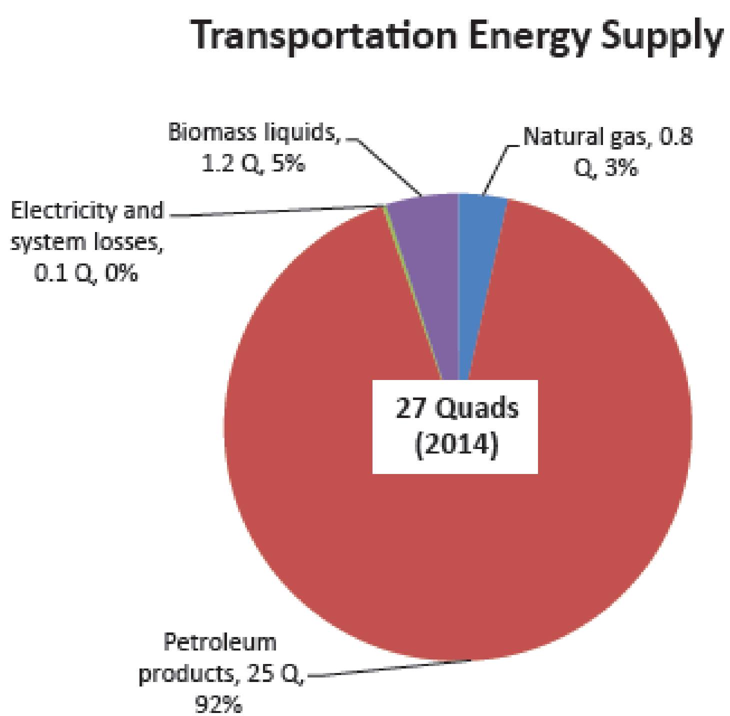
Macau, China – December 14, 2017

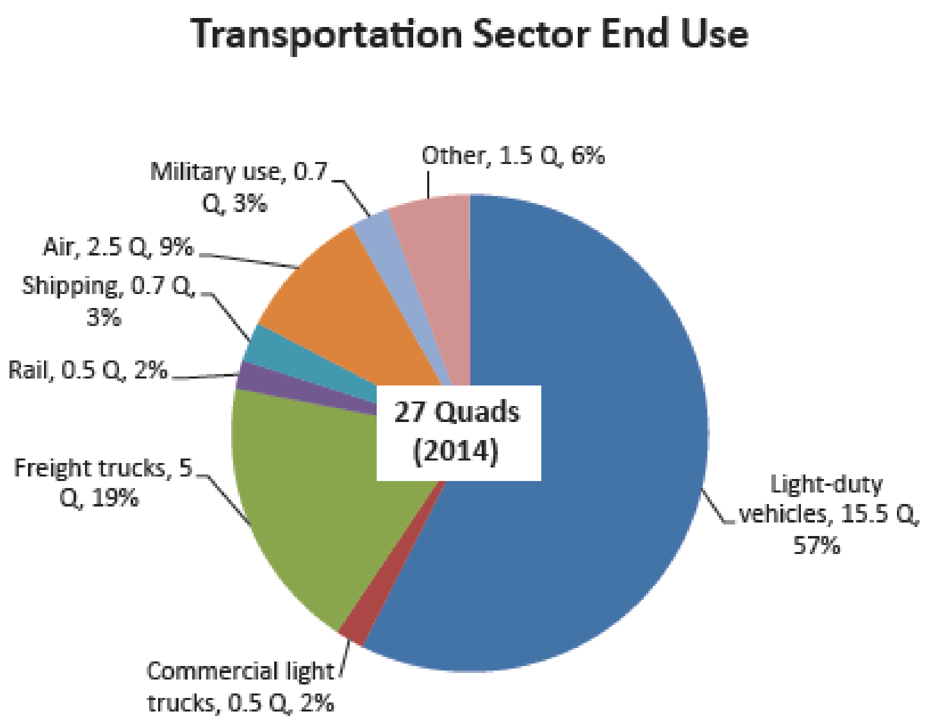
All of the Above Energy Portfolio



U.S. Transportation Energy Supply and Use

- **Over 90% of transportation sector relies on petroleum**

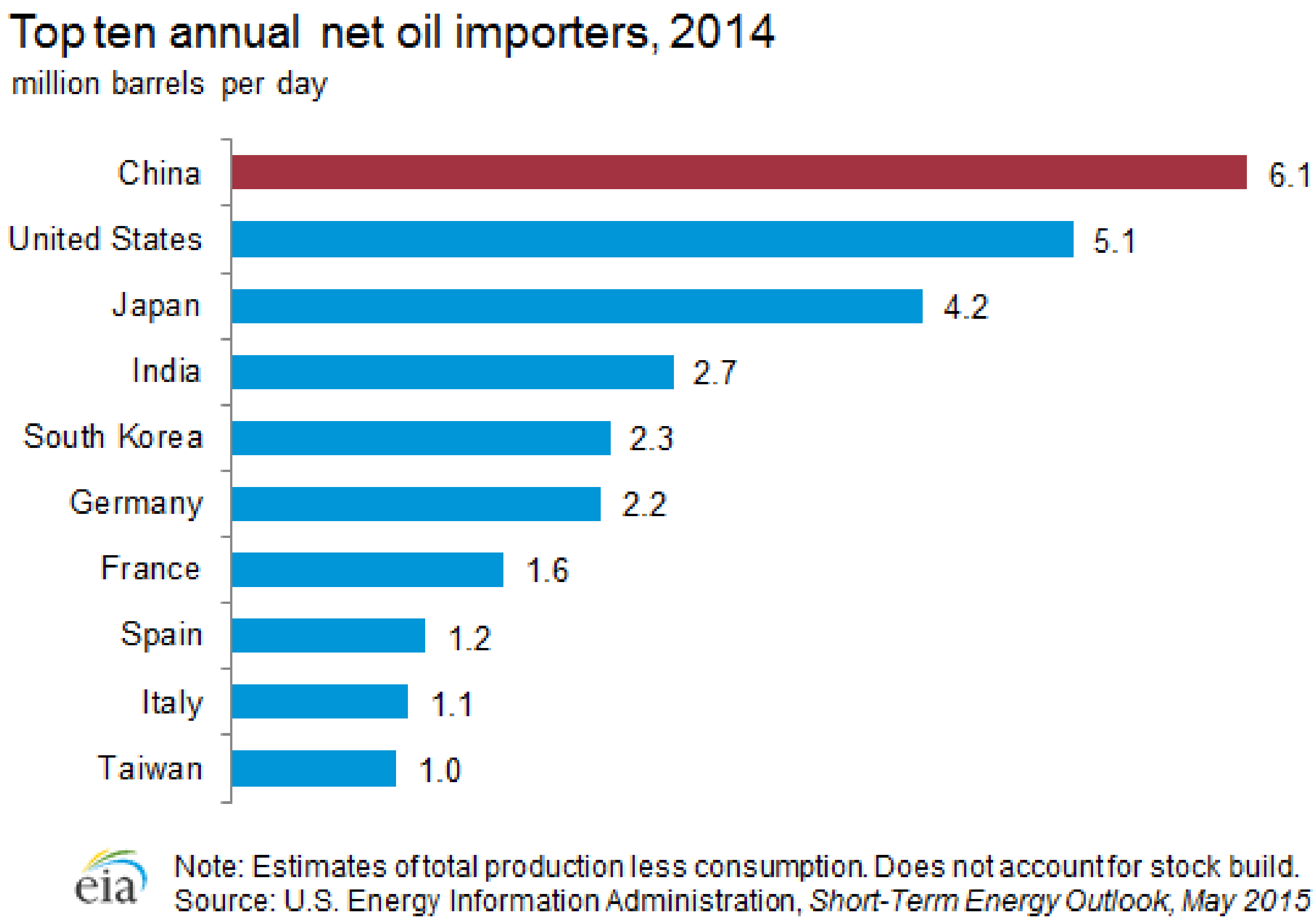




Source: DOE QTR (2015)

*ORNL, 2015

Mutual Drivers: Reducing Oil Imports



https://www.eia.gov/beta/international/analysis.cfm?iso=CHN

Common Global Drivers: Air Quality

Shanghai skyline: http://www.scmp.com/news/china/society/article/2106410/air-pollution-suspected-sharp-rise-china-lung-cancer-rate

PM 2.5 < 10 mg/m^3 (WHO limit)

Examples cited in China: 47, 100, > 300 mg/m^3

The Beginning of the DOE Fuel Cell Program…

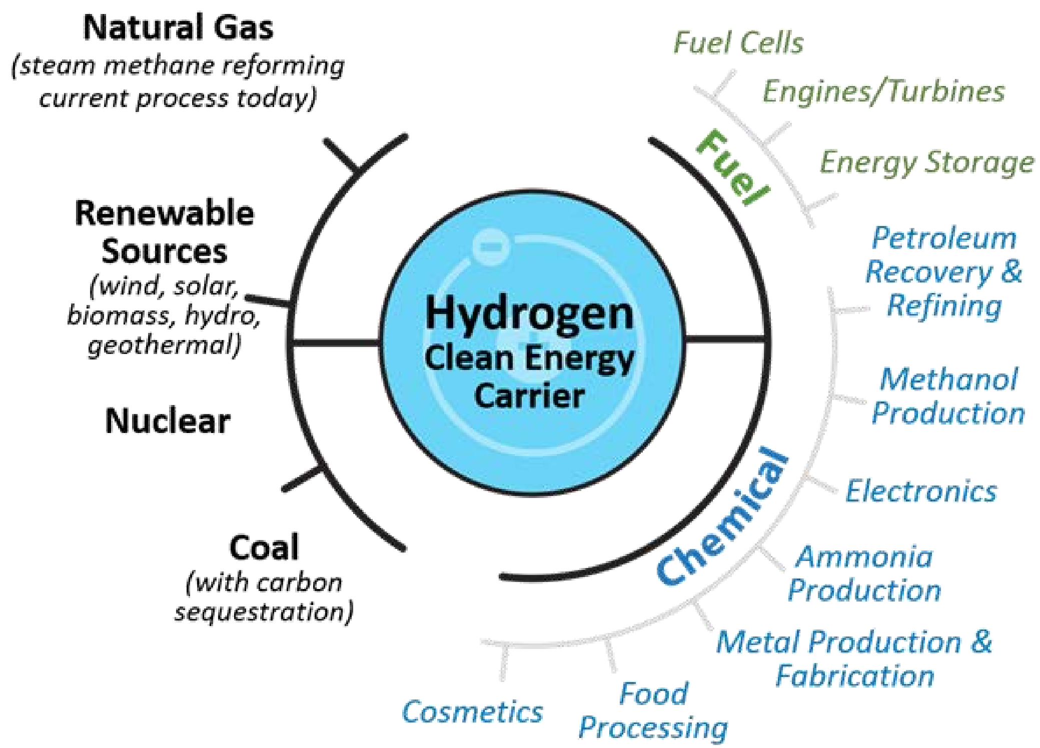
1970s | **A group from labs, government and industry met at Los Alamos to set the foundation for DOE fuel cell programs**

Lab researchers taught scientists around the world how to fabricate fuel cell electrodes. Group from GM relocated to Los Alamos.

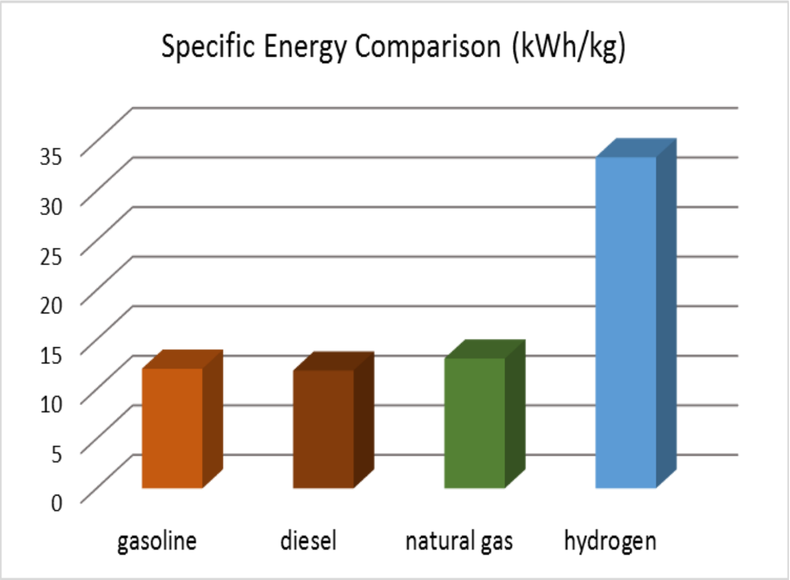
Hydrogen is one part of an All of the Above Portfolio

H_2 can be produced from diverse domestic sources

Many applications rely on or could benefit from H_2



Very High Specific Energy



About *three times* more energy by mass than gasoline. But worse in terms of volume.

Clean , sustainable, versatile, and efficient energy carrier

Progress

For the first time in history….

Hyundai Tucson Fuel Cell SUV

Toyota Mirai

Honda Clarity

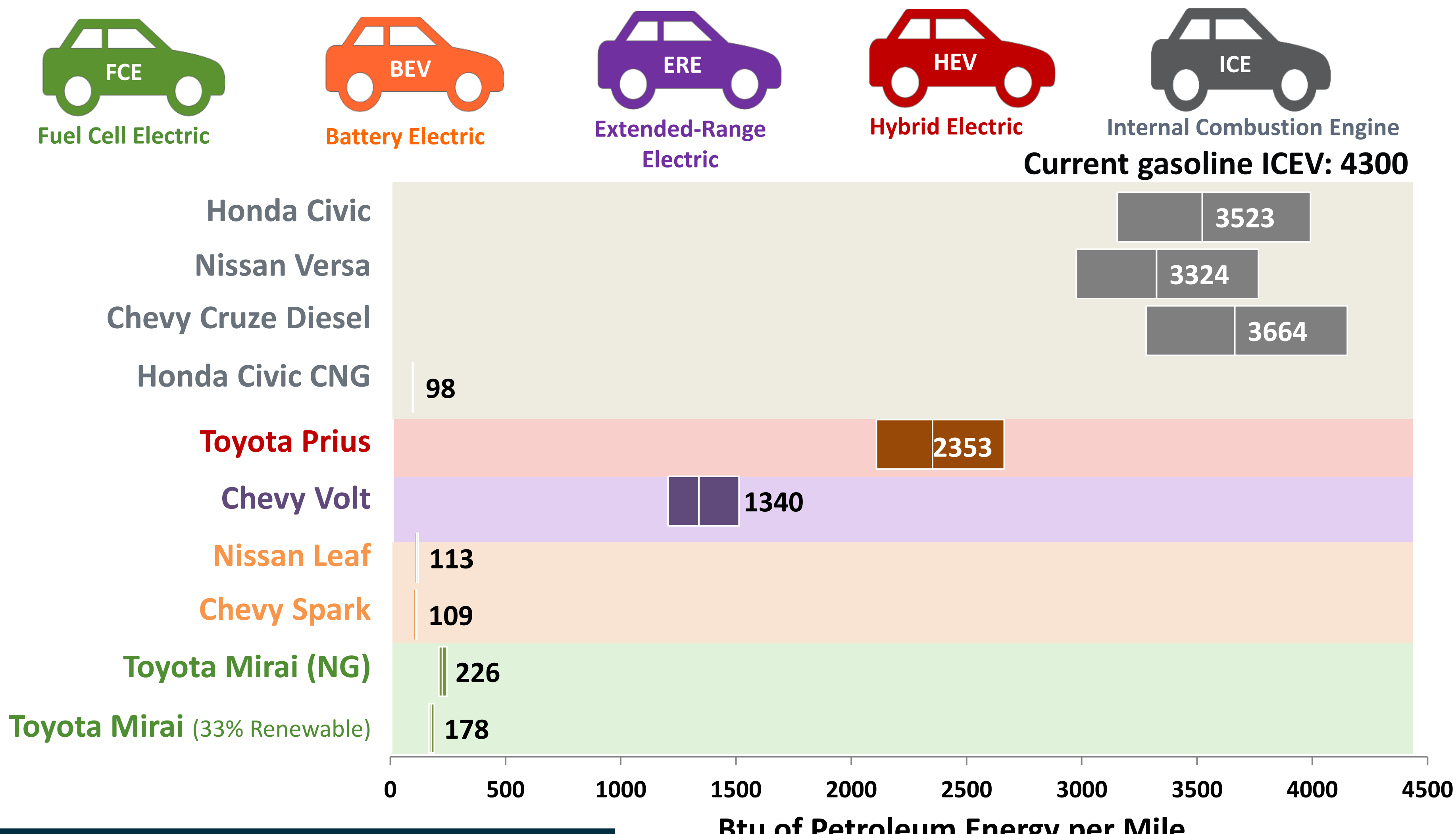
Commercial **fuel cell electric cars are here!**

Over **3,000** | **sold or leased** in the United States

- No petroleum, no pollution
- Refuels in minutes
- More than 360 mi driving range
- Over 60 mpgge

Life-Cycle Petroleum Use- Today's Cars

Low, Medium & High Petroleum Energy/Mile for 2015 Technology

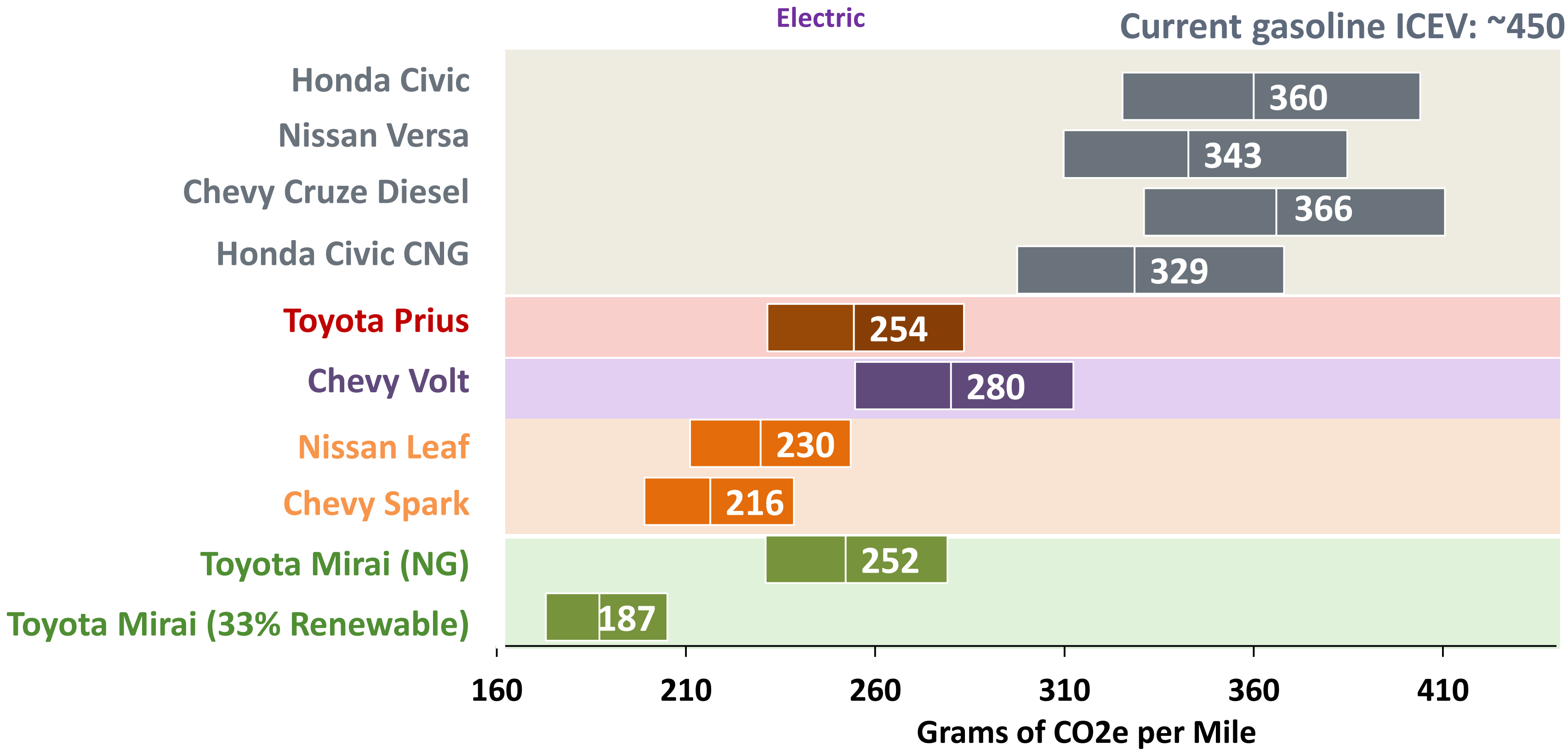


DOE cross office analysis example

Source: Program Record 16004 (https://www.hydrogen.energy.gov/pdfs/16004_life-cycle_ghg_oil_use_cars.pdf)

Life-cycle Emissions- Today's Cars

Low, Medium & High Emissions/Mile for 2015 Technology



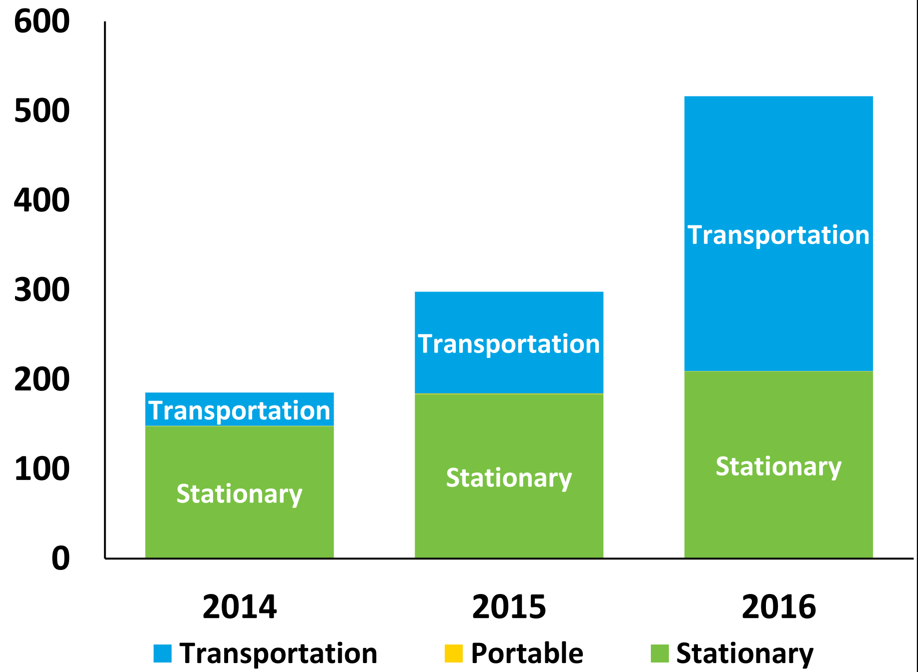
DOE cross office analysis example

Source: Program Record 16004 (https://www.hydrogen.energy.gov/pdfs/16004_life-cycle_ghg_oil_use_cars.pdf)

2016 Global Shipments – Trends

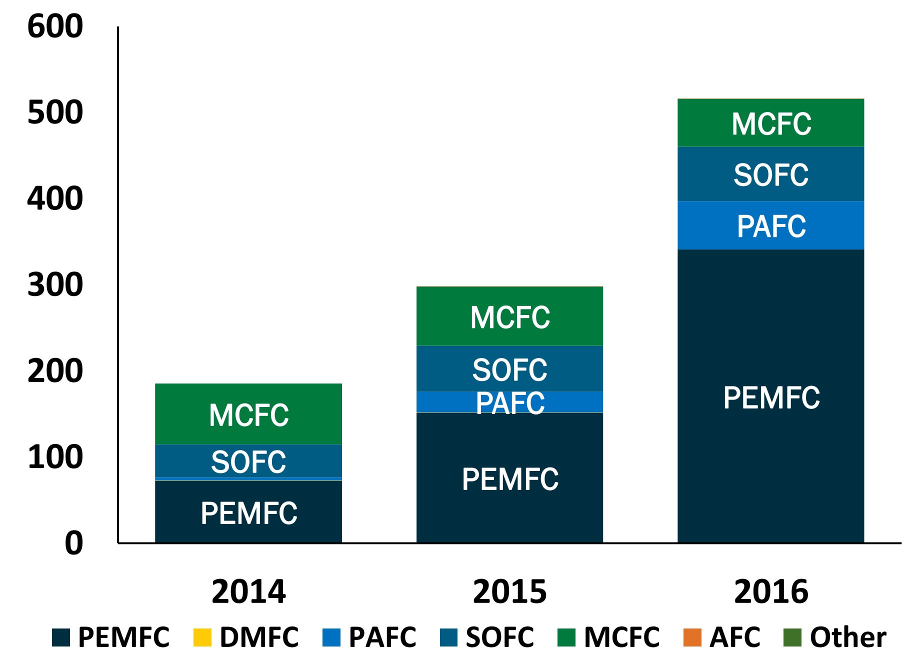
Total power (in MW) shipped by application

Growth in Transportation



Total power (in MW) shipped by fuel cell chemistry

Growth in PEMFC



500 MW fuel cell power shipped worldwide

62,000 fuel cell units shipped worldwide

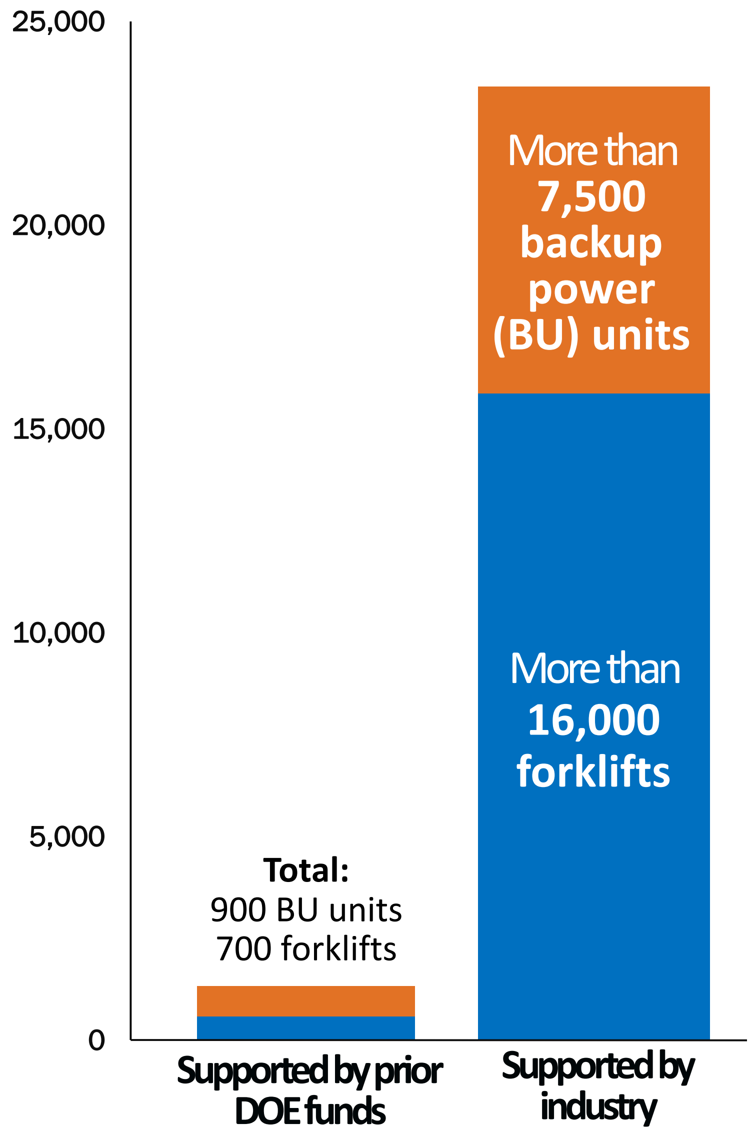
Approximately **$1.6 Billion** fuel cell revenue

Source: E4tech

Catalyzing Early Markets for Fuel Cells

Credit: BMW Manufacturing

Credit: Fuel Cell Energy



Heavy Duty Vehicle Applications Emerging- Examples

Fuel cell buses in CA surpass 17M passengers

Fuel cell delivery and parcel trucks starting deliveries in CA and NY

Industry demonstrates first heavy duty fuel cell truck in CA

Market Segmentation Analysis Underway

FCEVs : Lower cost for large size classes and longer driving range

Year 2040: FCEV minus BEV-X Total Cost of Ownership
Green shows where FCEVs are more cost effective

	50 mi.	100 mi.	150 mi.	200 mi.	250 mi.	300 mi.	350 mi.
Two-seaters	$0.05	$0.01	-$0.03	-$0.07	-$0.11	-$0.15	-$0.19
Minicompacts	$0.05	$0.02	-$0.01	-$0.04	-$0.07	-$0.10	-$0.13
Subcompacts	$0.05	$0.02	-$0.01	-$0.04	-$0.07	-$0.11	-$0.14
Compacts	$0.04	$0.01	-$0.02	-$0.05	-$0.09	-$0.12	-$0.15
Midsize Cars	$0.05	$0.01	-$0.03	-$0.06	-$0.10	-$0.13	-$0.17
Large Cars	$0.04	$0.01	-$0.02	-$0.06	-$0.09	-$0.12	-$0.16
Small Station Wagons	$0.05	$0.01	-$0.03	-$0.07	-$0.11	-$0.15	-$0.19
Pass Van	$0.03	-$0.01	-$0.06	-$0.11	-$0.15	-$0.20	-$0.24
SUV	$0.03	-$0.02	-$0.08	-$0.14	-$0.19	-$0.25	-$0.30
Std Pickup	$0.14	$0.11	$0.07	$0.04	$0.01	-$0.03	-$0.06
Small Pickup	$0.06	$0.02	-$0.02	-$0.07	-$0.11	-$0.15	-$0.19

Stationary Power Applications Emerging – Examples

Fuel cells provided backup power during Hurricane Sandy in the U.S. Northeast

Fuel cells used to power new World Trade Center in NYC

Fuel cell power for maritime ports demonstrated in Honolulu, Hawaii

Over 235 MW of fuel cell stationary power installed across more than 40 US states

Photo credit: Fukuoka Pref.

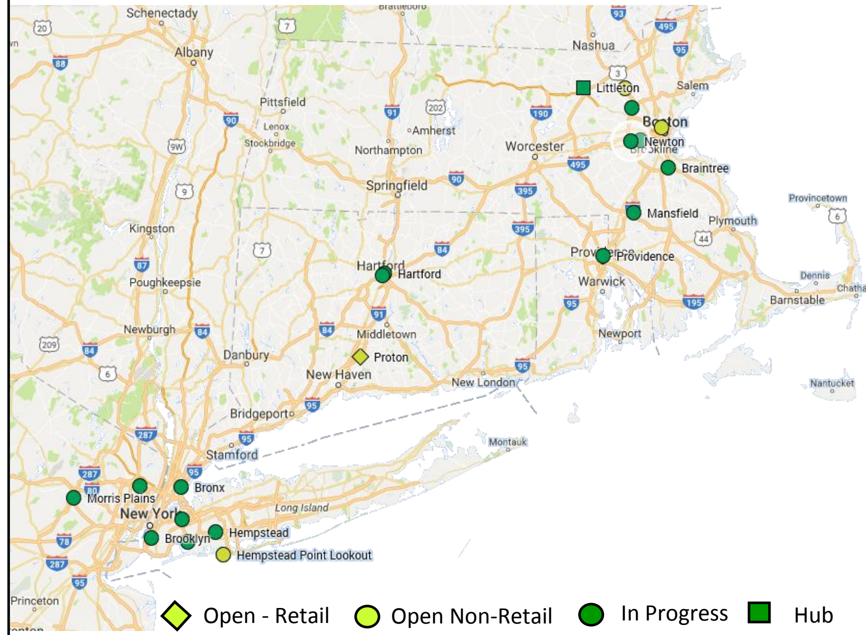

Challenges

U.S. Hydrogen Refueling Stations

California

Over 30 open retail

Funding for 100



Northeast

Approx. 12 to 25 stations planned

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

What can we learn from history?

Henry Ford's Quadricycle in 1896 to Model T in 1908

FORD CARS

1909 MODELS

The enormous demand for the new 4-cylinder Model "T" touring car makes it impossible for us to get these cars on short notice; deliveries will be made strictly in the order given. If you want one of these cars, see us soon.

$850 f. o. b. factory

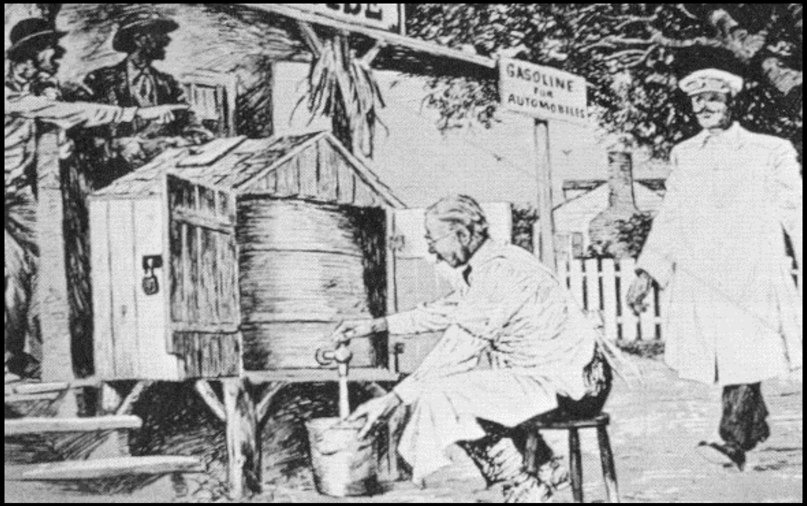
Colorado Auto Supply Co.
Distributers
8-10 E. BIJOU STREET

Three or four splendid second-hand cars for sale cheap.

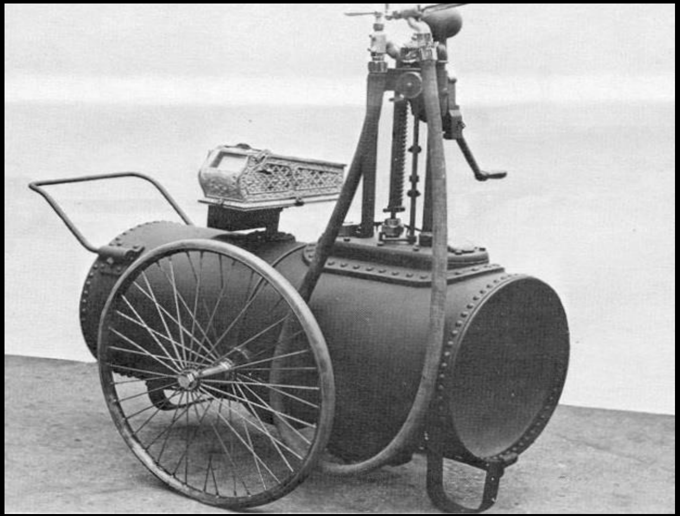
Gasoline History: Many diverse options

Cans, barrels, home models, mobile refuelers

Source: M. Melaina 2008.



Source: Vieyra, 1979

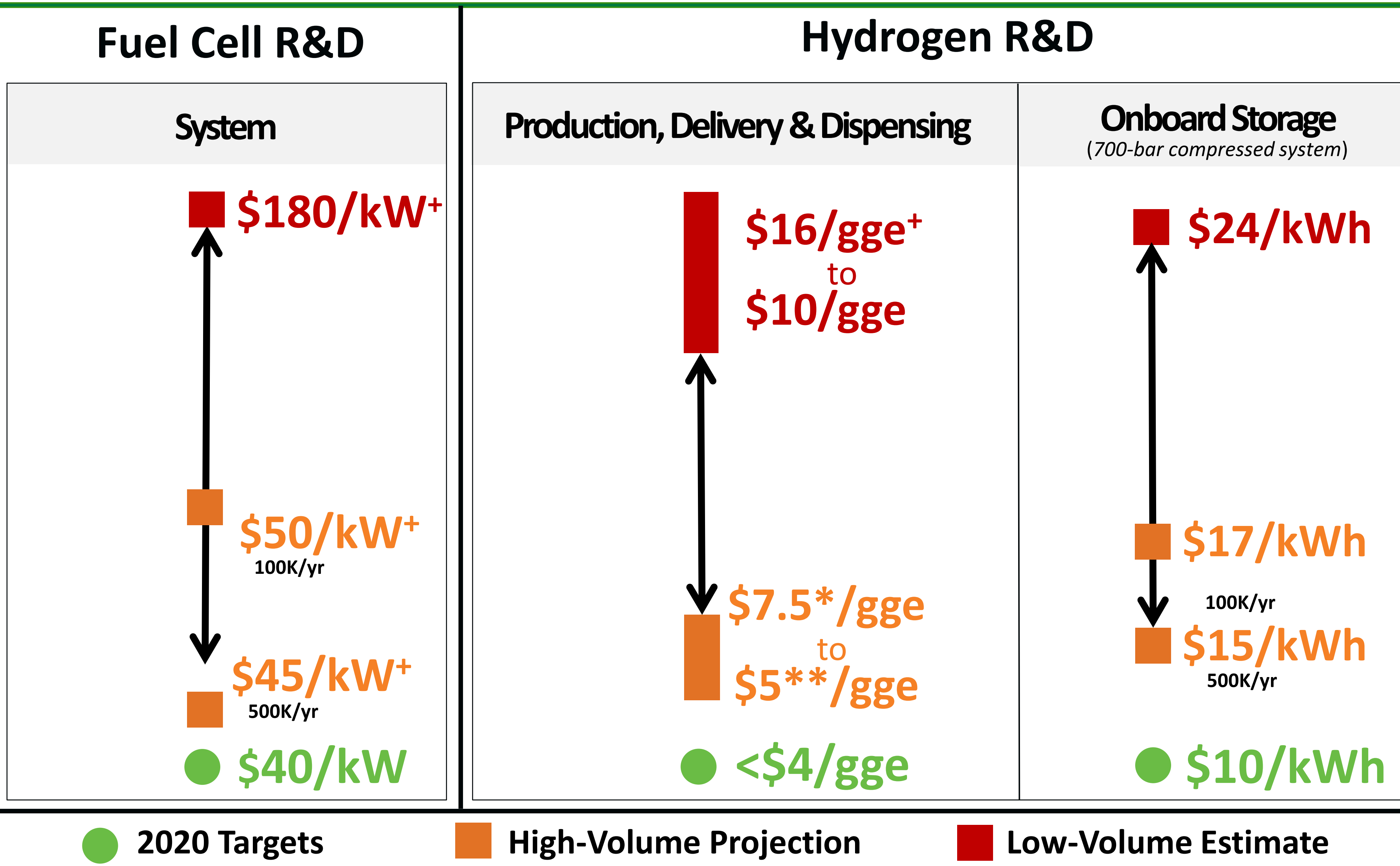

Source: Milkues, 1978

Challenges

- **Cost**
- **Reliability**
- **Availability**

A hydrogen fueling station in San Francisco, CA. | Photo courtesy of the California Fuel Cell Partnership

DOE Cost Status and Targets for R&D



*Based on Electrolysis **Based on NG SMR + Preliminary, updates underway
Onboard storage cost status from DOE Program Record 15013

Note: Graphs not drawn to scale and are for illustration purposes only.

H_2 Production Early Stage R&D

Pathway using domestic natural gas can be competitive today

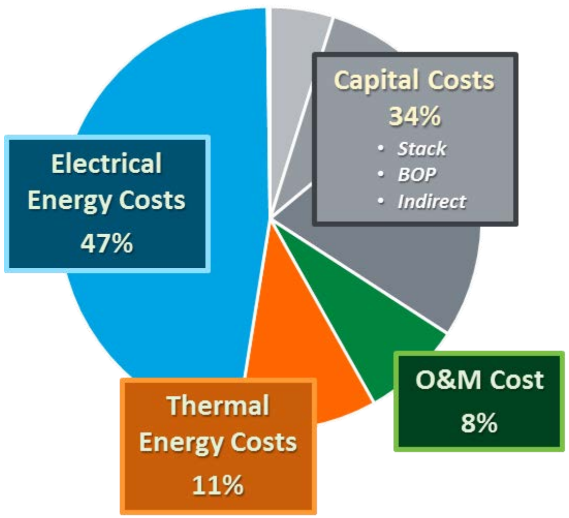
Portfolio Covers*:

- Fossil Resources
- Waste and Biomass
- Water-splitting

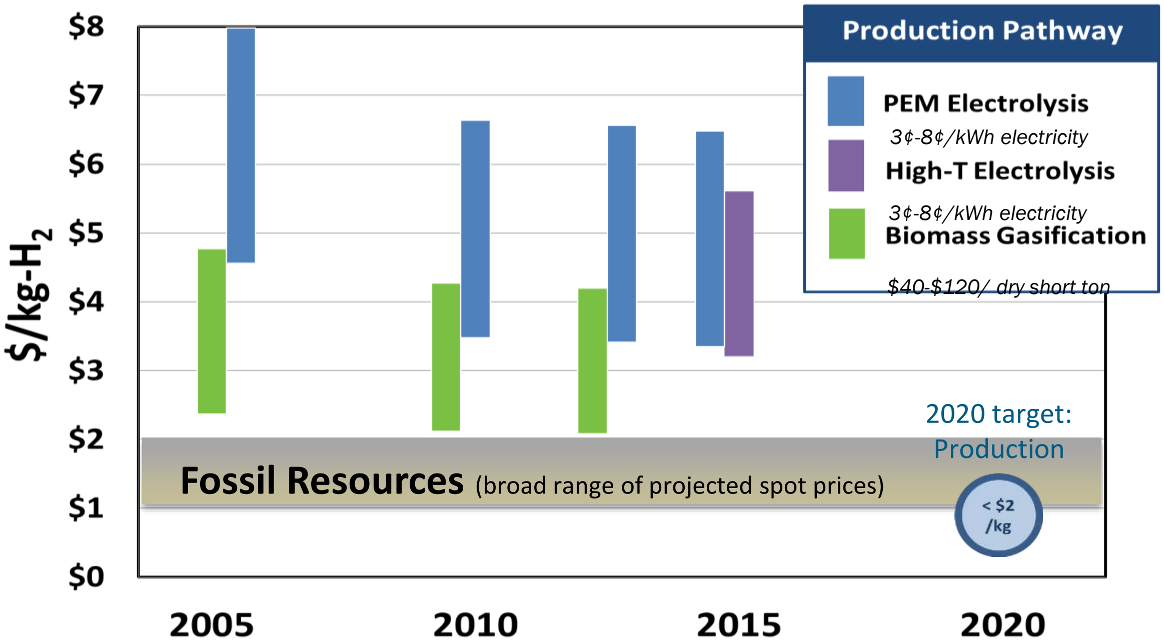
*examples

Cost by Component

High-T Electrolysis Example



Projected Production Cost* by Pathway

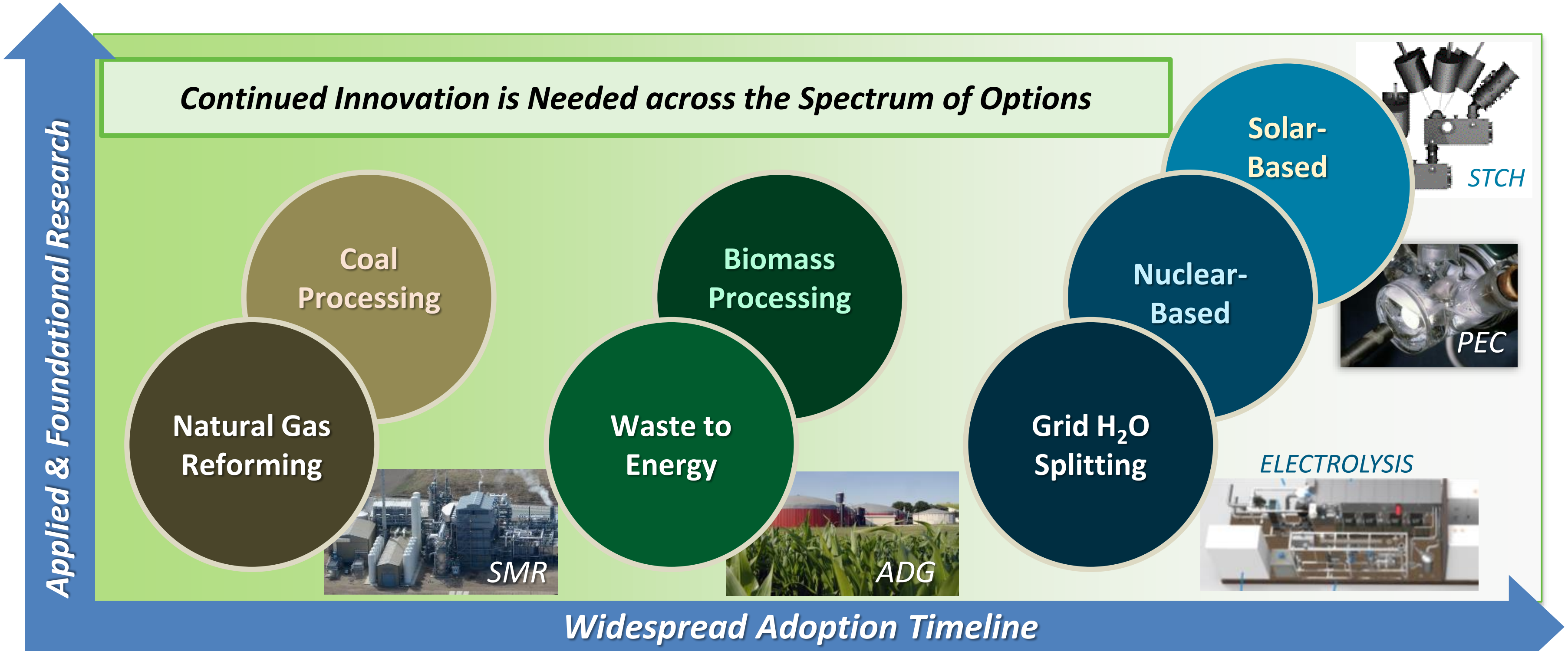


*Ranges with sensitivities to feedstock price variations

Early-Stage Applied R&D Examples:

- Innovative Reactors Concepts
- Novel Devices and Components
- Materials Development (PEC, STCH, electrolysis)

H_2 Production fro Diverse Domestic Resources



FOSSIL RESOURCES

- Low-cost, large scale H_2 production with CCUS options
- New options offer scalability and byproduct benefits (e.g. CHHP)

WASTE/BIOMASS

- Options included biogas reforming & fermentation of waste streams
- Byproduct benefits include clean water, electricity & chemicals

WATER SPLITTING

- Grid electrolysis is proven process being improved with innovation
- Emerging nuclear/solar options offer long-term sustainable H2

Opportunities

Example: High-Temp. Steam (HTSE) Electrolysis and Nuclear

Benefits

- High electrical efficiency
- Scalable
- Leverages heat sources from nuclear
- Improves economics of nuclear reactors
- Can operate over wide range of loads

Needs

- Electrolyzer cell/stack durability improvements
- Load following capability dependent on time-frame (minutes vs hours)
- System-level demonstration

Gen IV Reactors produce process heat compatible with high-temp. steam electrolysis (HTSE)

New Applications Emerging- Examples

China

Eight Fuel Cell Trams

Capacity: 285 passengers
Maximum speed: 70 km/hr.

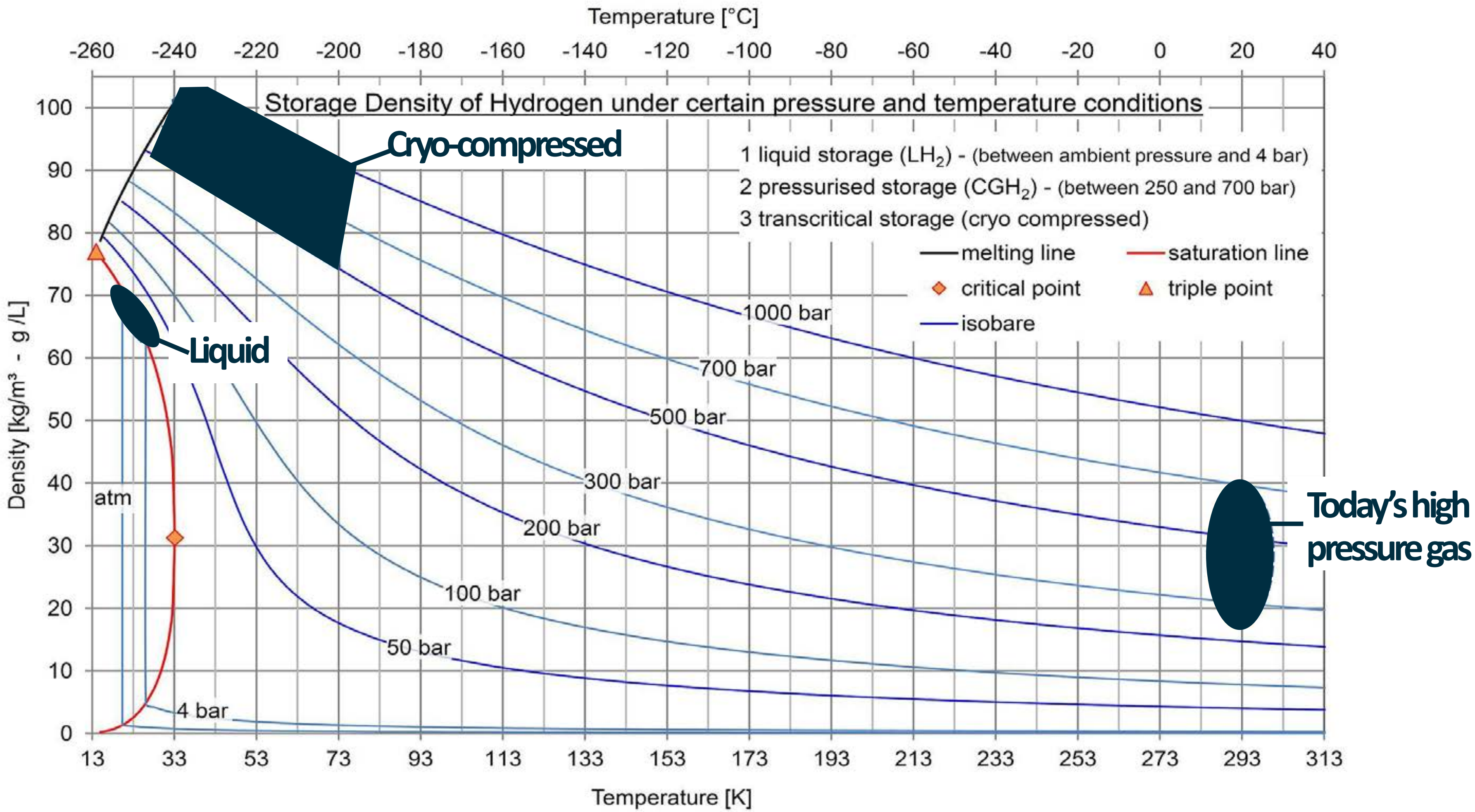
Other Examples

Trains to operate in Germany in 2018

Capacity: 300 passengers
Maximum speed: 140 km/hr.

Example: Potential Option for Heavy Duty Vehicles

Cryo-compression can offer densities higher than liquid hydrogen



https://en.wikipedia.org/wiki/Hydrogen_storage#/media/File:Storage_Density_of_Hydrogen.jpg

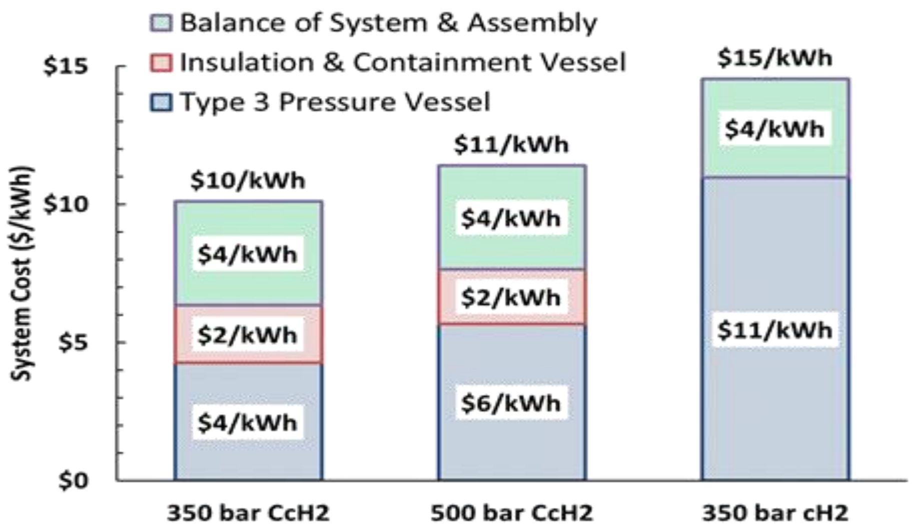
Advantages of CryoCompressed in Buses - Examples

- **Over 210% increase in storage density**
- **Over 90% higher gravimetric capacity and 175% higher volumetric capacity**
- **46% saving in carbon fiber composite**
- **Over 25% lower cost** at 5,000 systems/year annual production

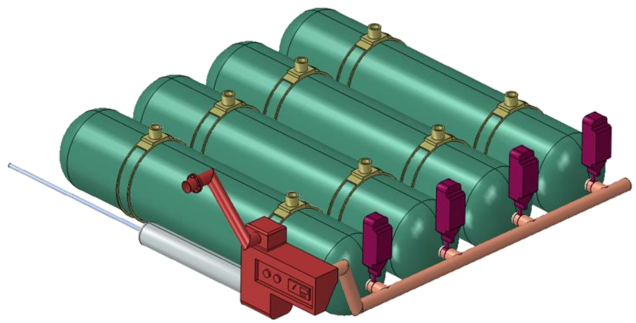
However, **significant work still required – no suppliers**

*Based on 500-bar Cch2 over type-3, 350- bar in buses today

Projected Cost at 5,000 systems per year

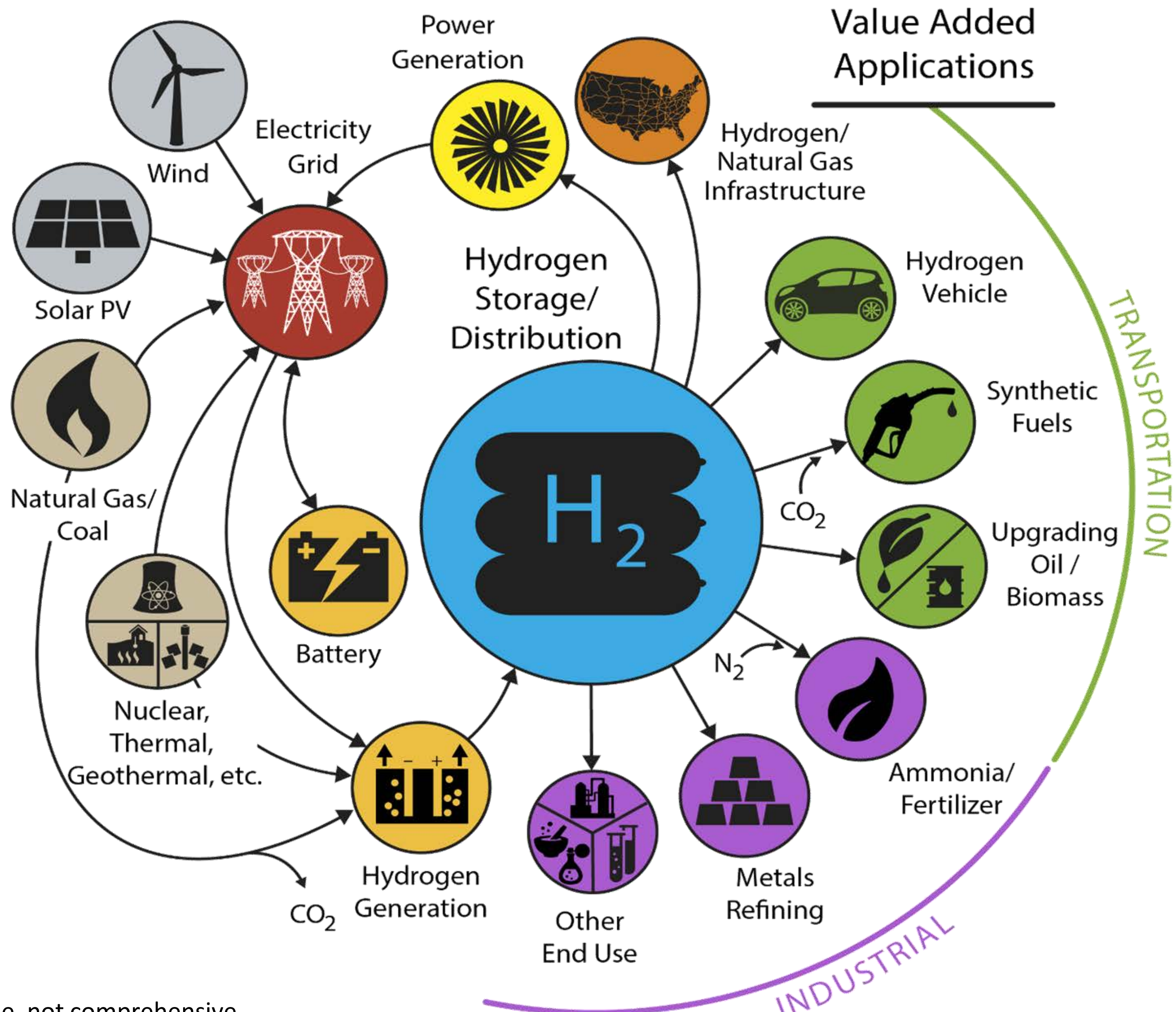


Potential Configuration for Liquid H_2 refueled, supercritical CcH_2 storage system in bus



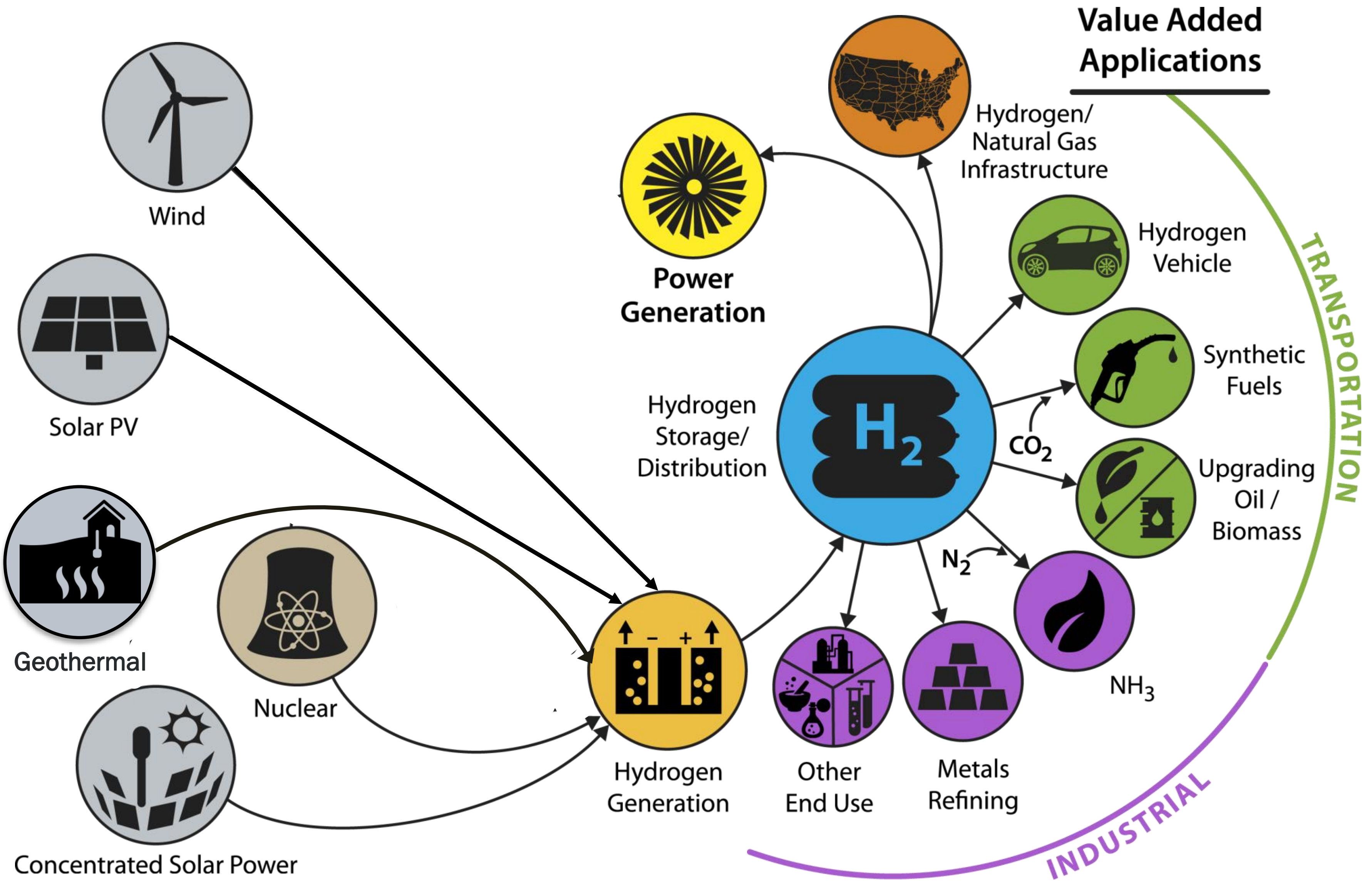
Source: DOE, ANL, Strategic Analysis (SA). Preliminary Results

H_2 at Scale Energy System



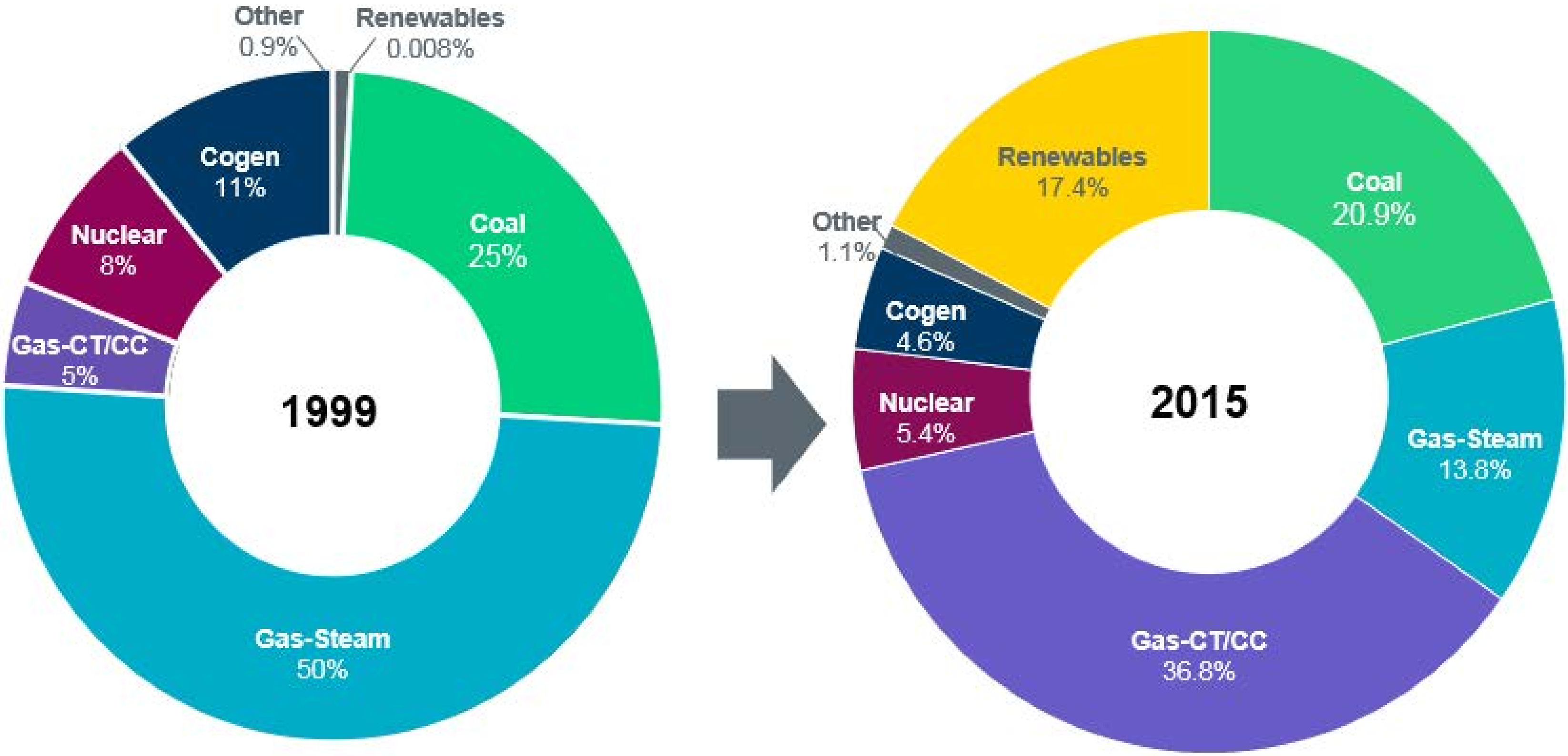
*Illustrative example, not comprehensive
Source: NREL

H_2 at Scale Energy System



Changing Energy Resource Mix for Electricity - Example

Installed Capacity in Texas



Source: ERCOT

Hydrogen Energy Storage is Scalable

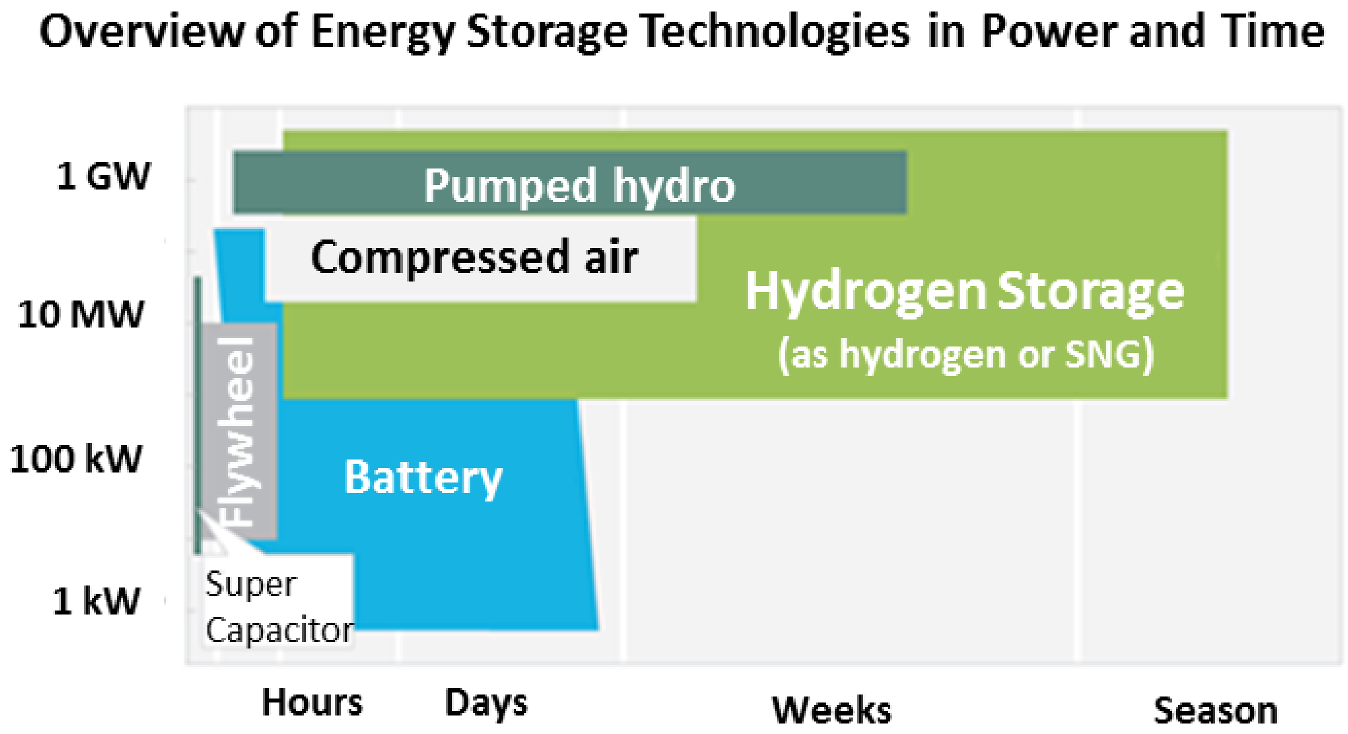


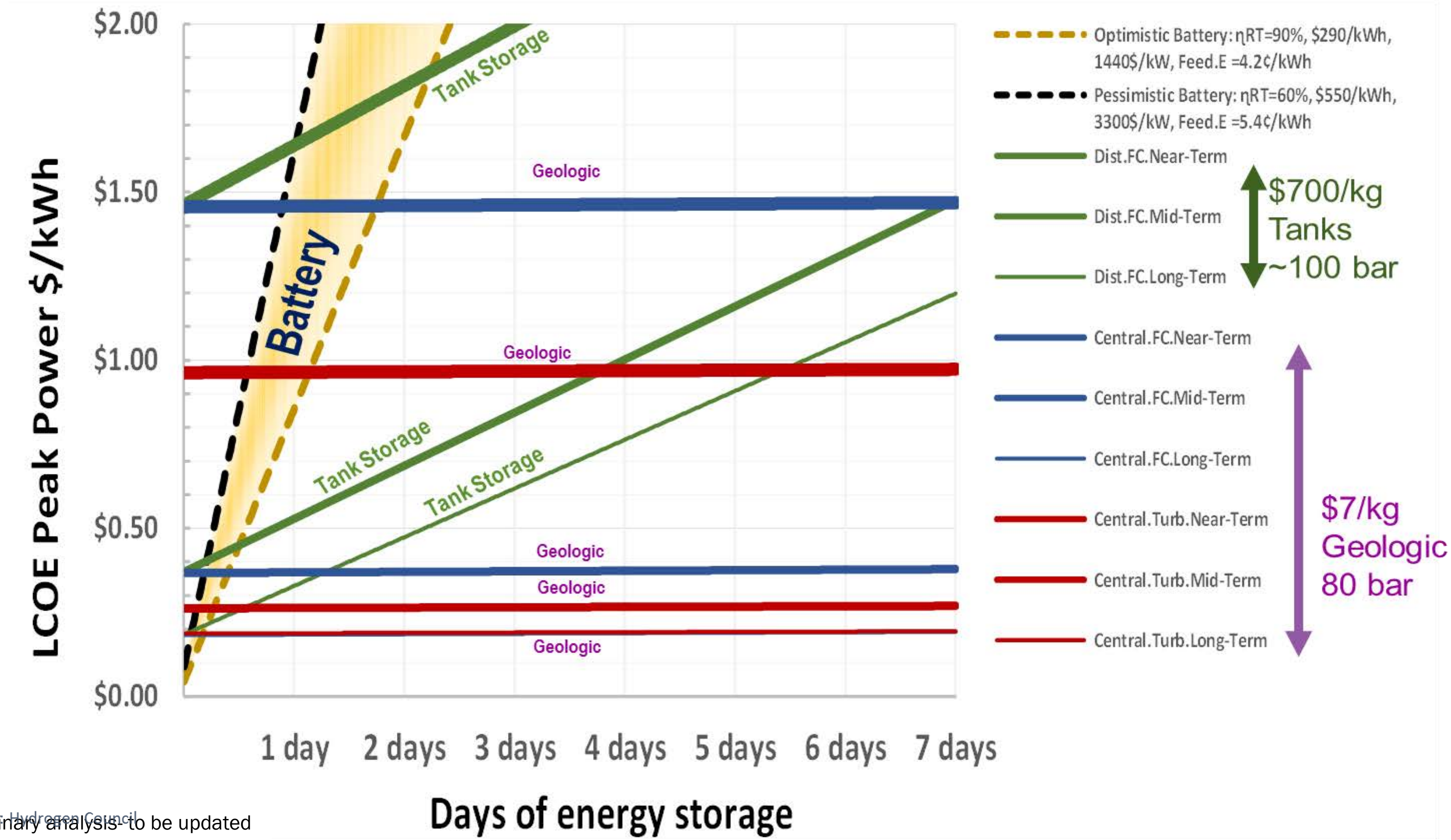
Image: Hydrogen Council

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

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.

Example of H_2 and Electrolyzer Benefits

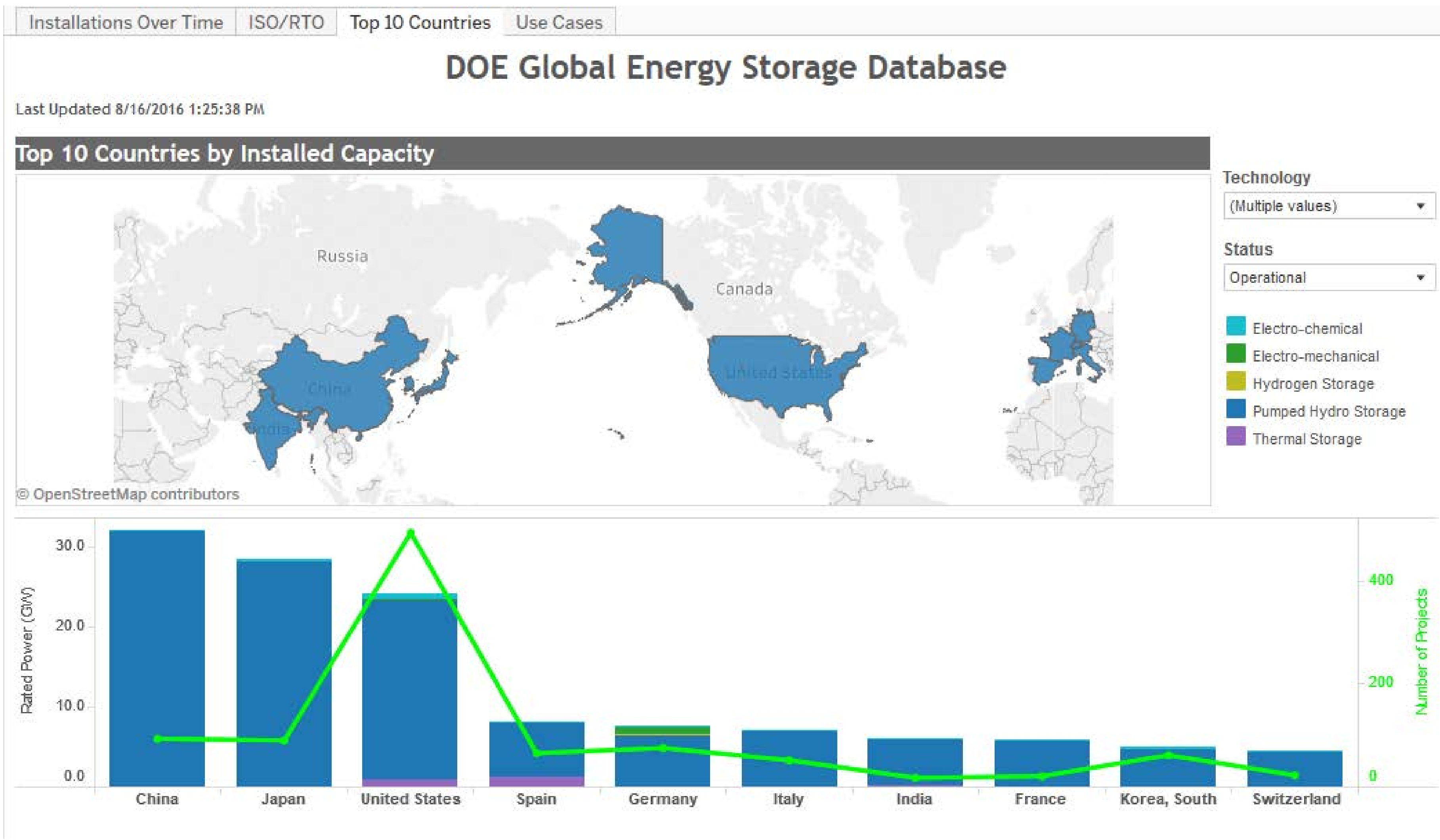
H_2 can be cost effective for long duration storage



Source: Hydrogen Council

Preliminary analysis- to be updated

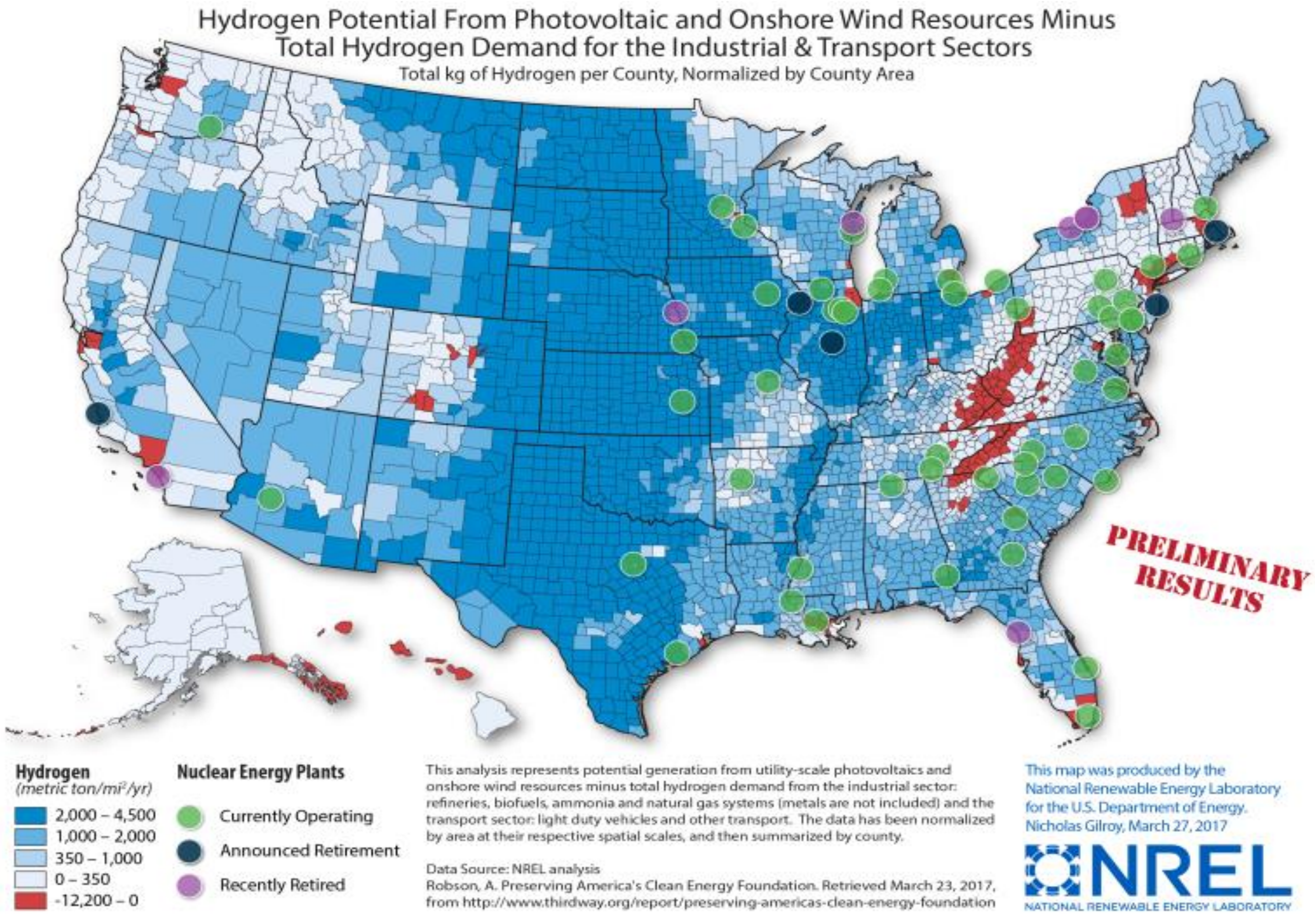
DOE Global Energy Storage Database



China and the U.S. in the lead: # GW and # of projects

Source: DOE Office of Electricity and Reliability

H2@Scale: Nationwide Resource Assessment



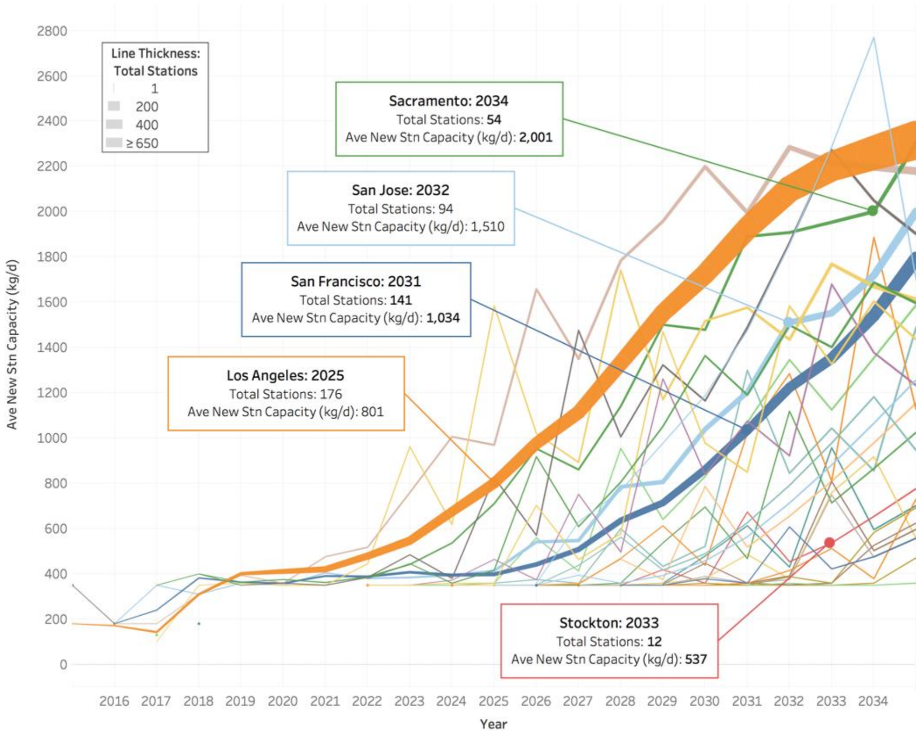
Lab PIs: Mark Ruth, Bryan Pivovar, Richard Boardman, et al

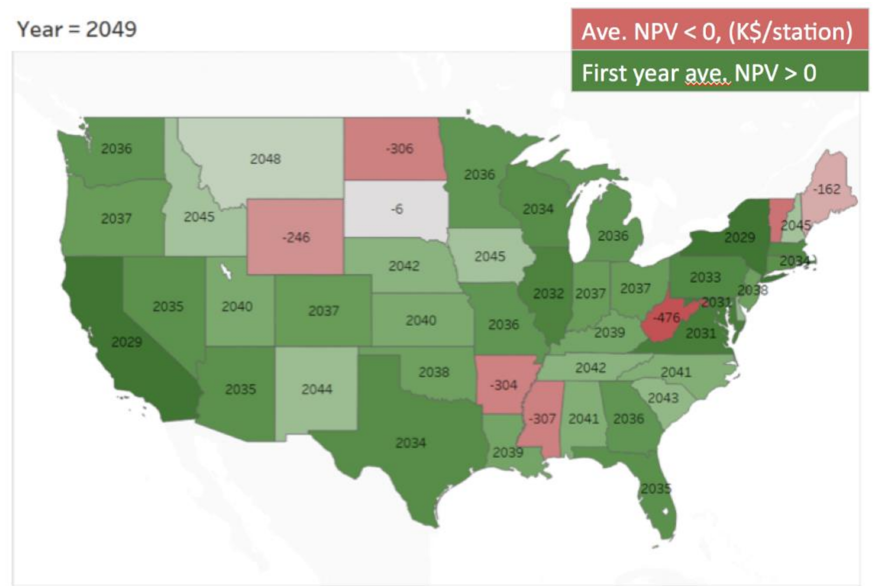
Labs assess resource availability. Most regions have sufficient resources.

Red: Only regions where projected industrial & transportation demand exceeds supply.

Analysis Examples

Finances are determined for individual stations, networks of stations within cities, states or regions, and for the entire United States





Station networks evolve at different rates and scale between urban areas

Simple representation of positive NPV for hydrogen stations in all U.S. states

Source: NREL, M. Melaina, et al

The Hydrogen Council formed in 2017

Investment	Estimated Impact
Over $10 billion	**$2.5 trillion**
towards hydrogen and fuel cells	in global revenues
Members	**30 million jobs**
	potentially created
Over 20 companies	**18% of total global**
Representing over $1.3T in revenues and 2M jobs	energy demand

More information: hydrogeneurope.eu

Collaboration and Resources

New Online Resources

Spread the word on
H_2 Safety Lessons Learned!

Share at regular team meetings

Provide feedback to FCTO and stakeholders

Find lessons learned at **H2tools.org**

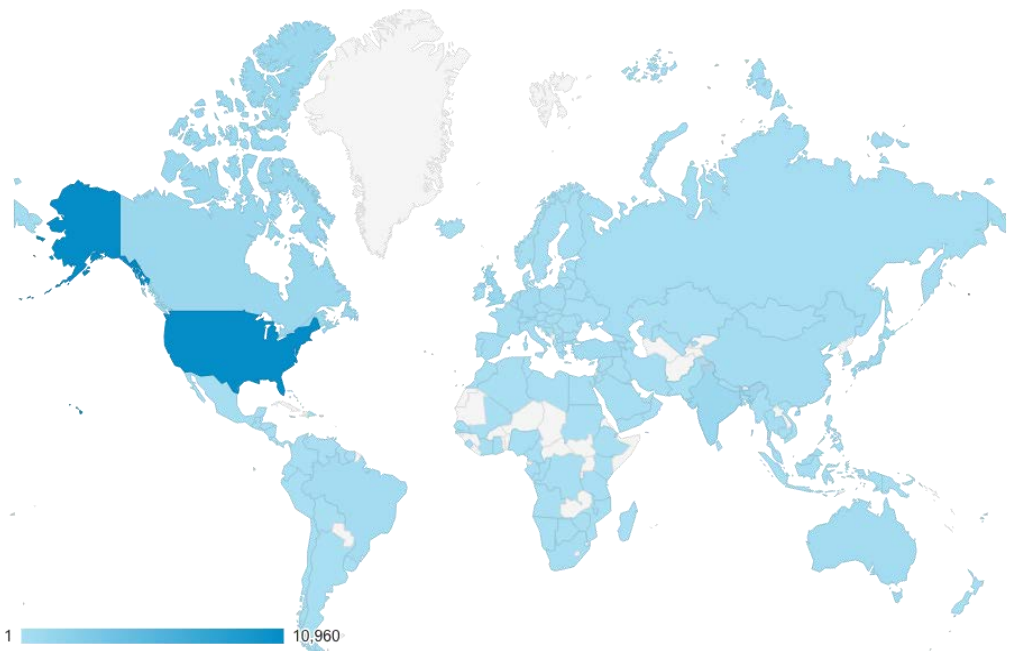
Safety Resources and Models Available

H2Tools.org disseminates information on hydrogen safety

A Global Resource

More than 150,000 visits since 2015 - 50% are international

Portions translated to Japanese, other languages underway



Hydrogen Risk Assessment Models (HyRAM) for risk analysis under various scenarios. Can be applied to develop:

- Conduct **Quantitative Risk Assessment (QRA)** to guide code requirements
- Assess **Liquid Hydrogen Separation Distances**

HyRAM HYDROGEN RISK ASSESSMENT MODELS

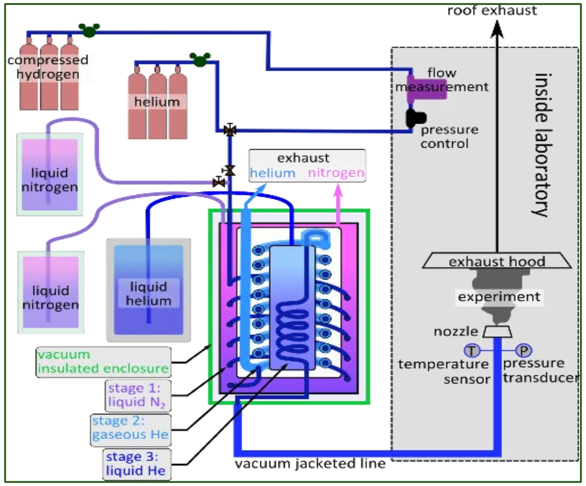
Hydrogen Behavior & Modeling

Leveraging science to enable infrastructure through understanding hydrogen behavior, analyzing risk, and implementing inherently safe design options

R&D to inform codes & standards development for both gaseous and liquid hydrogen.

- **NFPA-2:** Draft revised setback distances for **bulk gaseous hydrogen storage** systems with reductions that would have a significant impact on the number of potential sites for hydrogen fueling, focusing on three parameters:
  1. ***Maximum release area****:* currently, this value is 3%
  2. ***Heat flux harm criteria***
  3. ***Lower flammability percentage for hydrogen in air****:* currently 4%

- **Science-based approach for liquid hydrogen:** Developed cryo-temperature laboratory to validate liquid hydrogen models to enable risk assessment tools.



Data Sharing Opportunities

Data Validation of Real World Applications through the NREL's NFCTEC

- Data products provide insights on technology improvements, issues and gaps

NFCTEC: The National Fuel Cell Technology Evaluation Center

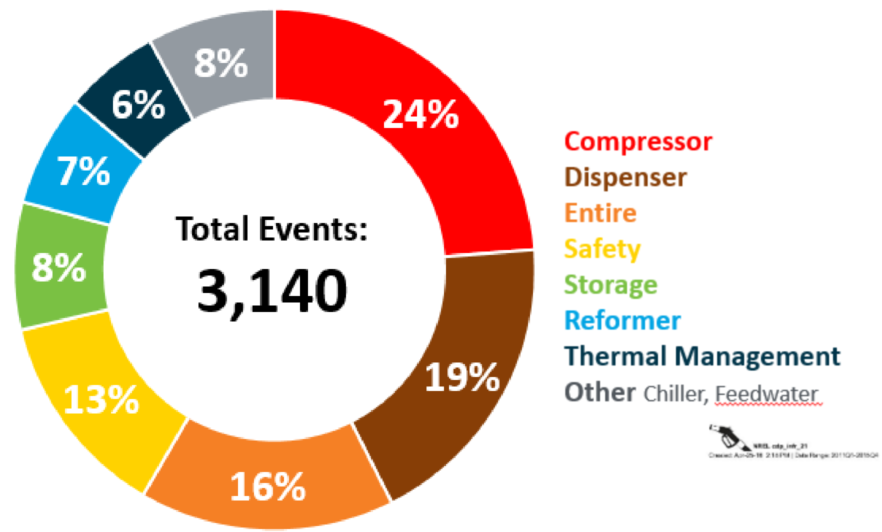
To Participate

techval@nrel.gov

Models "Toolbox" Online

- Financial, technical and economic models covering H_2 infrastructure, jobs, and more.
- Visit: **energy.gov/eere/fuelcells/hydrogen-analysis-toolbox**

Example: Sources of H_2 Infrastructure Maintenance



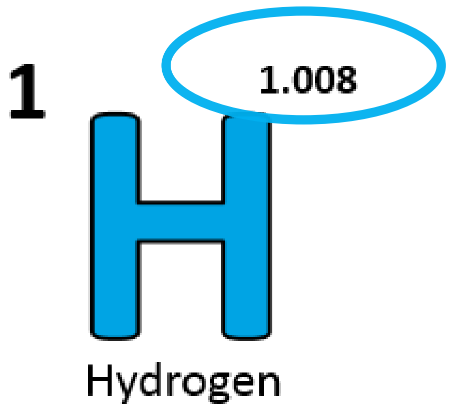
Most maintenance related to compressors and dispensers

Increasing Awareness

Celebrate Hydrogen & Fuel Cell Day

October 8 or 10/8

(Held on its very own atomic- weight-day)



Learn more:

energy.gov/eere/fuelcells

Save the Date

June 12-15, 2018

Annual Merit Review

Washington, DC

INCREASE YOUR H_2IQ

Download slide deck for free at at:

energy.gov/eere/fuelcells/downloads /increase-your-h2iq-training-resource

Powered by
Hydrogen Fuel Cells

Working Together

"It is literally true that you can succeed best and quickest by helping others to succeed"

Napoleon Hill

Thank You

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energy.gov/eere/fuelcells