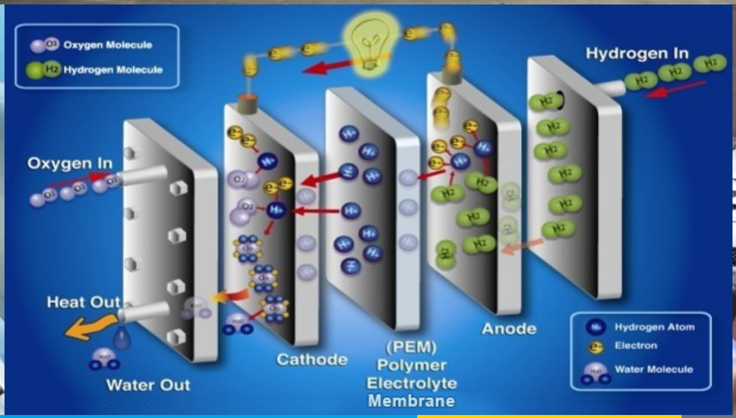
U.S. Department of Energy Fuel Cell Technologies Office

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy



Hydrogen and Fuel Cells Progress Overview

Houston, TX

May 23, 2017

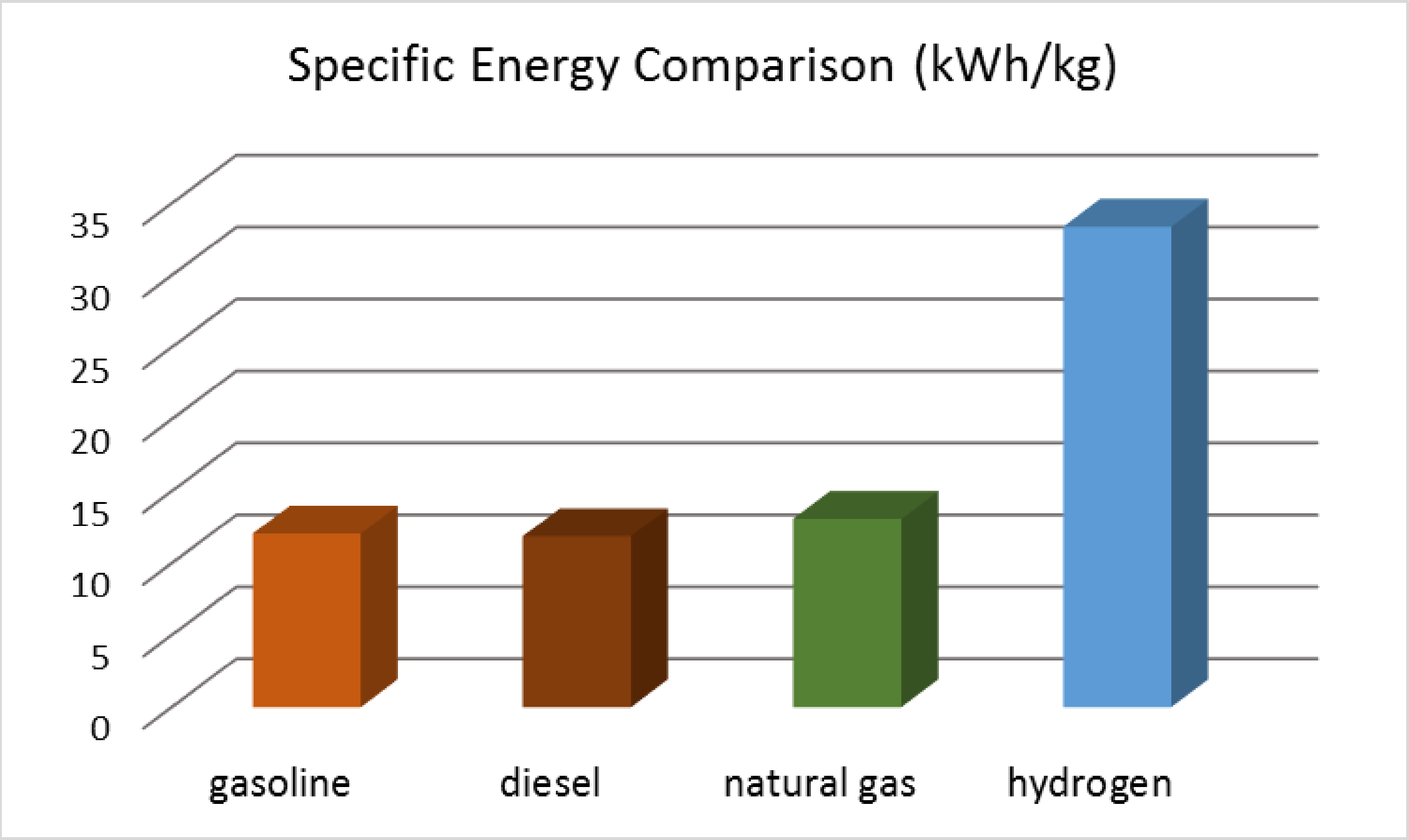
Dr. Sunita Satyapal

Director
Fuel Cell Technologies Office
U.S. Department of Energy

Napoleon Hill

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

Energy Content of Fuels 101

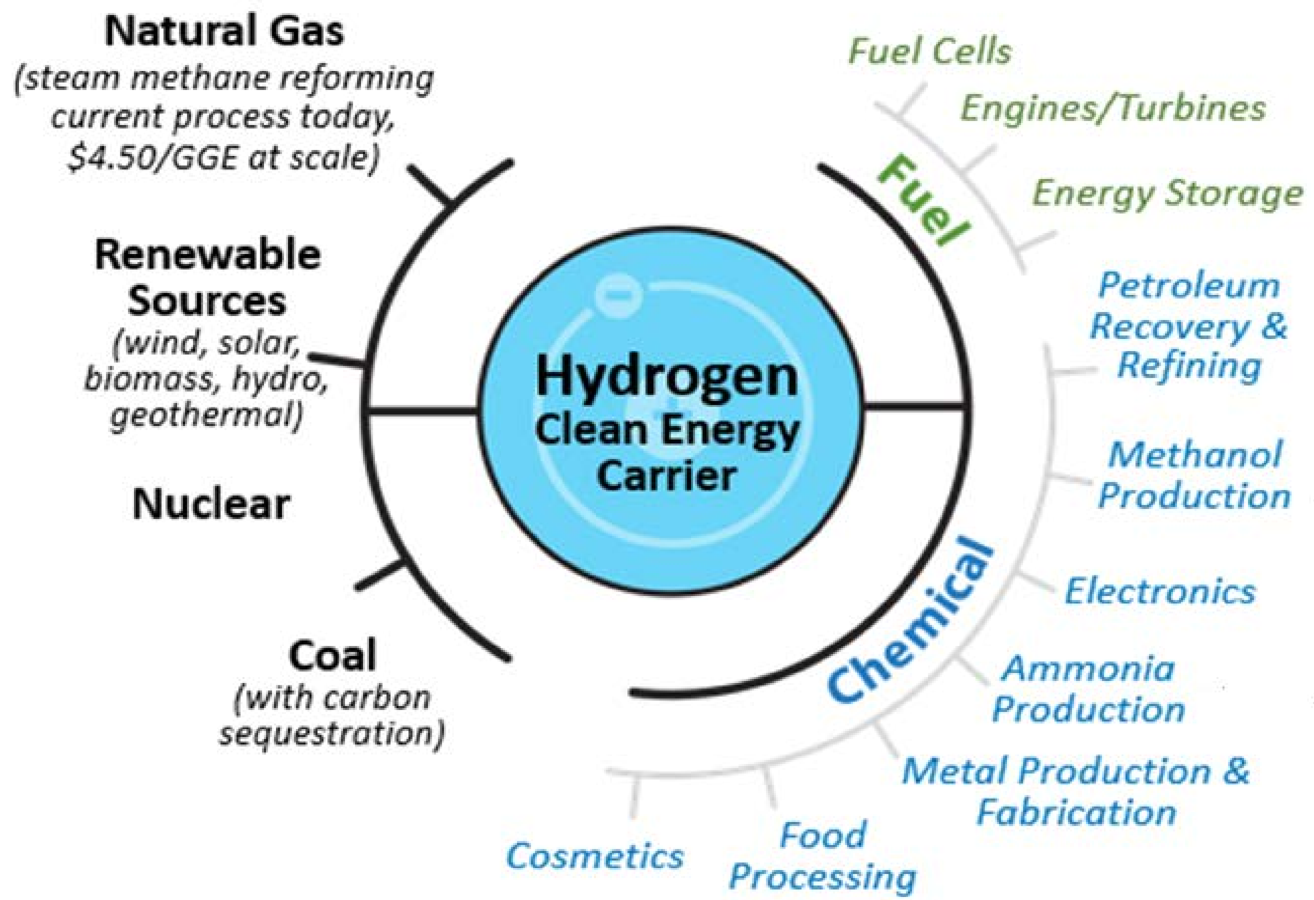


~ *Three times* more energy by mass than most other fuels but need higher volumes to store

Hydrogen- A Clean, Flexible Energy Carrier

Diverse domestic sources can be used to produce H_2

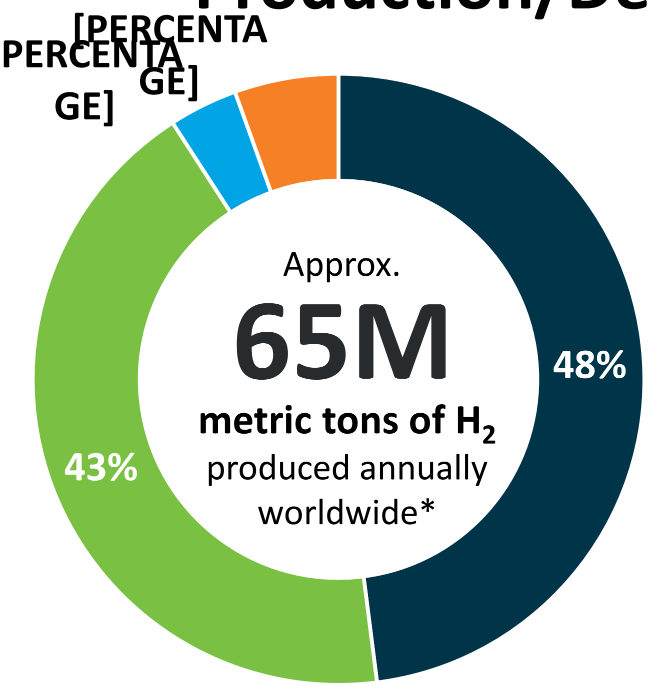
Many applications rely on or could benefit from H_2



Hydrogen is a versatile, clean, and efficient energy carrier

H_2 Production & Infrastructure: Current Status

Global Annual H_2 Production/Demand



Petroleum Refining

Ammonia Production

Methanol Production

Others including:

- Metal fabrication
- Electronics
- Food Processing

Steam methane reforming of natural gas (SMR): currently most cost-competitive process to produce H_2

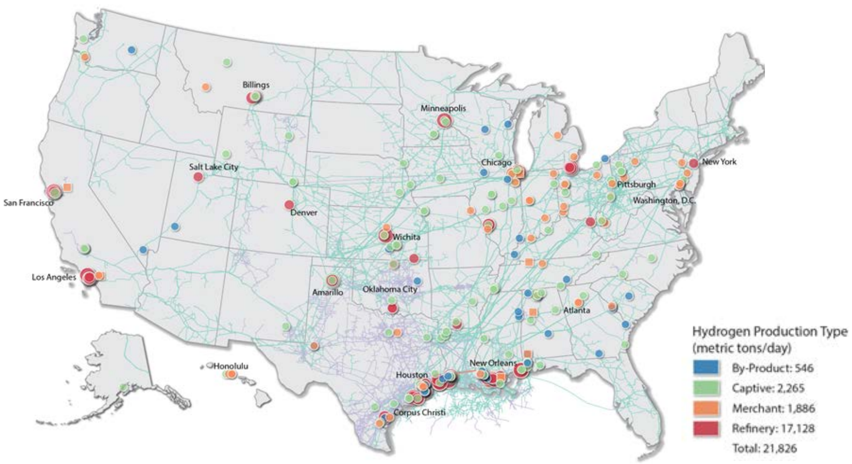
Source: Markets and Markets. Hydrogen Generation Market: Global Trends & Forecasts to 2019, 2014.

Current H_2 Infrastructure:

1,600 miles of H_2 pipeline

>50 H_2 Stations (27 public)

Centralized H_2 production facilities in the U.S.



Source: NREL

10 million metric tons of H_2 produced every year in the U.S.

Cost- Competitive H_2 Fuel

- **H_2 from Natural Gas** through SMR
- **At-scale** production
- **<$2/gge produced** (low pressure, at source)

The Beginning of the DOE Fuel Cell Program…

1970s | Government and industry stakeholders met at Los Alamos, 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.

Forty years later, for the first time in history….

Hyundai Tucson Fuel Cell SUV

Toyota Mirai

Honda Clarity

Commercial fuel cell electric cars are here!

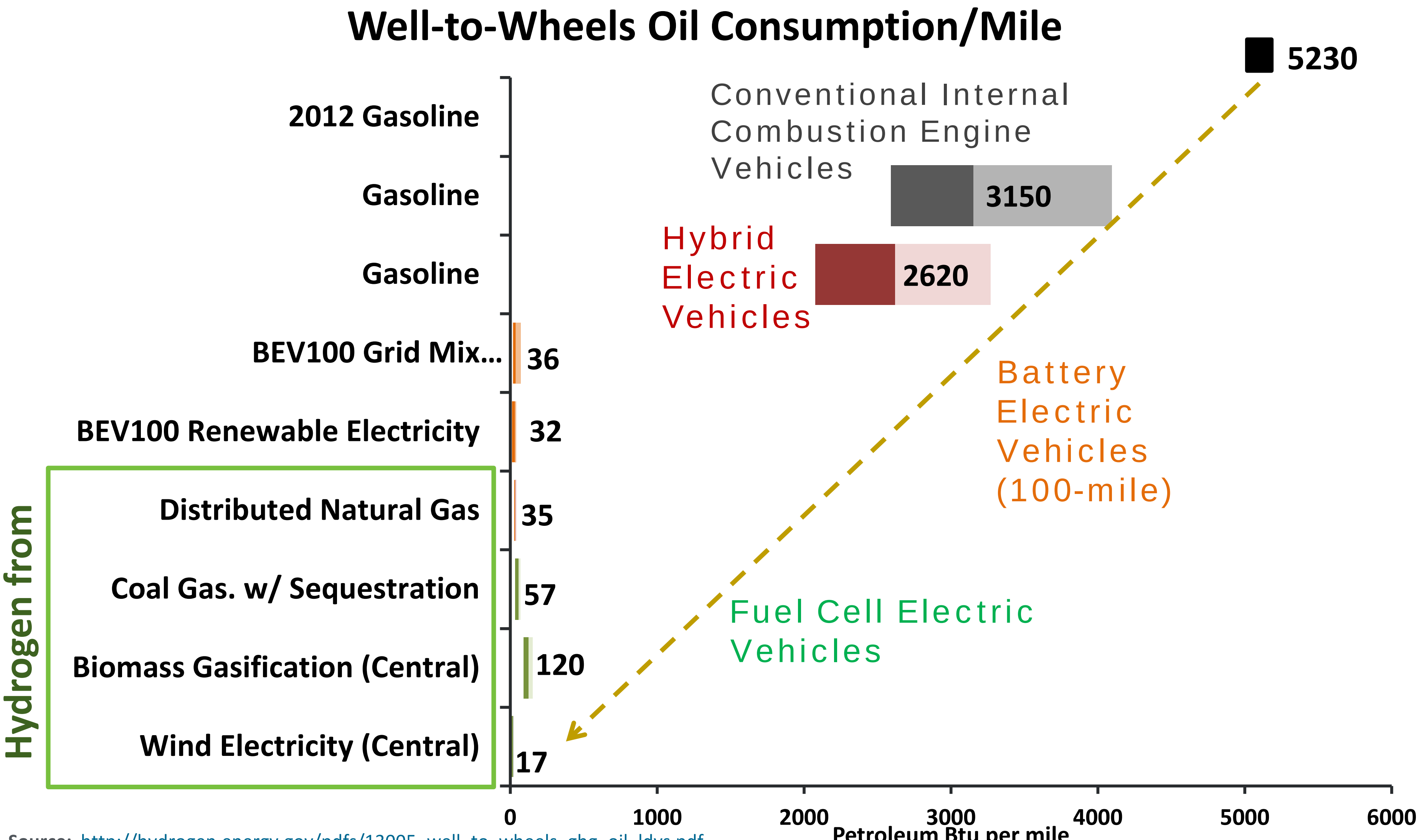
Power, performance, petroleum-free, pollution-free

Refuels in minutes

>360 mi driving range

>60 mpgge

Significant Oil Reductions with FCEVs



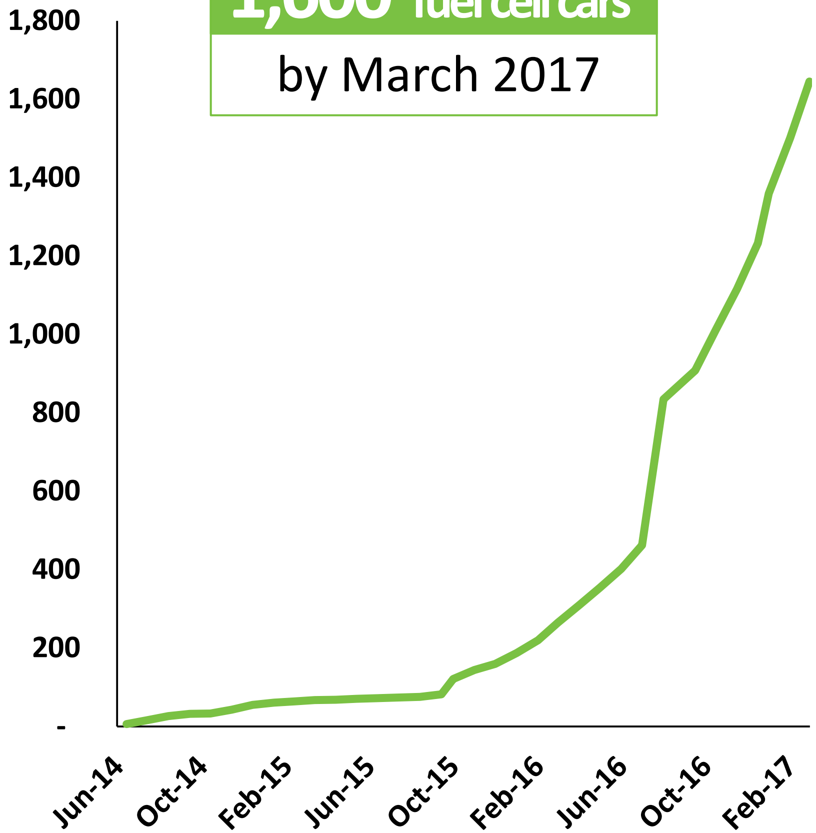
Source: http://hydrogen.energy.gov/pdfs/13005_well_to_wheels_ghg_oil_ldvs.pdf
Advanced 2035 technologies

If DOE targets are met, petroleum use by LDVs would decline by 80% by 2050.

Fuel Cell Car Sales and H_2 Stations on the Rise

U.S. Fuel Cell Car Sales Growing Exponentially

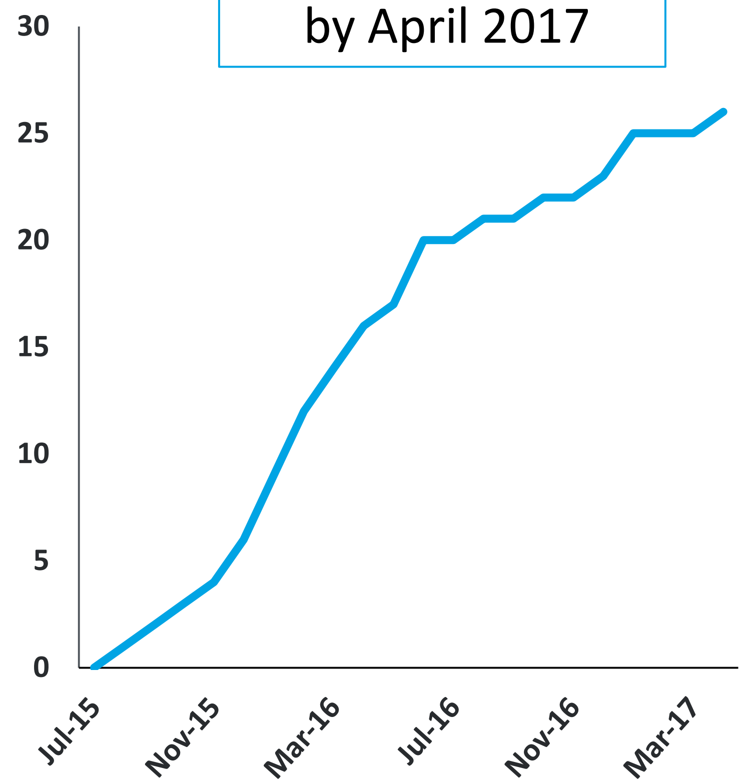
More than **1,600** fuel cell cars by March 2017



Note: Cumulative number of vehicles sold/leased. Source: hybridcars.com

Number of Retail H_2 Stations in CA Increasing

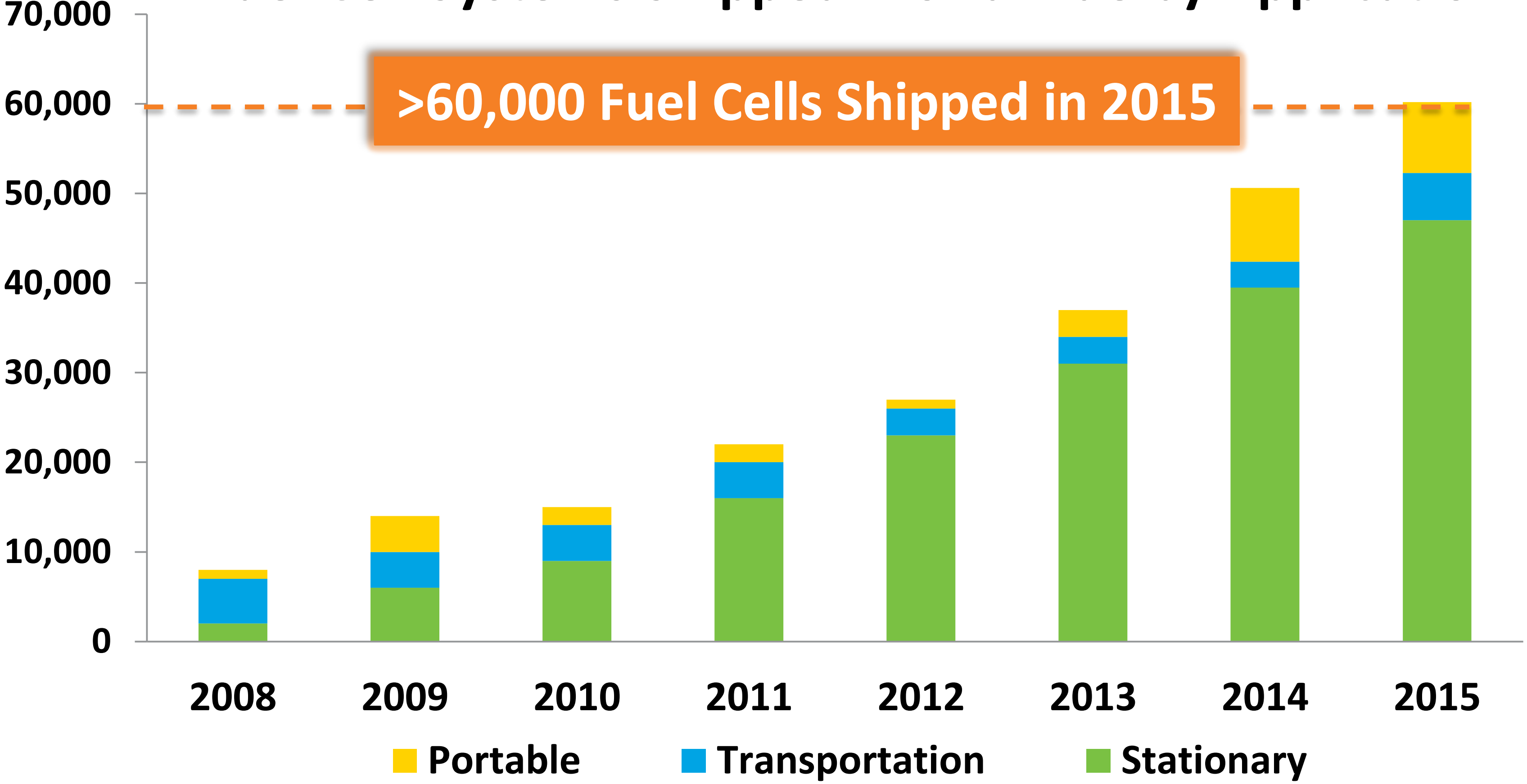
27 Retail H_2 stations by April 2017



Sources: CaFCP

Market Growth in Fuel Cells

Fuel Cell Systems Shipped Worldwide by Application



Capacity shipped **in 2015** → Approximately **300 MW** & **~2X** → the capacity **in 2014**

Source: Navigant Research (2008-2013) & E4tech (2014-2015)

Consistent ~30% annual growth since 2010

Stationary Fuel Cells- Opportunities Emerging

Data centers require non-stop electrical power

Reliable power is vital at hospitals

Supermarkets- growing interest for reliable power

Fuel Cell Stationary Power in the U.S.

Installations

More than
235 MW
in at least
43 states

Top States

- **By unit size:** DE (30 MW) and CT (14.9 MW)
- **By number of units** CA (480 systems)

Source: DOE Fuel Cell Technologies Office. State of the States Report (2016)

New World Trade Center using fuel cells

Fuel Cells: Recent Highlights

Over 10,000 fuel cell forklifts
~ 5 million H_2 refuelings

Fuel cell buses surpass 15M passengers

Industry demonstrates first heavy duty truck

ZH2: U.S. Army and GM collaboration
First of its kind

Fuel Cells: Emerging Applications

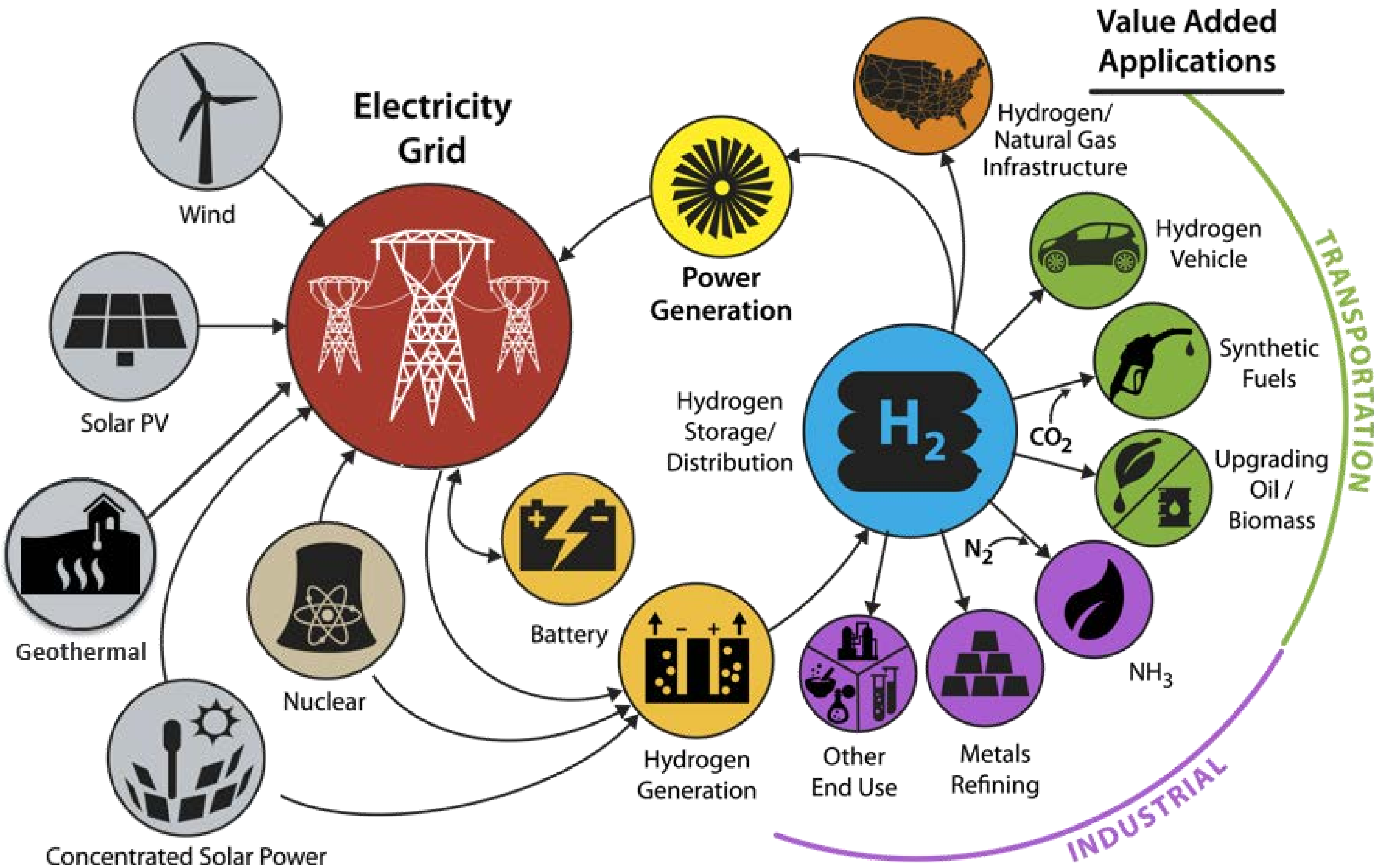
World's first hydrogen fuel cell train in Germany

First fuel cell cargo truck at U.S. airport

World's first fuel cell for maritime ports

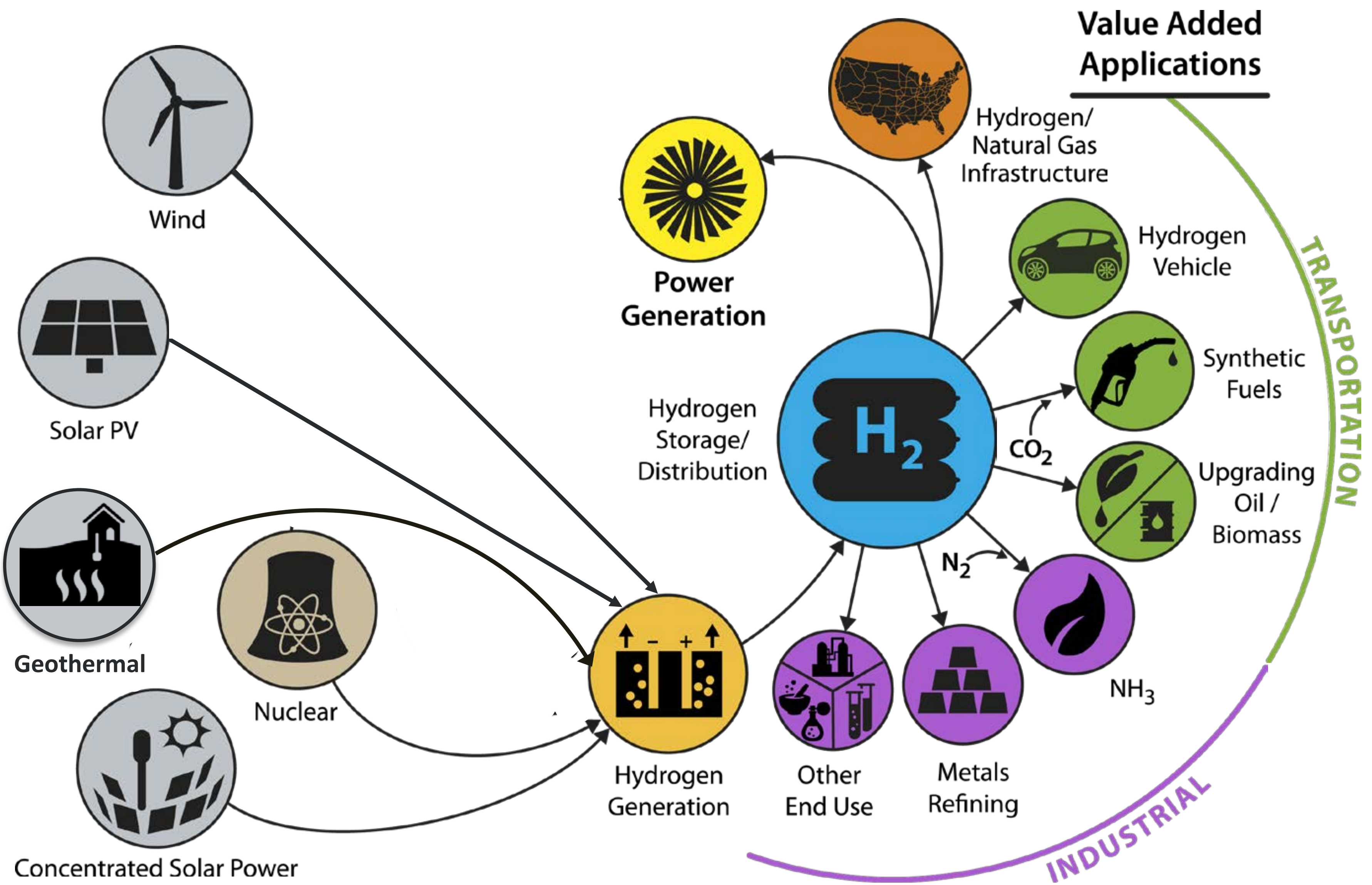
Fuel cell powered lights at Super Bowl

Conceptual H2 @ Scale Energy System



*Illustrative example, not comprehensive
Source: NREL

Conceptual H2 @ Scale Energy System



The Hydrogen Council: A Global Initiative

Launched in 2017

Position **hydrogen among the key solutions** of the energy transition at a global level by:

- **Showcase hydrogen technology and benefits** to the world
- **Accelerate investment** in the industry
- **Engage key stakeholders**

Formed by 13 companies

Air Liquide (co-chair) | ALSTOM | AngloAmerican | BMW GROUP
DAIMLER | ENGIE | HONDA | HYUNDAI
Kawasaki | Shell | THE LINDE GROUP | TOTAL | TOYOTA (co-chair)

Revenues of >$1 Trillion and 1.7 Million Jobs*

Commitment

$10.7 Billion

in the hydrogen and fuel cells

More information: [Hydrogen Empowers the Energy Transition- 2017 Report](http://hydrogeneurope.eu/) (http://hydrogeneurope.eu/)

* Indicates total number of employees working at member companies.

How much H_2 is needed for 100M FCEVs?

How much hydrogen for 1 car?

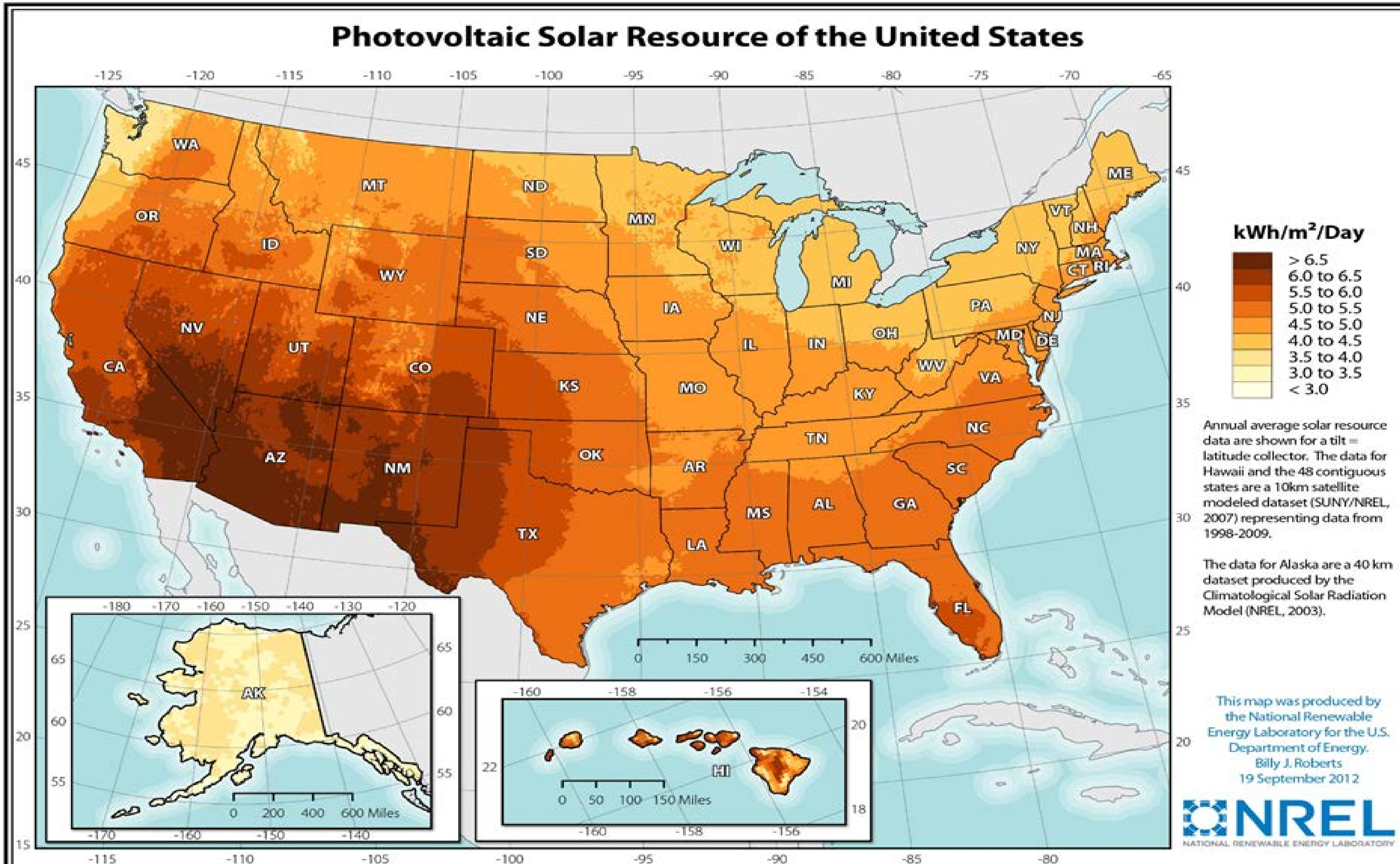
$$\frac{\textbf{12,000 miles per year}}{\textbf{60 miles per kilogram}} = \textbf{200 kg per year or 0.2 tonnes per year}$$

How much hydrogen for many cars?

1 M cars	0.2 M tonnes H_2 per year 200 M kg H_2 per year
(car icon) = 100,000 cars	

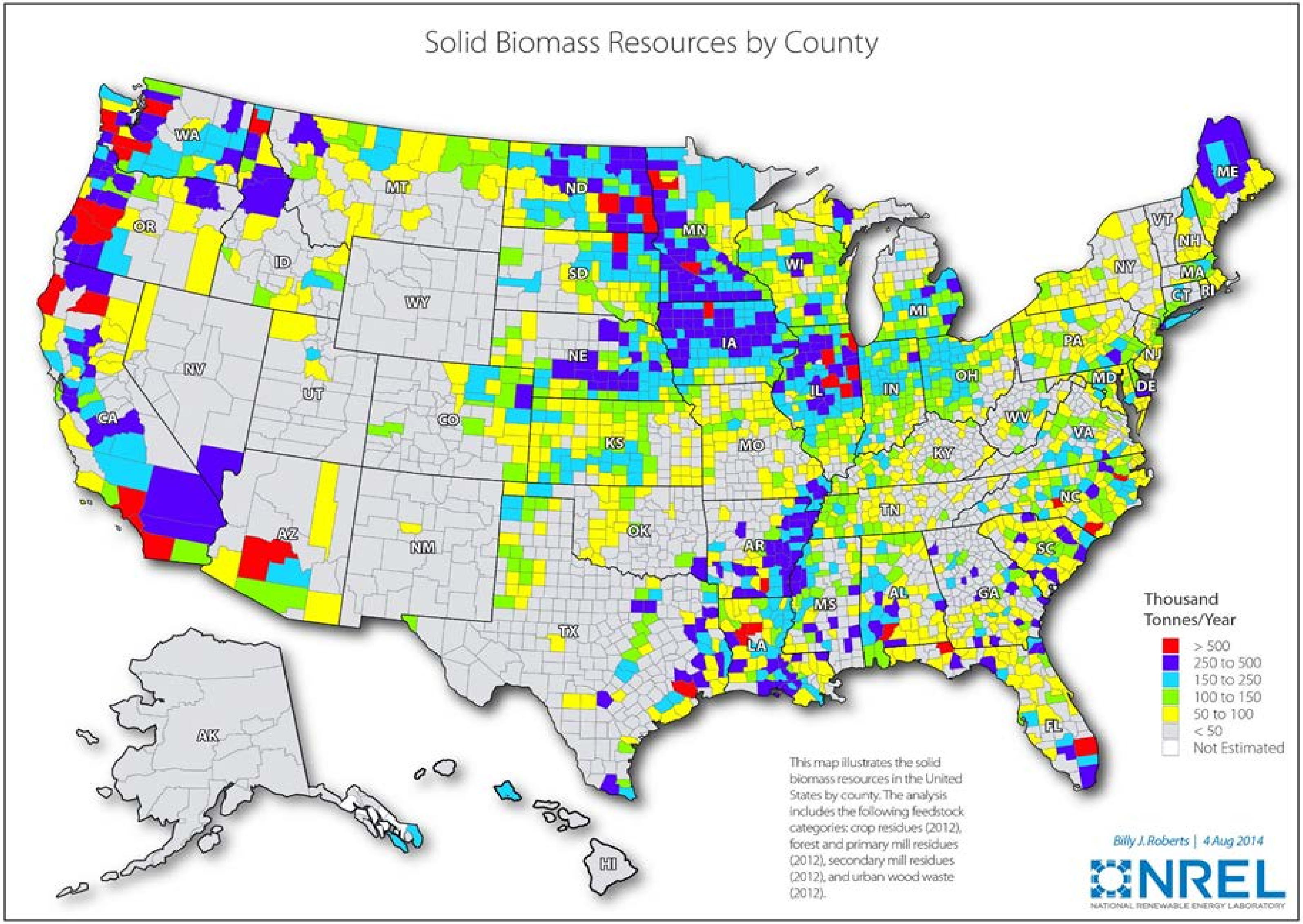
100 M cars	20M tons H_2 per year 20 B kg H_2 per year
(car icon) = 10M cars	

Solar Sources: Opportunity for Renewable H_2



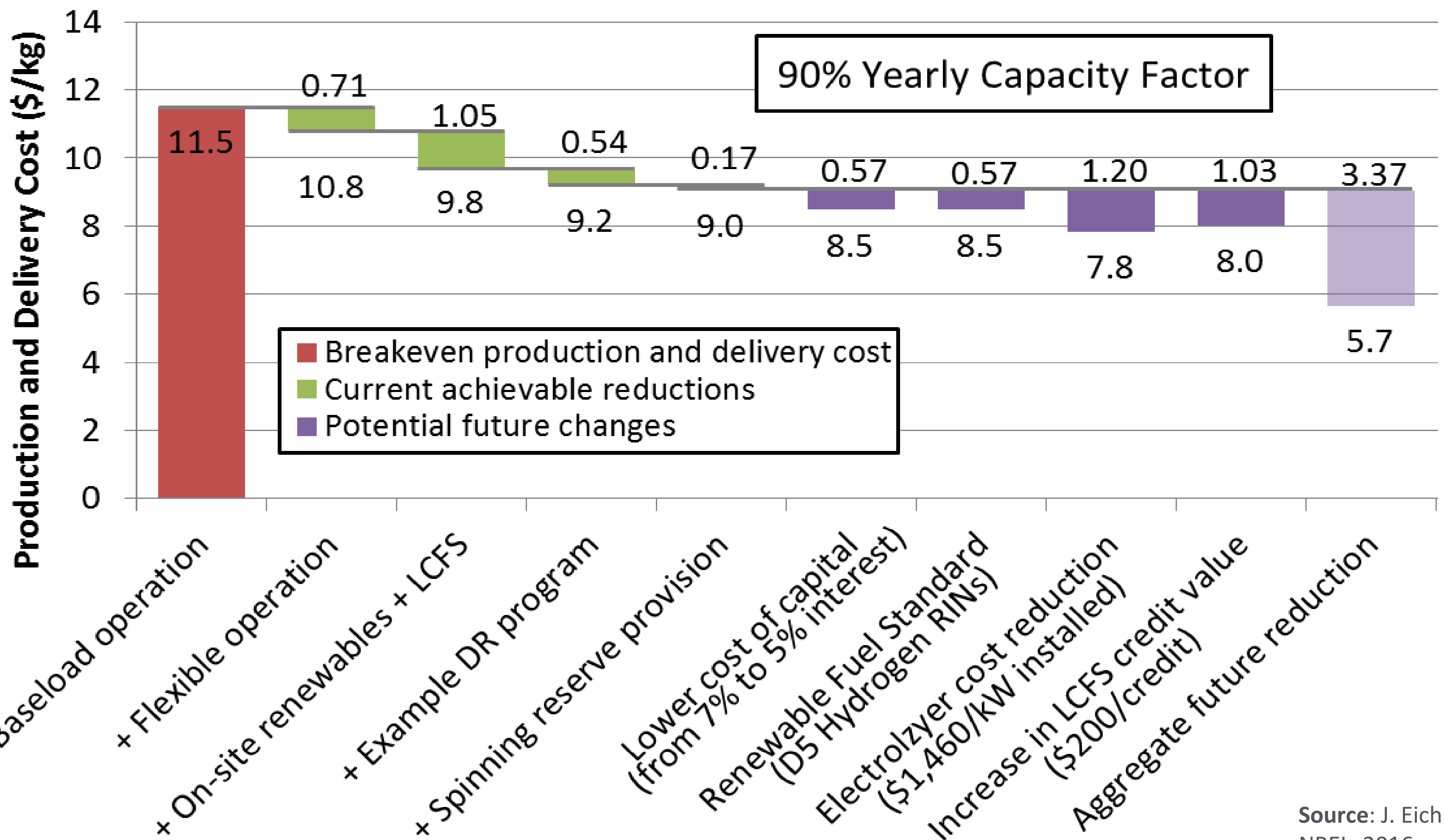
Analysis being updated for hydrogen resource availability

Biomass Resources: Opportunity for Renewable H_2



Bio-feedstock reforming is a near term option

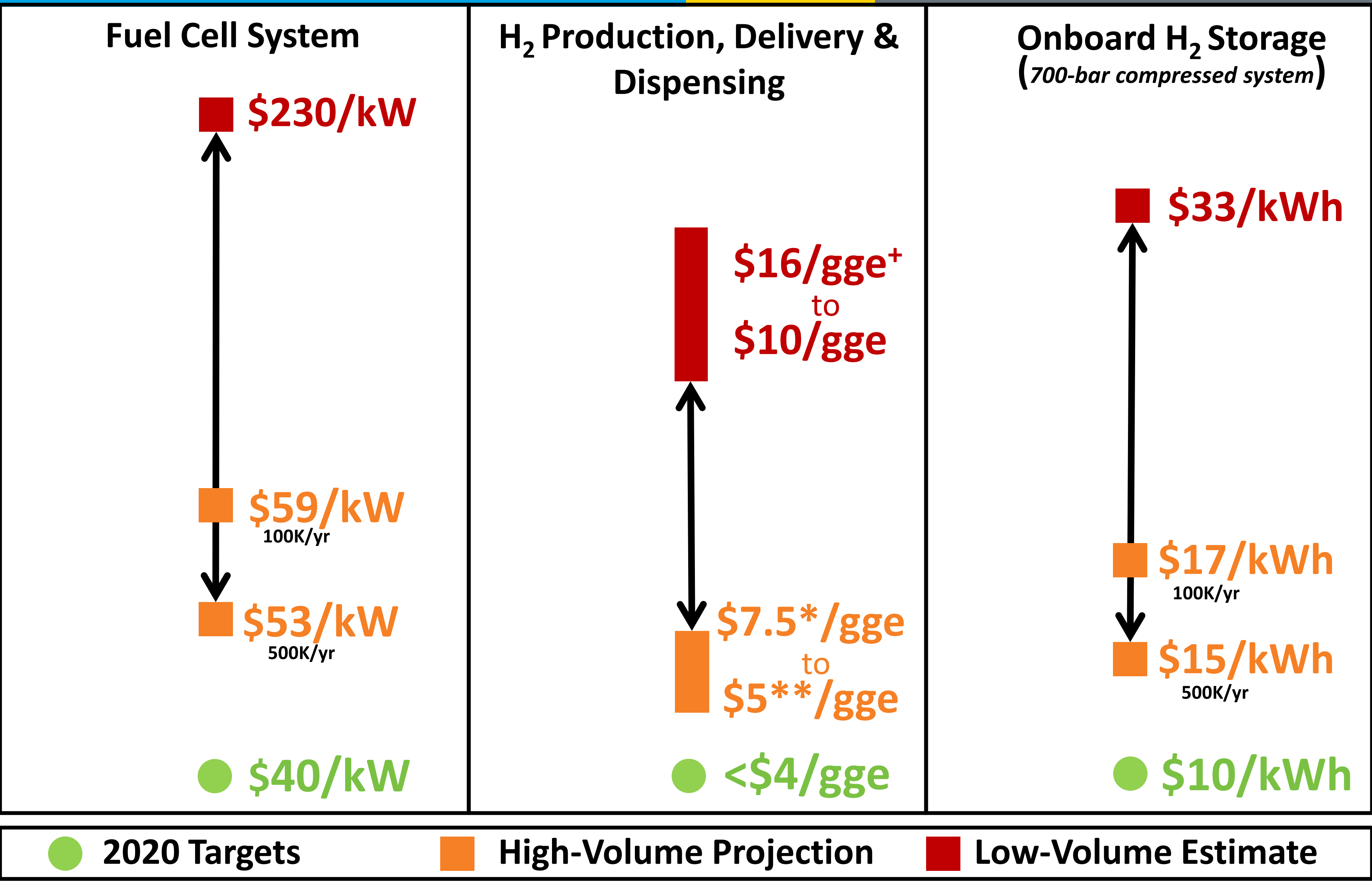
Business case assessment for electrolytic H_2 production



Source: J. Eichman, NREL, 2016

Integration with the electric grid, capital cost reductions and credit market opportunities help provide a path to low cost H_2

DOE Cost Status and Targets

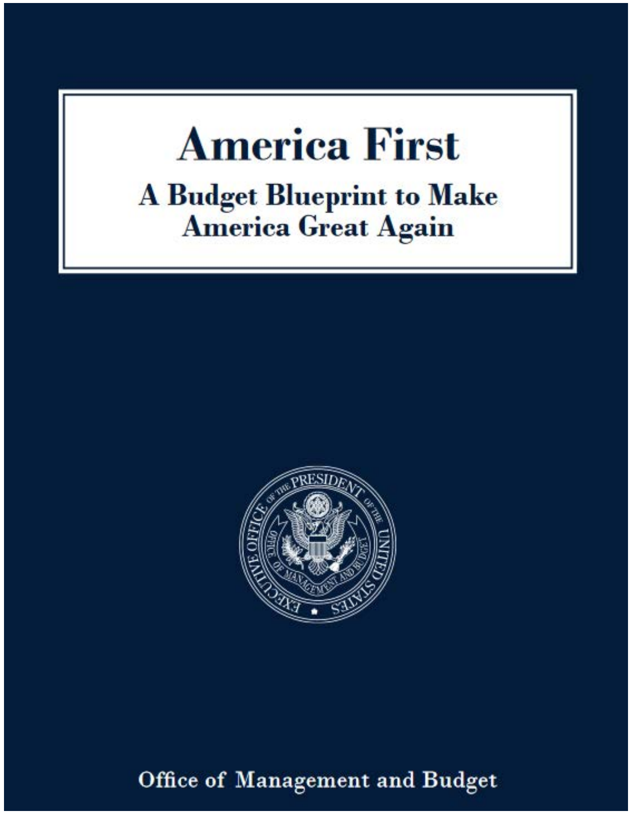


*Based on Electrolysis **Based on NG SMR + Preliminary, updates underway

*For illustration purposes only, not drawn to scale

- Former Governor of Texas **Rick Perry sworn in as the Energy Secretary** on March 2

- White House **budget proposal released**
  - "…reflects an **increased reliance on the private sector to fund later-stage research, development, and commercialization** of energy technologies…"
  - "… **focuses resources toward early-stage research and development.**"



WH Budget Blueprint released on March 16

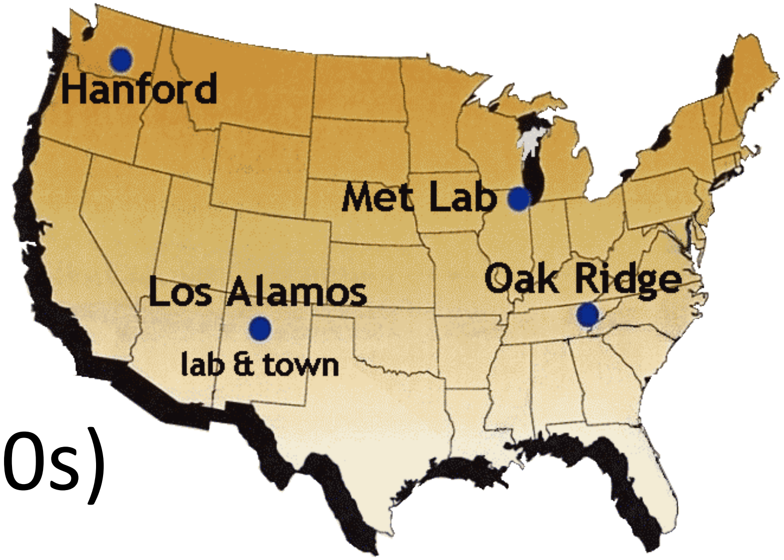
Collaboration

is

Critical

The Beginning….

- DOE founded the National Laboratory system in the 1940s.
- The war effort motivated breakthrough scientific work
  - Manhattan Project
  - Development of Radar
- DOE invested a few $M ('40s) to today ~ $10B



Places of the Manhattan Project

Examples of Lab Innovations

Modern water-purification techniques

Resilient passenger jets

Supercomputers

Fluorescent lights

Satellite technology

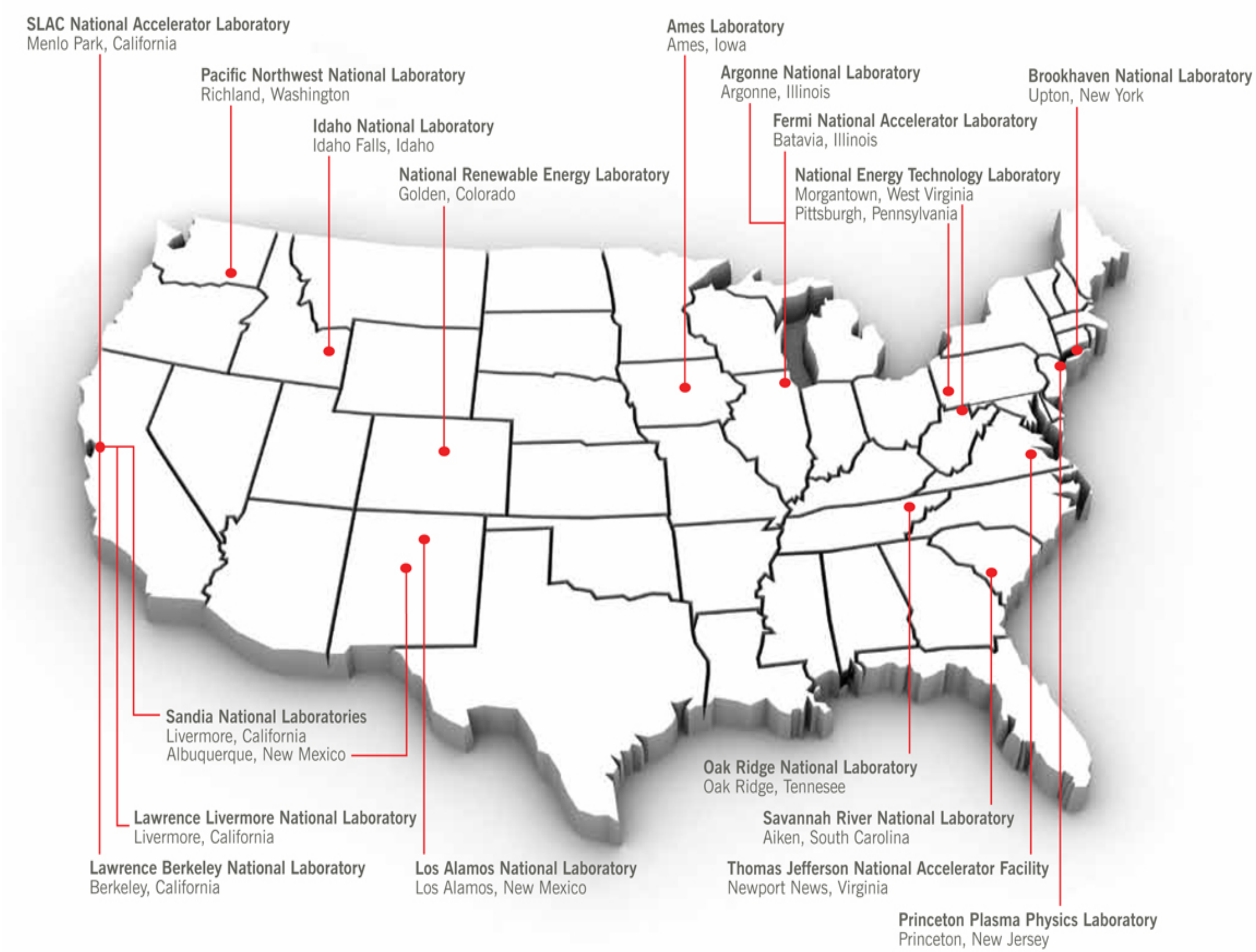
Advanced batteries

Better cancer therapies

Optical digital recording technology

DOE Labs: A Reservoir of Talent for Science and Technology

Where in the US?



Graphic taken from "A Decade of Discovery" DOE. 2008

How Many?

17 Facilities

- 10 Office of Science
- 3 NNSA
- 1 Nuclear Energy
- 1 Fossil Energy
- 1 Energy Efficiency and Renewable Energy
- 1 Environmental Management

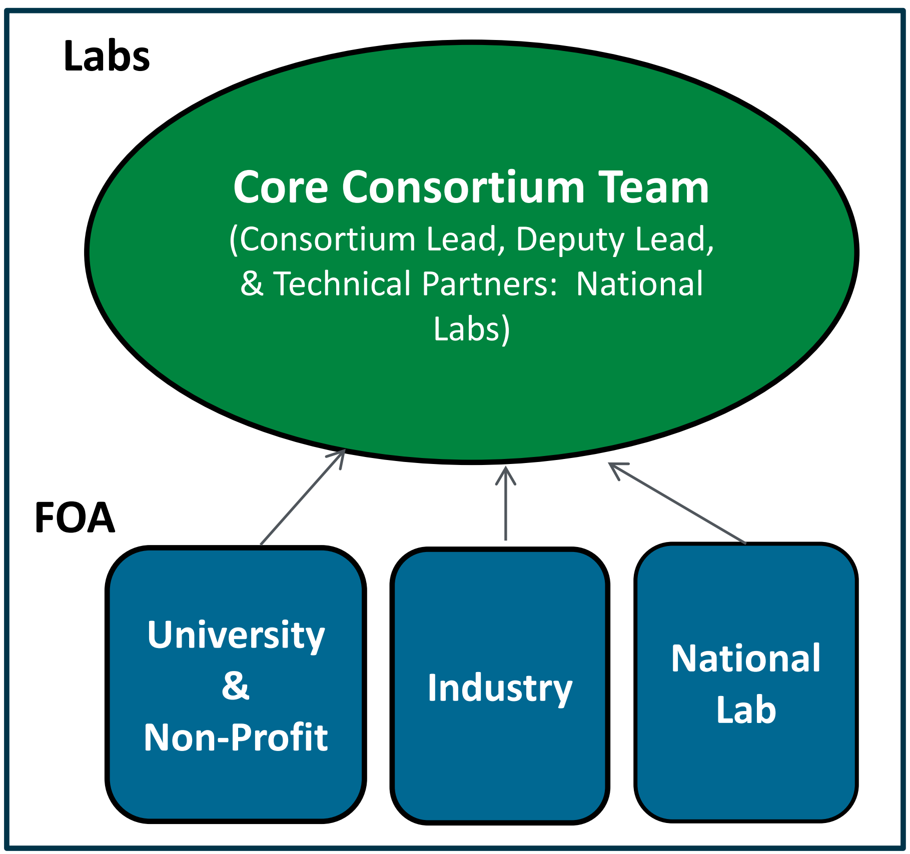
~ 66,000 Total Employees

Over 50 Nobel laureates affiliated with DOE Labs

R&D Addressing Needs: Materials (Example)

Consortium Approach

Multi-lab core capabilities with steady influx of new partners



Consortia Launched

Improved PEM fuel cells

FCPAD – FUEL CELL PERFORMANCE AND DURABILITY

PGM-free catalysts

ElectroCat – Electrocatalysis Consortium

Advanced H_2 materials storage

HyMARC – Hydrogen Materials Advanced Research Consortium

Materials for renewable H_2 production

HydroGEN – Advanced Water Splitting Materials

Other Lab Capabilities (Examples- Draft)

Modeling and Analysis

Examples

- Value proposition
- Demand/market projection
- Cost/benefit, financial and application evaluation
- Scenario analysis
- Resource assessment

Labs

Argonne National Laboratory, NREL National Renewable Energy Laboratory

H_2 – Materials Compatibility R&D

Examples

- H_2 materials exposure effects testing
- Materials selection and innovation

Labs

Oak Ridge National Laboratory, Sandia National Laboratories, SRNL Savannah River National Laboratory, Pacific Northwest National Laboratory

Simulation and Testing

Examples

- Grid simulation
- Electrolyzer performance testing
- Model Validation

Labs

INL Idaho National Laboratory, NREL National Renewable Energy Laboratory, Pacific Northwest National Laboratory

Safety R&D

Examples

- Hydrogen behavior assessment
- Safety training and outreach
- Certification/permitting
- Quantitative risk assessment
- Safety testing and model validation
- Project/Facility safety review

Labs

Sandia National Laboratories, Pacific Northwest National Laboratory

H_2 safety panel

Example:
ORNL Materials Characterization Core (MCC)

Materials Characterization Capabilities

Transmission Electron Microscopy

Electron Probe Microanalysis

Scanning Electron Microscopy

Focused Ion Beam

X-ray Photoelectron Spectroscopy

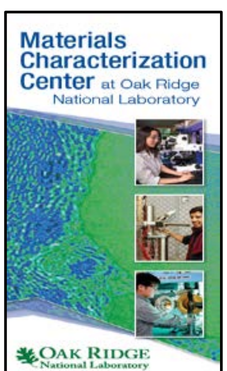
Future Additions
- Time-of-Flight SIMS
- Nuclear Magnetic Resonance (NMR)
- X-Ray Diffractometer (XRD)

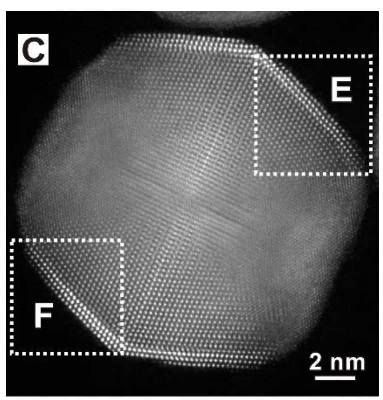
Examples of Applications and Industries

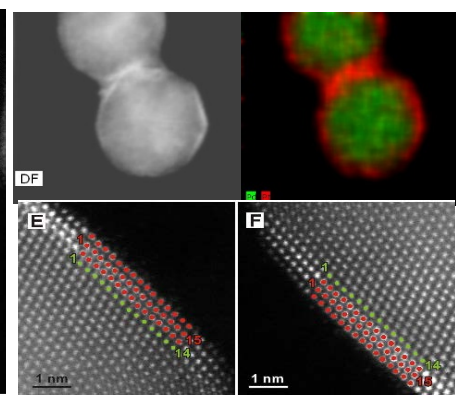
Catalysts, alloys, films/interfaces, polymers, coatings, high temp. materials *(e.g.. 1000 °C in situ XRD),* **etc.**

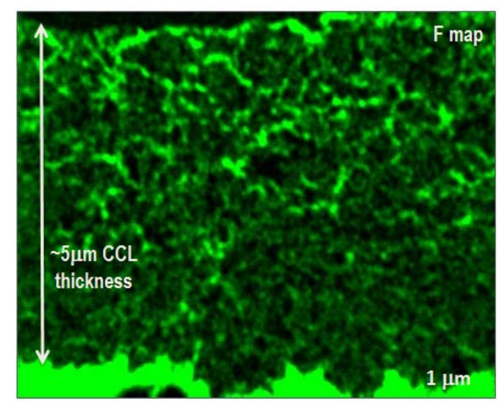
Fuel cells, compressors, motors, seals valves, sensors, batteries, heat exchangers, etc.

Renewables, Energy Efficiency, Oil & Gas, Nuclear









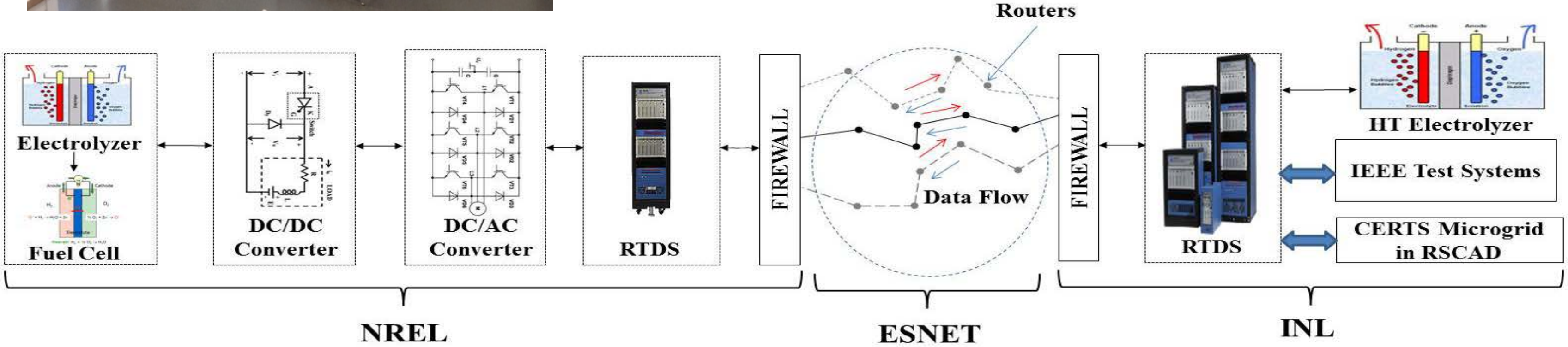
For more information contact Karren More (morekl1@ornl.gov)

R&D Addressing Needs: Integration (Example)

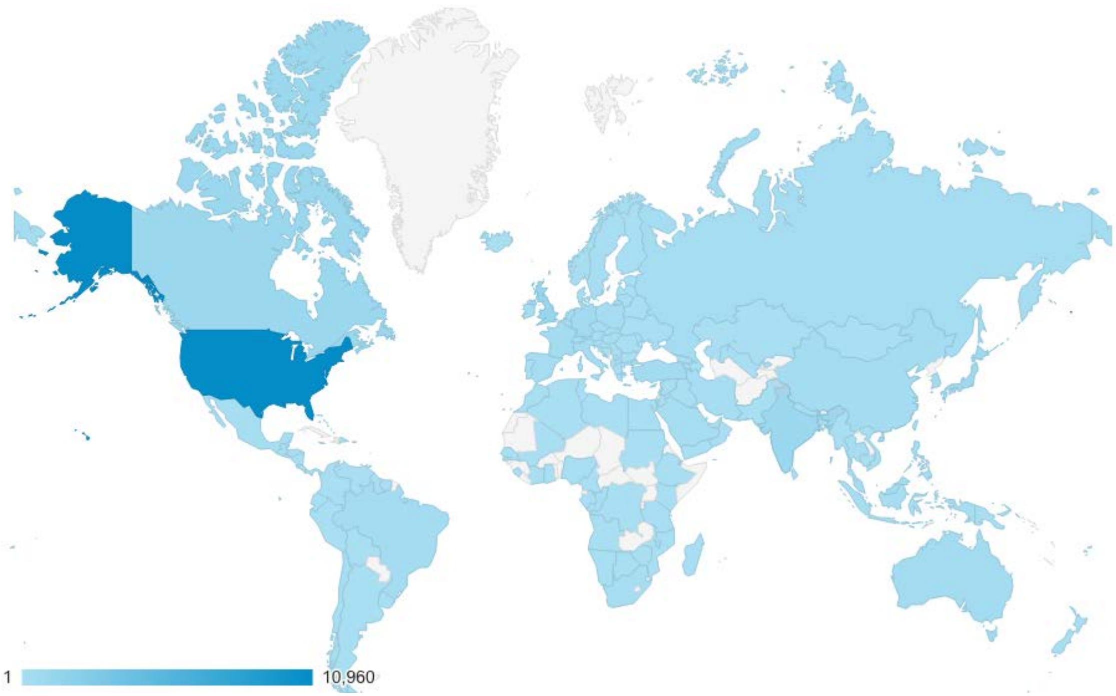
To characterize **cost value and impact of integrating electrolyzers with electric grids** that serve hydrogen fueling station networks in various regions of California and the Northeast.

NREL

INL



H_2Tools: One-stop for H_2 safety knowledge



- Includes resources on **safety** best practices, **first responder training**, and **H_2 codes & standards**
- **Educated >36,000 code officials and first responders**

- **50%** of visits are **international**
- Over **150,000 site visits** since 2015
- Training resource **translated into Japanese**

Enabling dissemination of safety information around the world

Summary of DOE Activities

- ✓ Lab Big Idea Summit
- ✓ Stakeholder Engagement- Workshops, Request for Information
- ✓ Analysis Task Initiated
- ✓ Initiate Roadmap Development
- ✓ Grid Simulation and Testing

Next Steps

- Complete Roadmap
- Identify and prioritize efforts
- Annual Merit Review (June 5, June 9)
- CRADA Call

H2@Scale requires collaboration across stakeholders!

Save the Dates!

2017 AMR
June 5-9
Washington, DC

National **Hydrogen** & **Fuel Cell** Day | 10·08
Participate in social media using
#HydrogenNow #FuelCellsNow

2017 Fuel Cell Seminar
November
Long Beach, LA

Summer 2018:
AMR and Industry Expo
Washington, DC

Workshop Objectives

Objectives:

- Gather stakeholder feedback on early-stage R&D needs to advance H2@Scale, as outlined in the draft Roadmap
- Identify opportunities to align R&D needs with industry priorities & national lab capabilities
- Identify regional and near-term opportunities to use domestic hydrogen production to support resiliency of power generation (align with industry and global needs)

H2@Scale Strategy Requires Collaboration

Thank you

Dr. Sunita Satyapal
Director
Fuel Cell Technologies Office
Sunita.Satyapal@ee.doe.gov

H2@Scale RFI Key Themes – Interest in:

1. **Innovative H_2 production technologies**
   - Electrolyzer cost reduction
   - Alternative feedstocks (e.g. solid and liquid waste, process gases)
   - Integrate H_2 production with waste heat (e.g. from nuclear or steelmaking)
2. **Integrated H_2 systems (e.g., reversible fuel cells,)**
3. **Innovative H_2 storage and delivery technologies**
   - Liquid organic carriers, metal organic frameworks; bulk storage
4. **Use of H_2 to enable grid stability and energy storage**
5. **Data collection & sharing on the value proposition and feasibility of H2@Scale**
   - Demonstration of electrolyzer integration with the grid; RD&D on power-to-gas
6. **Deployments of H_2 in near-term markets, including for buses, ammonia, & steel**

RFI & workshop will guide cross-cutting H2@Scale RD&D Roadmap.

Next Steps...

H2@Scale RD&D Roadmap that addresses issues including:

- ✓ **Hydrogen production from diverse domestic sources**
- ✓ **Hydrogen for grid stability and energy storage**
- ✓ **Development of industrial scale hydrogen delivery and storage infrastructure**
- ✓ **Penetration of clean/sustainable (including renewable) hydrogen in current and future end-use markets- e.g. industrial applications**

H2@Scale requires collaboration across stakeholders!

Key Tasks:

1. Economic criteria that must be met for H2@Scale.
2. Forecast hydrogen supply curves.
3. Forecast hydrogen demand curves.
4. Determine economic penetration of hydrogen.
5. Develop Sankey diagrams, and down-select scenarios.
6. Analysis of down-selected scenarios.
7. Analyze spatial issues of H2@Scale (e.g. proximity of supply and demand).
8. Comparison of H2@Scale impact with base case business as usual.

Techno-economic analysis will forecast the resource requirements and impact of H2@Scale.

Previous Workshops: H2 Energy Storage, 2014

Key barriers:

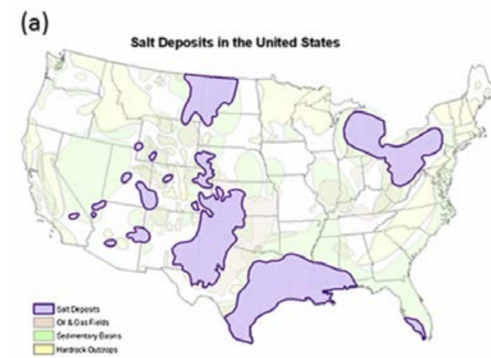
- Technical and economic viability
- Ability of hydrogen to serve multiple end uses
- Unified supportive policy
- Partnerships and coordination

Next Steps:

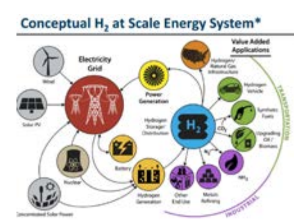
- Demonstration/pilot projects
- Partnerships/coordination
- Assess technical viability
- Education/outreach
- Pathway to successful business case- **upcoming lab project!**
- Develop roadmap and implement H2 plan and targets- **2016 RFI!**
- Develop/revise policy, regulations, codes and standards
- Determine probability of success

NREL partnership with SoCal Gas and National Fuel Cell Research Center to evaluate power-to-gas

Electrolyzer integration with grid (INL/NREL)



Techno-economic analysis of geologic storage of hydrogen



H2@Scale webinars and presentations

FCTO has been addressing previously identified barriers through collaborative RD&D.

Previous Workshops: Electrolysis, 2014

Key Barriers for Commercial Electrolysis:

- Stack performance, durability, cost, and efficiency
- Scale-up to megawatt capacity
- High-pressure performance to reduce downstream compression
- Identifying best markets to penetrate
  - Power-to-gas
  - Ancillary grid services
  - Renewable hydrogen for petroleum refining
  - Material handling equipment
- Grid Integration

HydroGEN
Advanced Water Splitting Materials

Consortium on water splitting R&D, including low- and high-temperature electrolysis

MW-scale electrolyzers now in commercial use!

BMW plant using H_2 from landfill gas

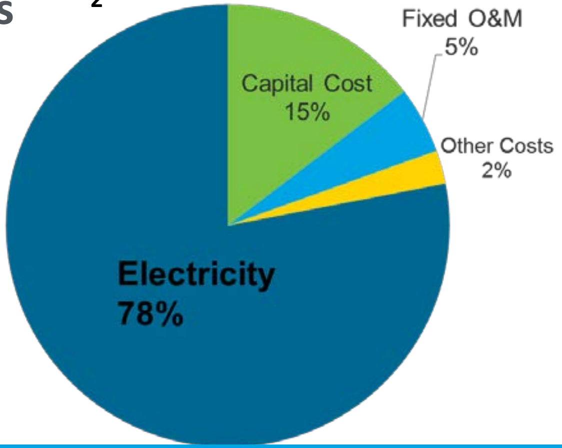
Testing of electrolyzer performance under variable load, and innovative drying technologies at NREL

Key barriers to commercial electrolysis are being addressed by DOE and industry.

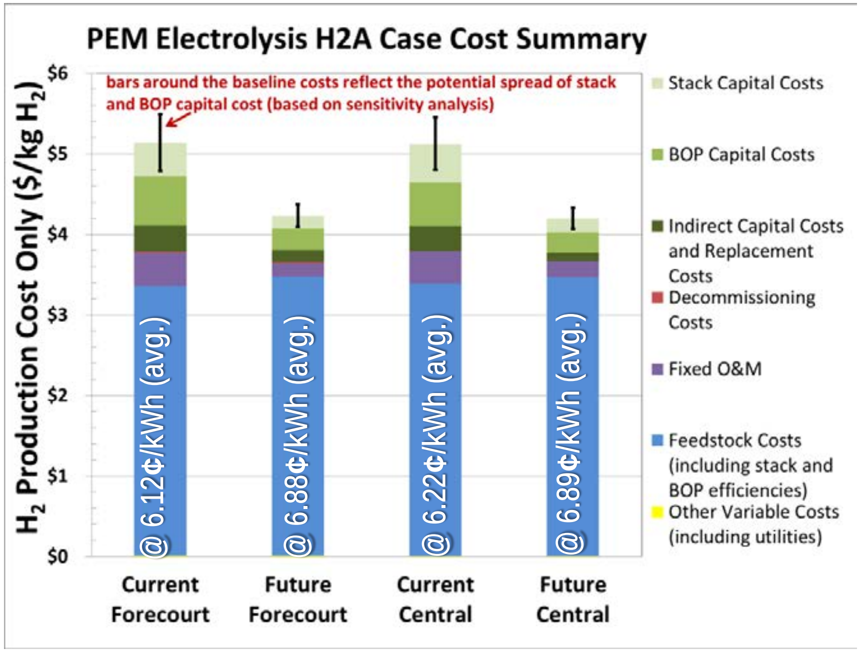
Significant R&D Achievements: Low- Temp PEM Electrolysis

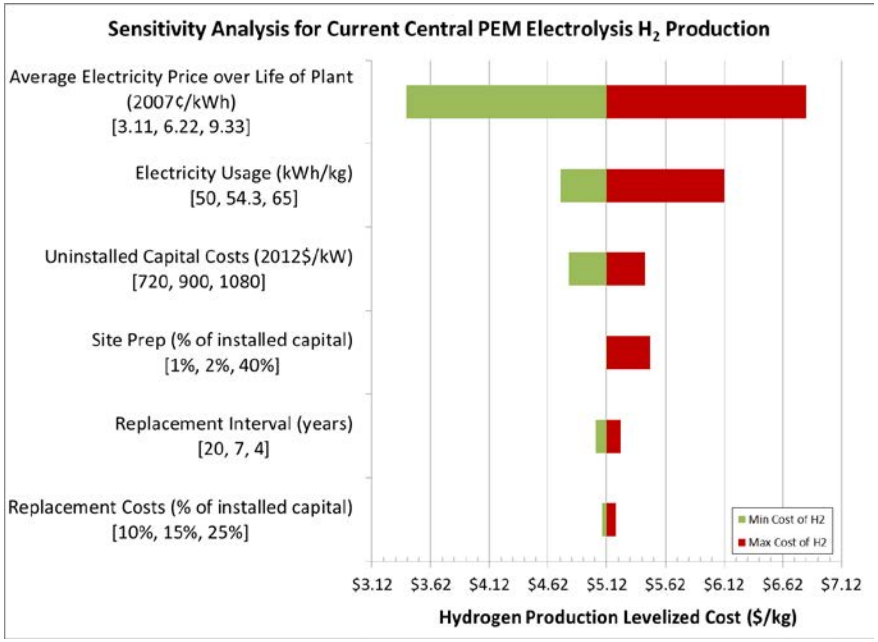
H_2 Production High Volume Cost Projections for PEM Electrolysis

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

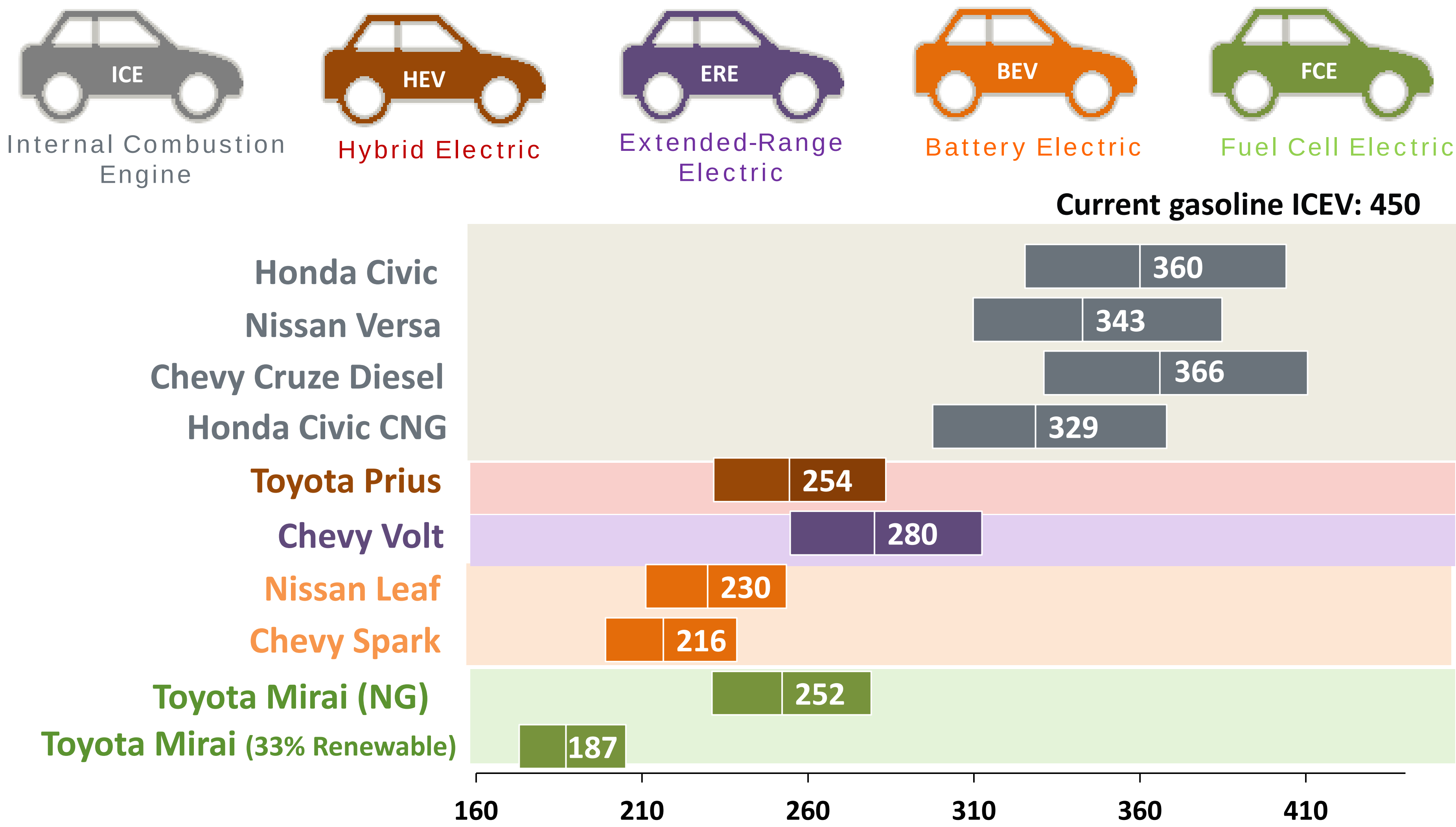


Electricity feedstock cost is largest cost driver





Life-Cycle GHG Emissions- Today's Cars



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

Almost 50% reduction in GHG can be achieved with today's FCEVs.