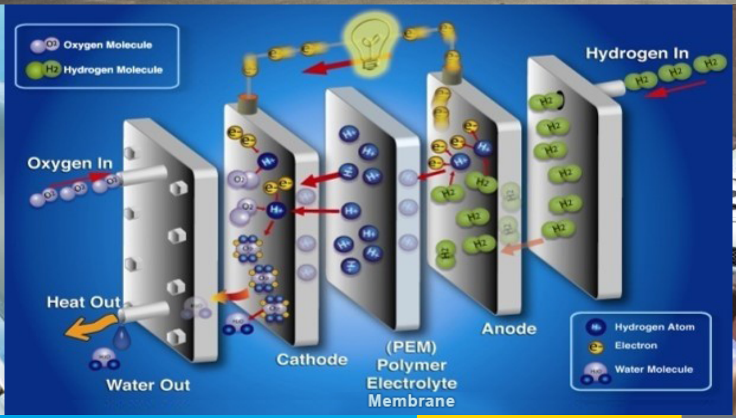
U.S. Department of Energy
Fuel Cell Technologies Office

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



H2@Scale Overview

Golden, CO

November 16, 2016

Reuben Sarkar
Deputy Assistant Secretary, Transportation
U.S. Department of Energy

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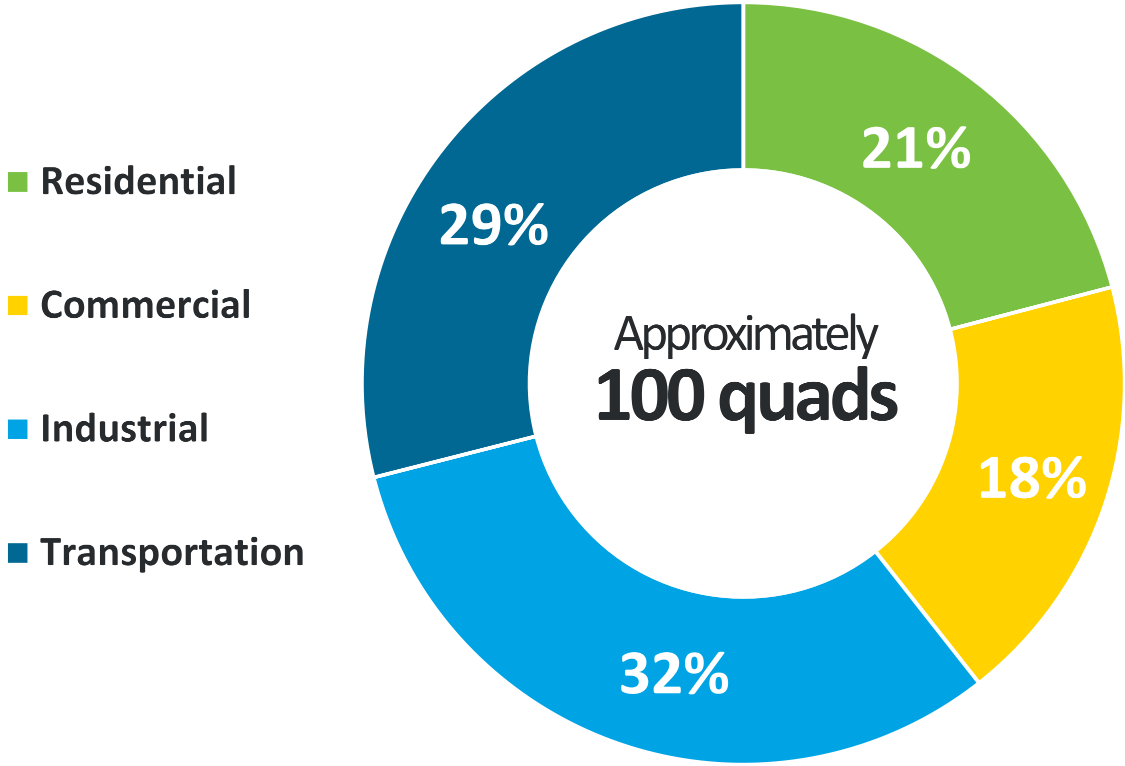
Fuel Cell Technologies Office

Energy Consumption in 2015

U.S. Energy Consumption* in 2015



World Energy Consumption | Approximately **600 quads**

*Includes electrical losses

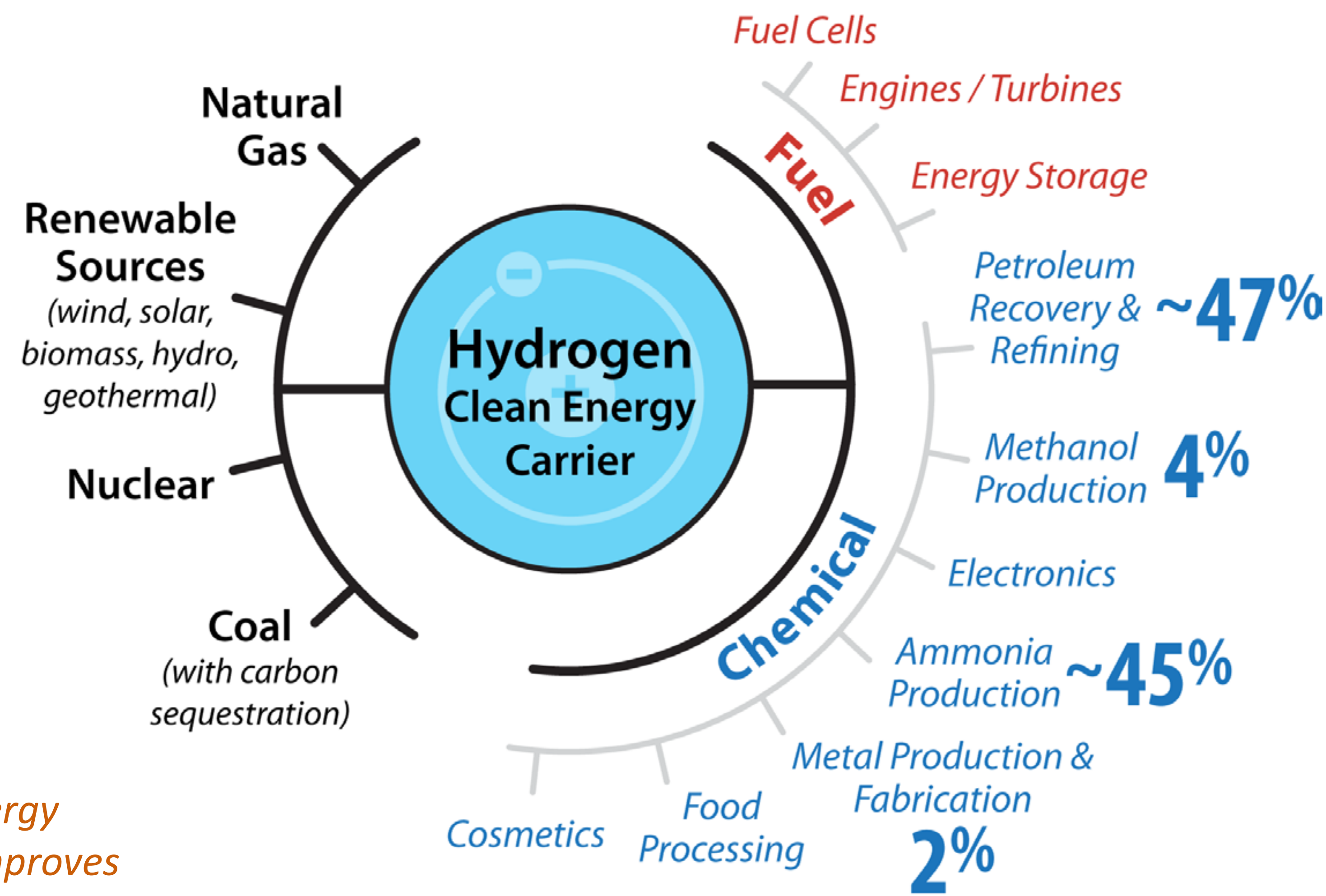
Source: EIA

Transportation and industry account for consumption

Hydrogen- A Clean, Flexible Energy Carrier

Diverse Energy Sources

Diverse Applications



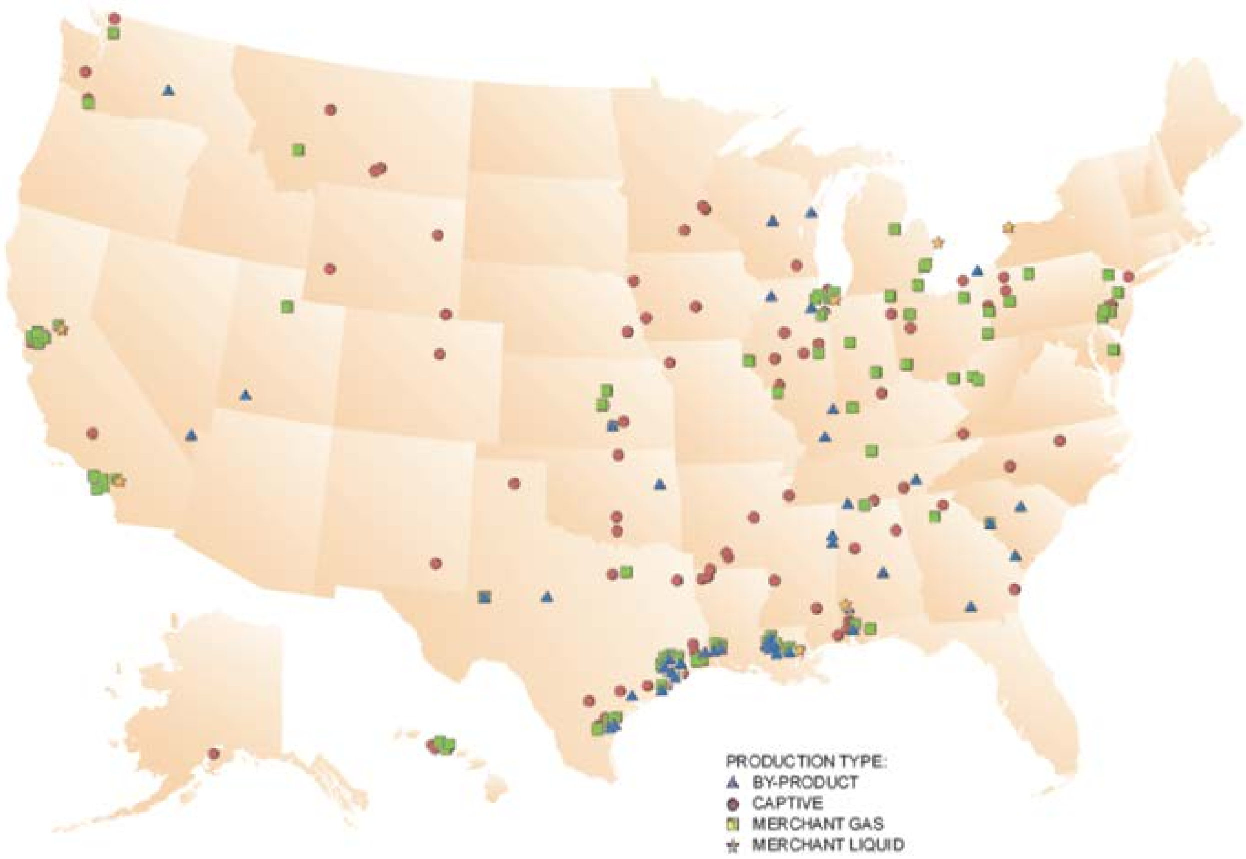
*Services all energy sectors AND improves **Energy Security** and **Domestic Economy***

Source: DOE, NREL, Hydrogen and Fuel Cell Program

Hydrogen Production Nationwide

We produce ~10M metric tons H_2/yr and have >**1600 mi.** of H_2 pipeline

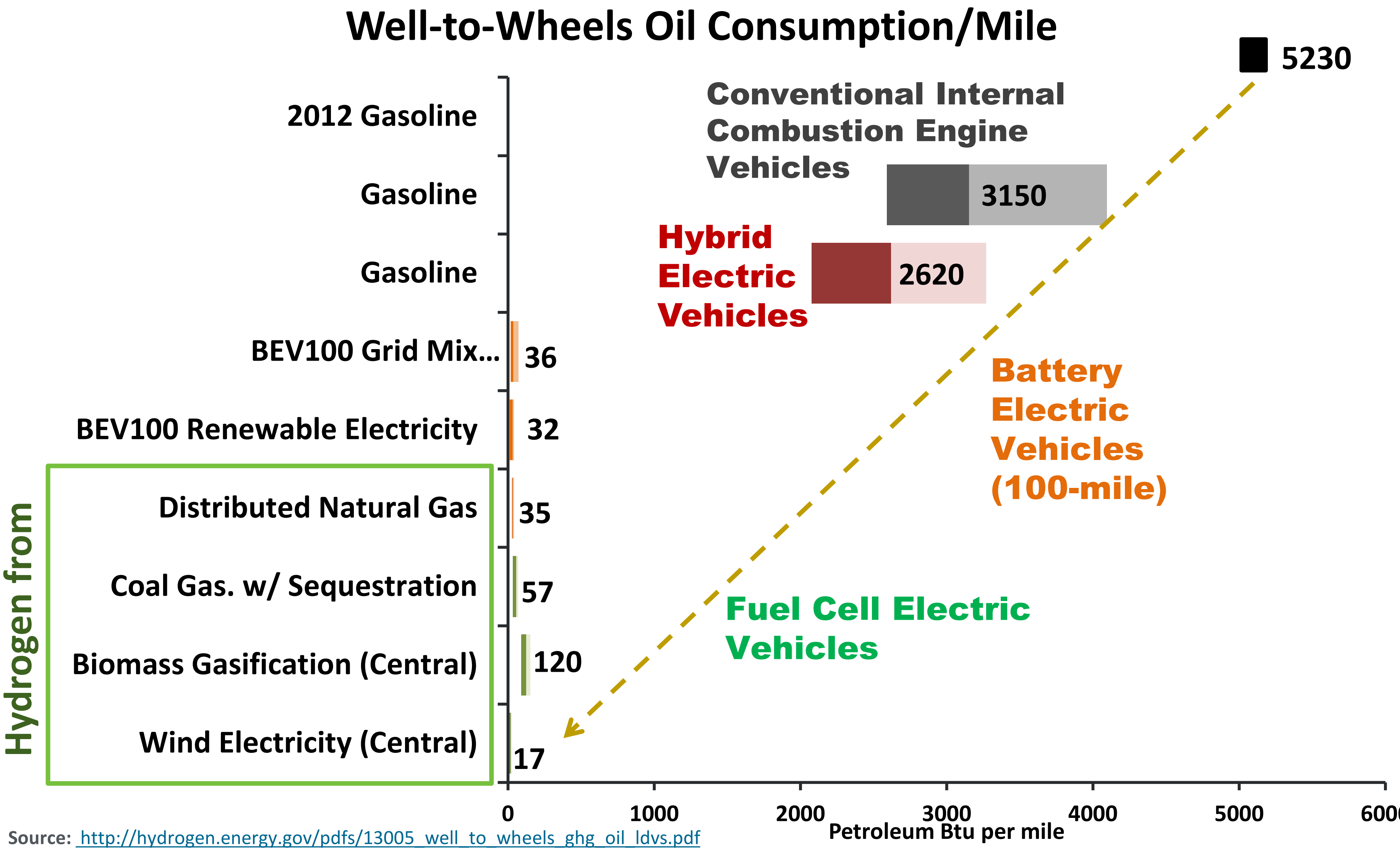
~50 fueling stations (~20 public)- 100 planned in CA, 12 in the Northeast



Centralized H_2 Production Facilities

Many states already produce many metric tons of hydrogen

Oil Dependency is Dominated by Vehicles



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.

How much H_2 is needed?

How much hydrogen for 1 car?

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

How much hydrogen for many cars?

1 M cars = 100,000 cars	**0.2 M tonnes** H_2 per year **200 M kg** H_2 per year

100 M cars = 10M cars	**20M tons** H_2 per year **20 B kg** H_2 per year

How much electricity would that take?

How to get hydrogen for 100M cars?

Solar/Wind Electrolysis

How much electricity would that take?

50 kWh per kilogram **X** **20B kg** H_2 per year **=** **1,000 TWh** per year

How does that compare with our current electricity use?

U.S. Electricity Consumption **=** Approximately **3,900 TWh** per year*

*2015 consumption. Source: EIA AEO 2016

How to get the H_2 needed?

How to get hydrogen for 100M cars?

Solar/Wind Electrolysis

50 kWh per kilogram **X** **20B kg** H_2 per year **=** **1,000 TWh** per year

High Temperature Nuclear + Electrolysis

67.2 mg U per kilogram **X** **20B kg** H_2 per year **=** **1.3 kT U** per year

Natural Gas Steam Methane Reforming

167.5 scf per kilogram **X** **20B kg** H_2 per year **=** **3.4 Tcf** per year

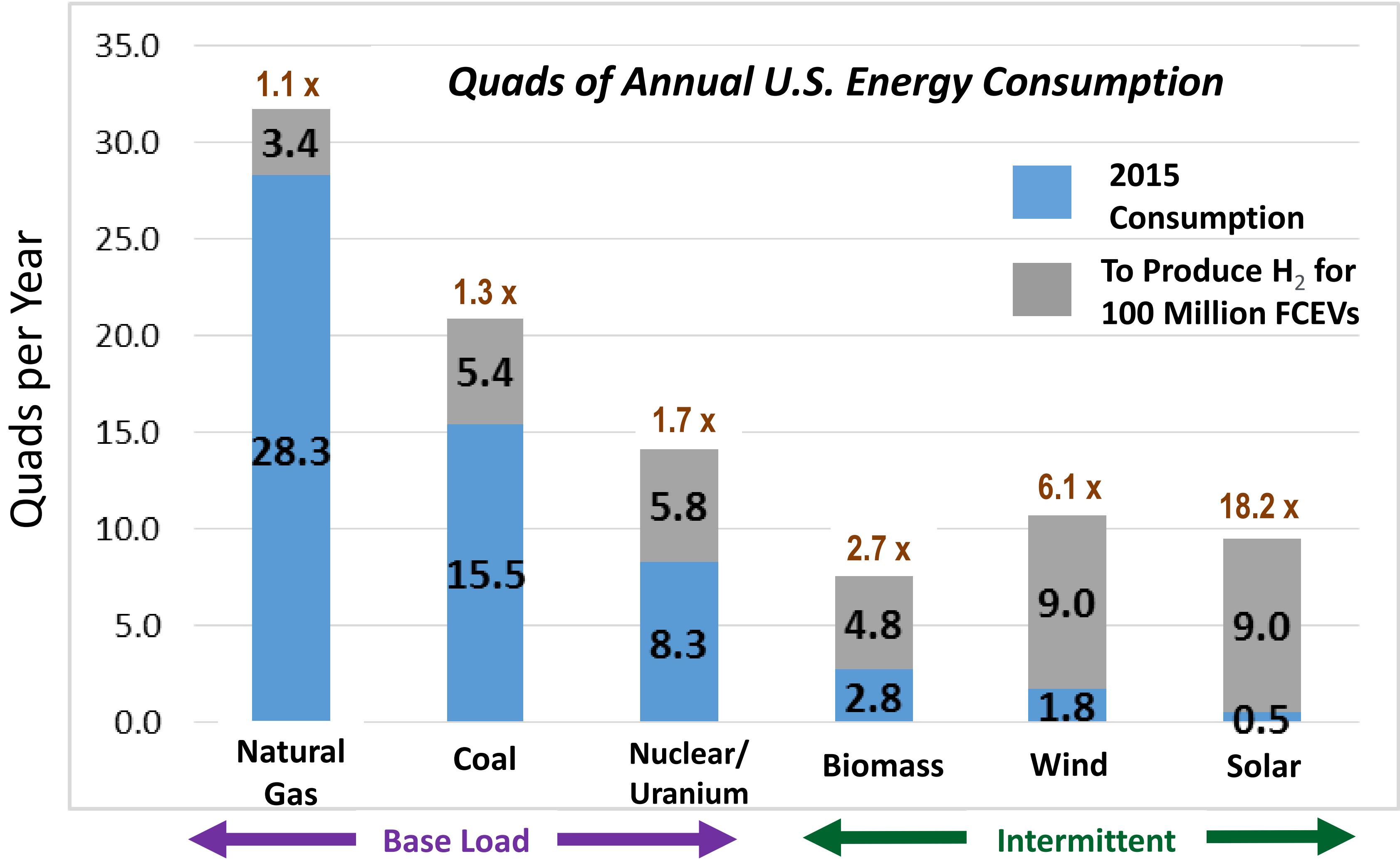
Coal with CCS

14 kg coal per kg H_2 **X** **20B kg** H_2 per year **=** **274 MT coal** per year

Source: Resource Assessment for Hydrogen Production: Hydrogen Production Potential from Fossil and Renewable Energy Resources. M. Melaina, M. Penev, D. Heimiller, National Renewable Energy Laboratory 2013

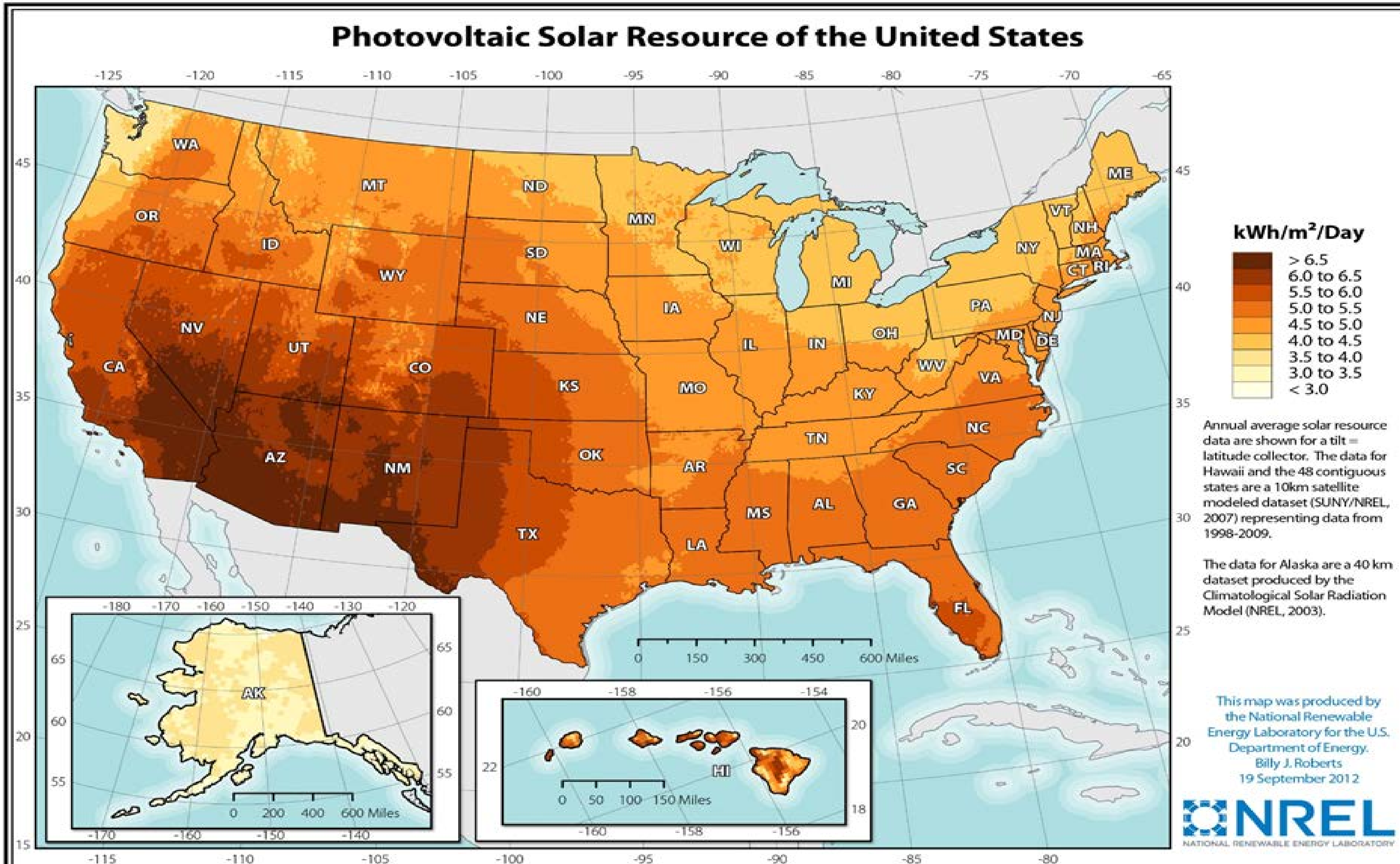
How much H_2 is needed?

How to get hydrogen for 100M FCEVs?



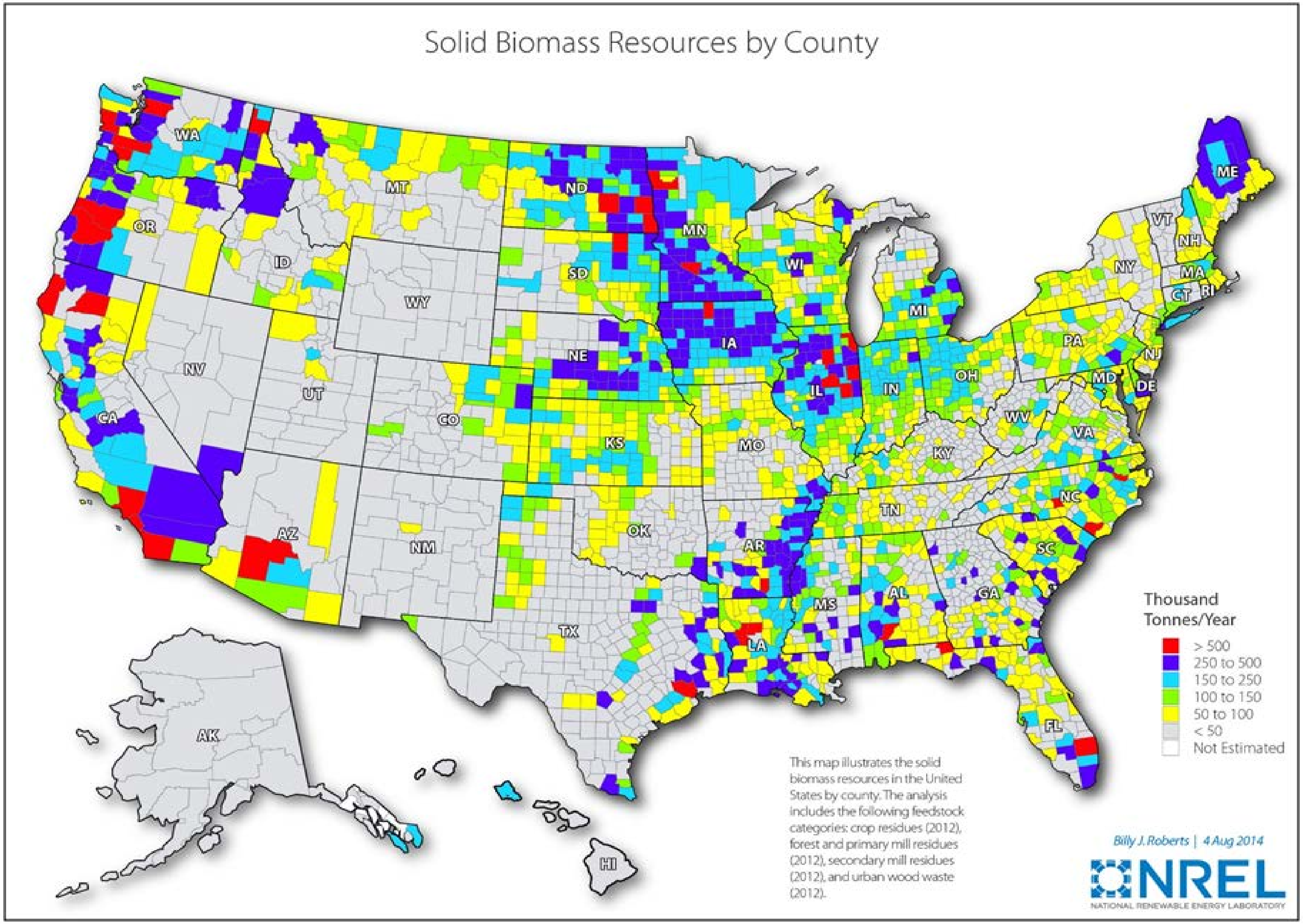
Source: Resource Assessment for Hydrogen Production: Hydrogen Production Potential from Fossil and Renewable Energy Resources. M. Melaina, M. Penev, D. Heimiller, National Renewable Energy Laboratory 2013; Annual Energy Outlook 2016; http://www.eia.gov/renewable/

Solar Sources: Opportunity for Renewable H_2



Solar water-splitting is an important longer term option

Biomass Resources: Opportunity for Renewable H_2



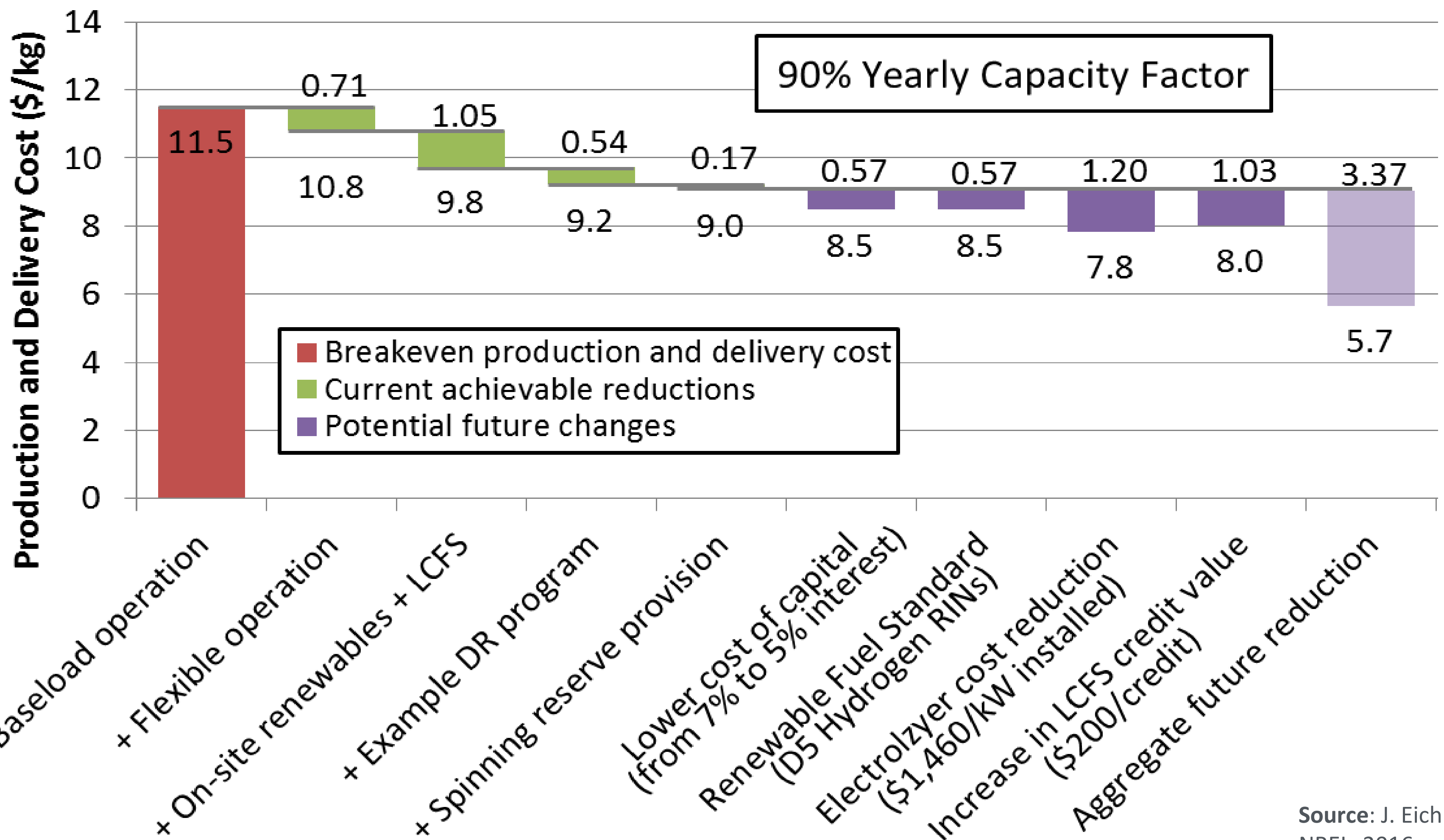
Bio-feedstock reforming is a near term option

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.

Business case assessment for electrolytic H_2 production



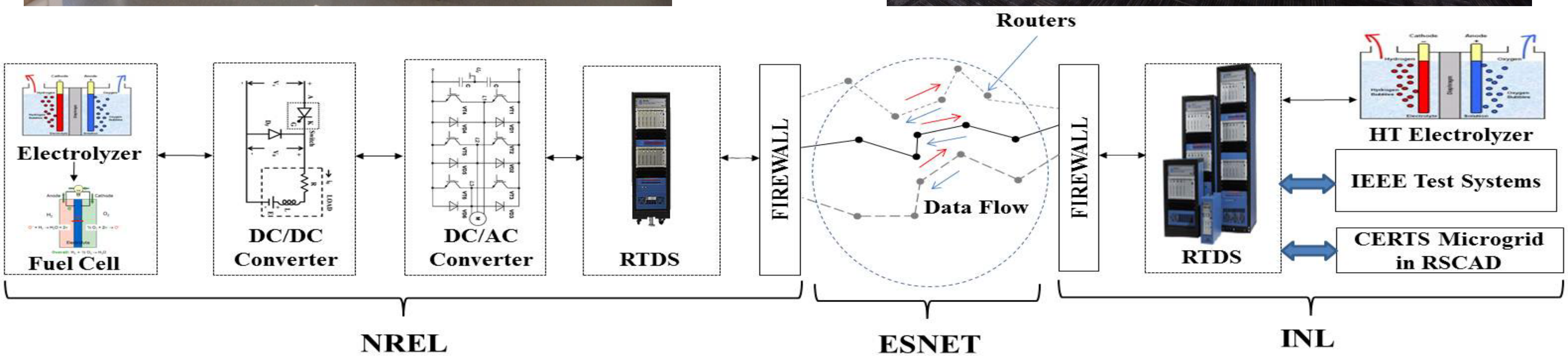
Source: J. Eichman, NREL, 2016

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

Demonstration of Electrolyzer Grid Integration

NREL

INL



FCTO is validating electrolyzer potential in energy storage.

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!

Thank you

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hydrogenandfuelcells.energy.gov

Oil Dependency is Dominated by Vehicles

- Transportation is responsible for **66%** of U.S. petroleum usage
- **27%** of GHG emissions
- On-Road vehicles responsible for **85%** of transportation petroleum usage

- **16.0M LDVs** sold in 2014.
- **240 million light-duty vehicles** on the road in the U.S
- **10-15 years** for annual sales penetration
- **10-15 years** to turn over fleet

Poses significant economic, energy and environmental risks to U.S.



Photos courtesy of Spc. Jordan Huettl, U.S. Army; U.S. Environmental Protection Agency; and M. Studinger, NASA

It takes decades of sustained effort to turn over the fleet

Previous Workshops: H2 Energy Storage, 2014

Key barriers:

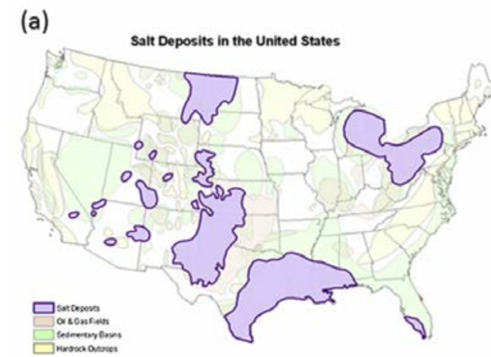
- Technical and economic viability
- Ability of hydrogen to serve multiple end uses
- Unified supportive policy
- Partnerships and coordination

Next Steps:

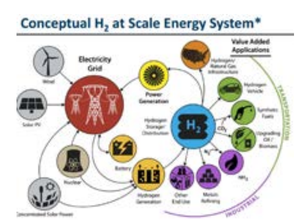
- Demonstration/pilot projects
- Partnerships/coordination
- Assess technical viability
- Education/outreach
- Pathway to successful business case- **upcoming lab project!**
- Develop roadmap and implement H2 plan and targets- **2016 RFI!**
- Develop/revise policy, regulations, codes and standards
-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

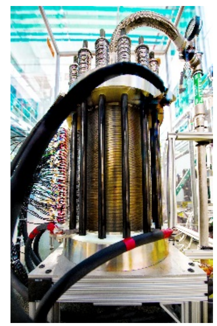
Previous Workshops: Electrolysis, 2014

Key Barriers for Commercial Electrolysis:

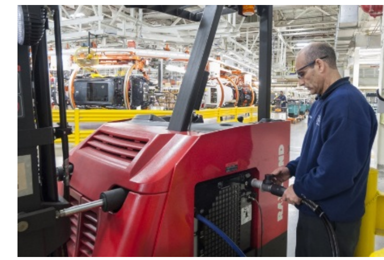
- Stack performance, durability, cost, and efficiency
- Scale-up to megawatt capacity
- High-pressure performance to reduce downstream compression
- Identifying best markets to penetrate
  - Power-to-gas
  - Ancillary grid services
  - Renewable hydrogen for petroleum refining
  - Material handling equipment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

HydroGEN Advanced Water Splitting Materials

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

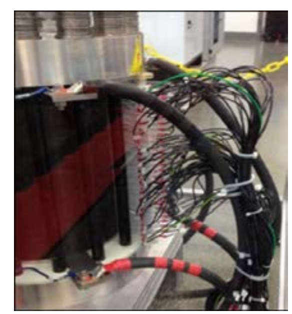


MW-scale electrolyzers now in commercial use!



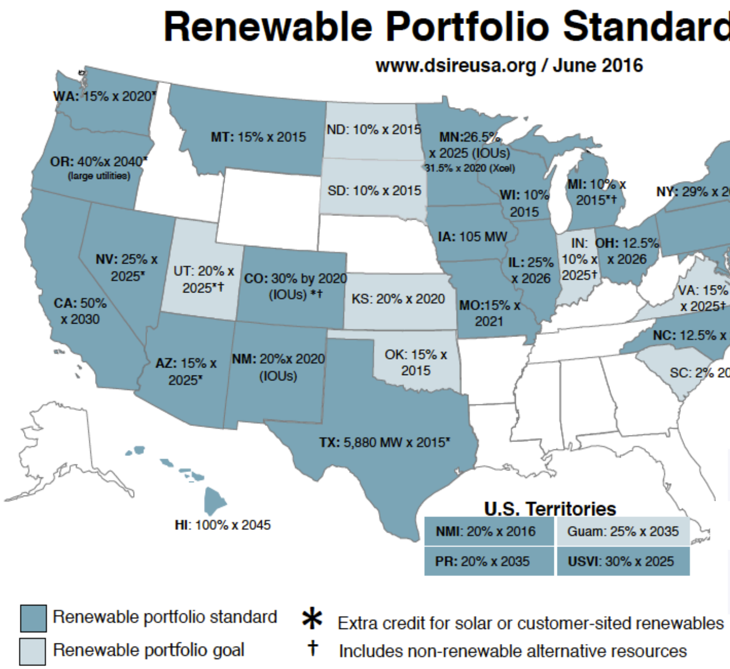
BMW plant using H_2 from landfill gas

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



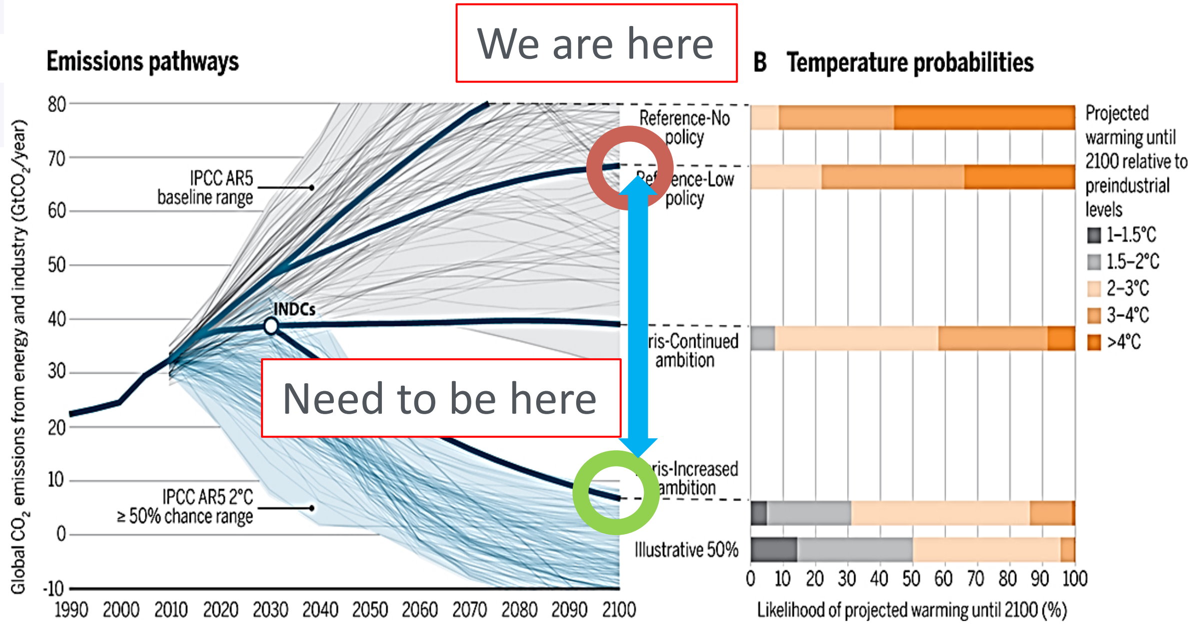
Key barriers to commercial electrolysis are being addressed by DOE and industry.

More Renewable Energy in Grid of Future



Source: http://ncsolarcen-prod.s3.amazonaws.com/wp-content/uploads/2014/11/Renewable-Portfolio-Standards.pdf

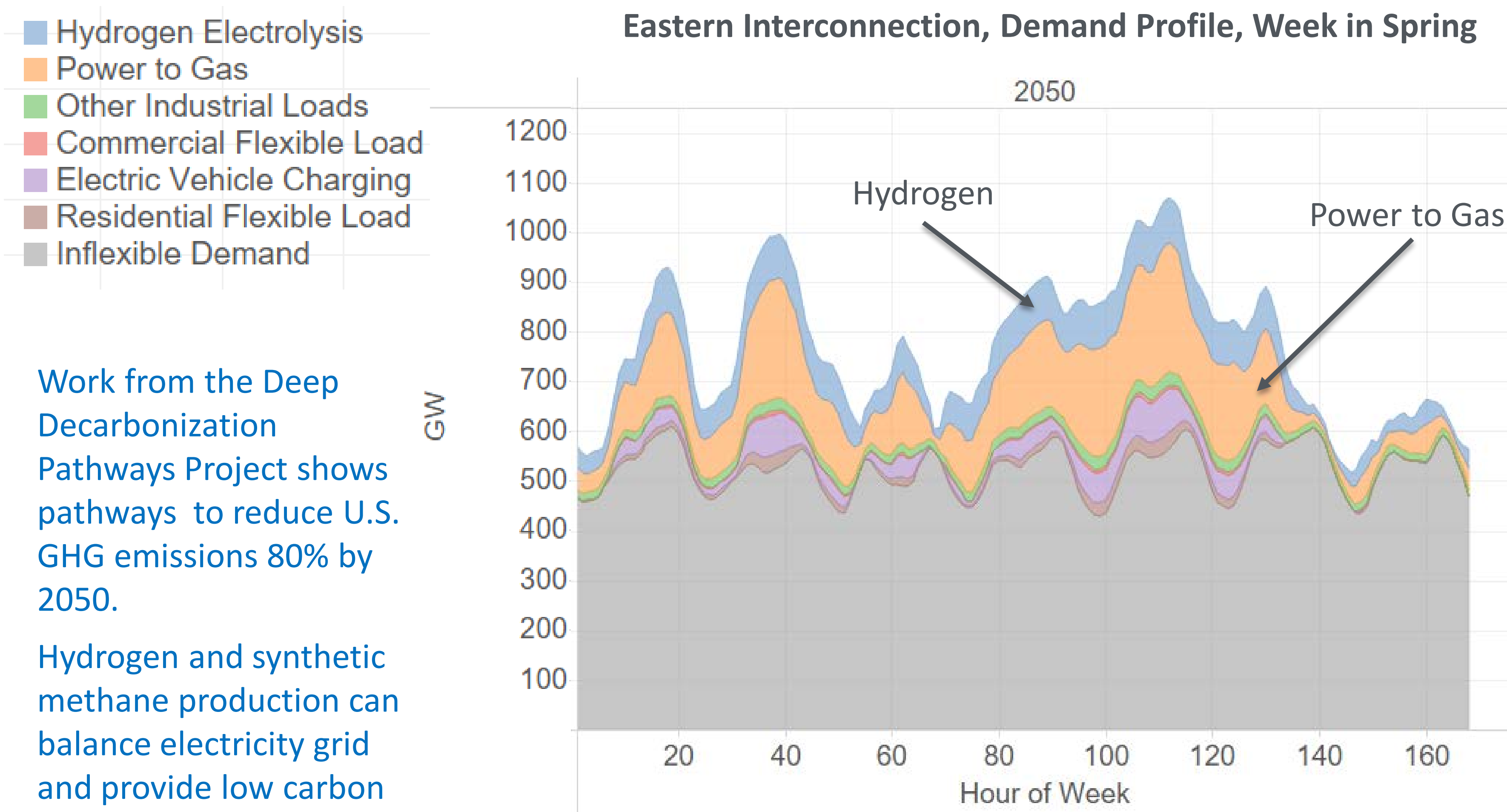
- Current RPS Standards on books, CA is most aggressive.
- Many studies suggest much greater grid decarbonization necessary.



Source: Fawcett et al 2015, sciencemag.org / S. Garman, “Perspectives on Low Carbon Energy Futures” DOE H2@Scale Meeting 7-12-16

Meeting COP 21 Climate Goals Requires Further Reduction in Emissions

H_2 for Seasonal Energy Storage



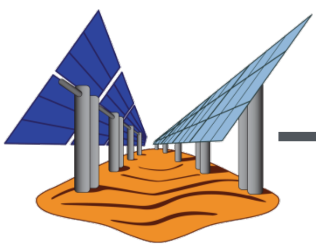
Source: B. Haley, R. Jones, G. Kwok, J. Williams, "Pathways to Deep Decarbonization," 9/1/16

- Work from the Deep Decarbonization Pathways Project shows pathways to reduce U.S. GHG emissions 80% by 2050.
- Hydrogen and synthetic methane production can balance electricity grid and provide low carbon fuels.

More Renewables Requires Storage/Transmission/Curtailment when Supply ≠ Demand

H_2 for Short Term Balancing

Wind



Solar

Geothermal

Electricity Grid

Ongoing work at U. Hawaii and NREL has shown potential for grid frequency modulation using dispatchable electrolyzers.

Electrolyzer

Ramp–up & Ramp-down capability for Grid stabilization

Oxygen Storage

Hydrogen Storage

Natural Gas Infrastructure

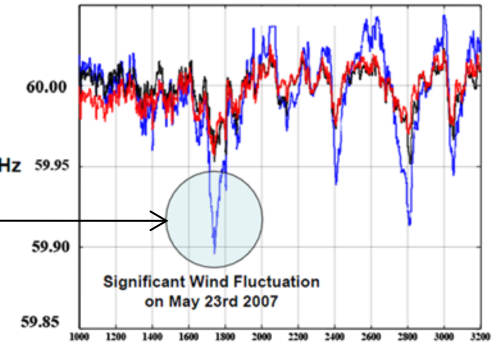
Value Added Applications

- Vehicle Fuel
- Fertilizer NH_3
- Emergency Backup FC

BLK 1 MW /1 minute of H_2 storage

BLUE No H_2 storage

RED 1 MW/∞



Models indicate modest energy storage mitigates negative effects of wind penetration

Adapted from: www.hydrogen.energy.gov/pdfs/review12/mt008_ewan_2012_o.pdf
Hawaii Natural Energy Institute Mitch Ewan, GE Transient PSLF™

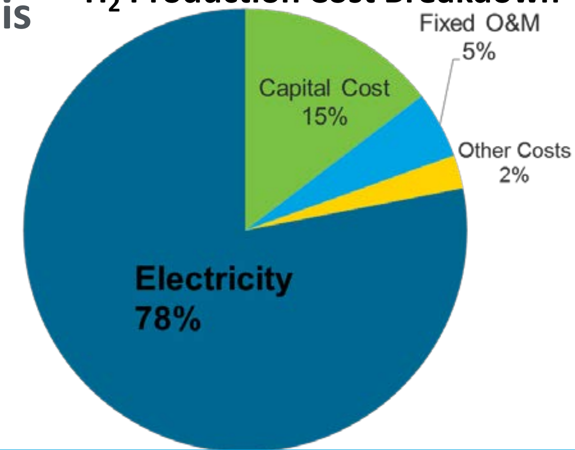
Hydrogen may be produced from a variety of renewable resources, and hydrogen-based energy storage could provide value to many applications and markets.

Significant R&D Achievements: Low- Temp PEM Electrolysis

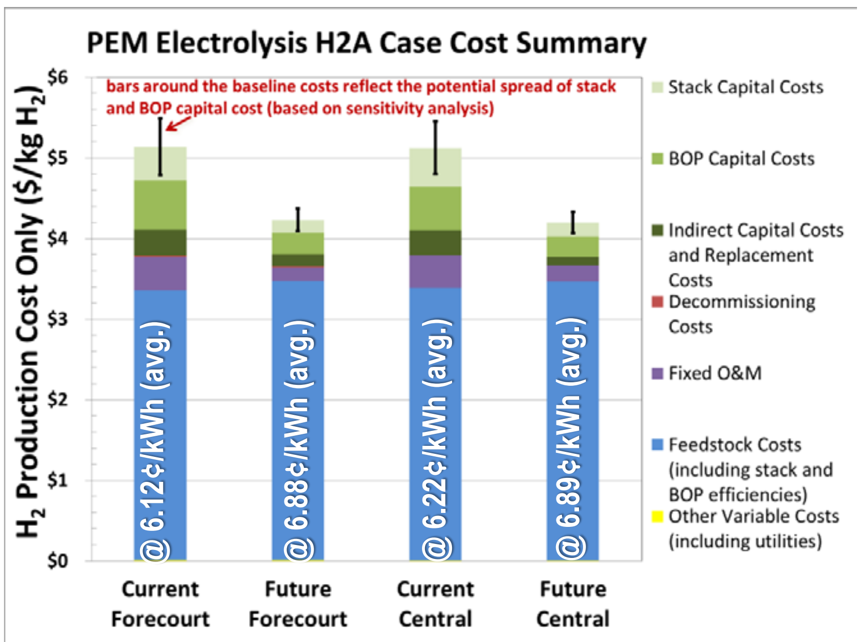
H_2 Production High Volume Cost Projections for PEM Electrolysis

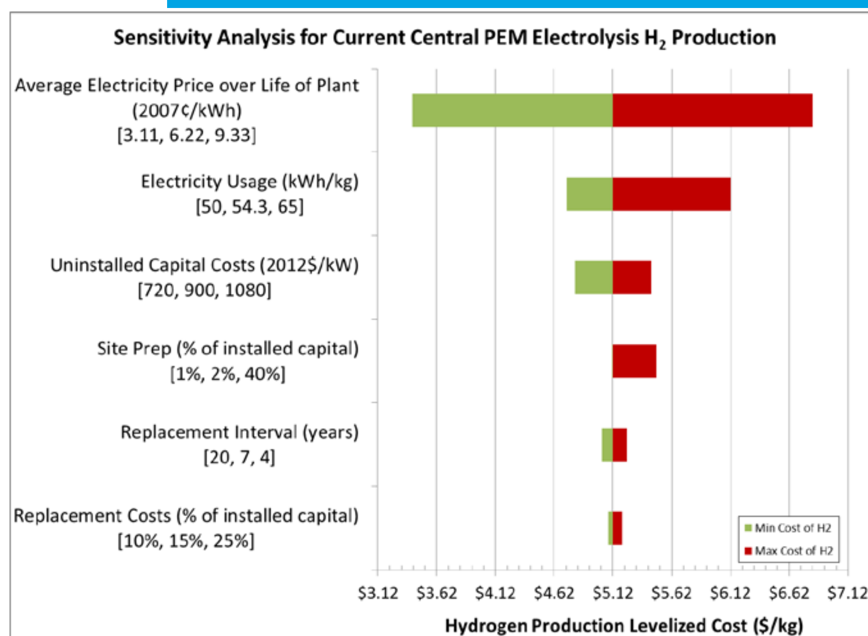
	Low Range ($/kg H_2)	Baseline Cost ($/kg H_2)	High Range ($/kg H_2)
Forecourt			
Current Case	$4.79	$5.14	$5.49
Future Case	$4.08	$4.23	$4.37
Central			
Current Case	$4.80	$5.12	$5.45
Future Case	$4.07	$4.20	$4.33

H_2 Production Cost Breakdown



Electricity feedstock cost is largest cost driver

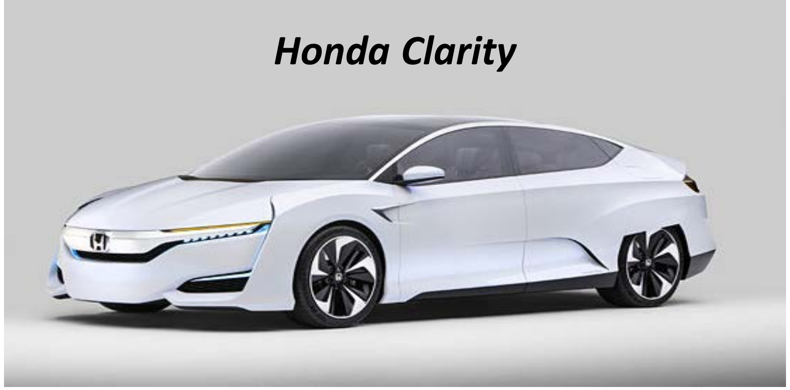




H_2@Scale as Key Part of Solution


Hyundai Tucson Fuel Cell SUV


Toyota Mirai

Honda Clarity


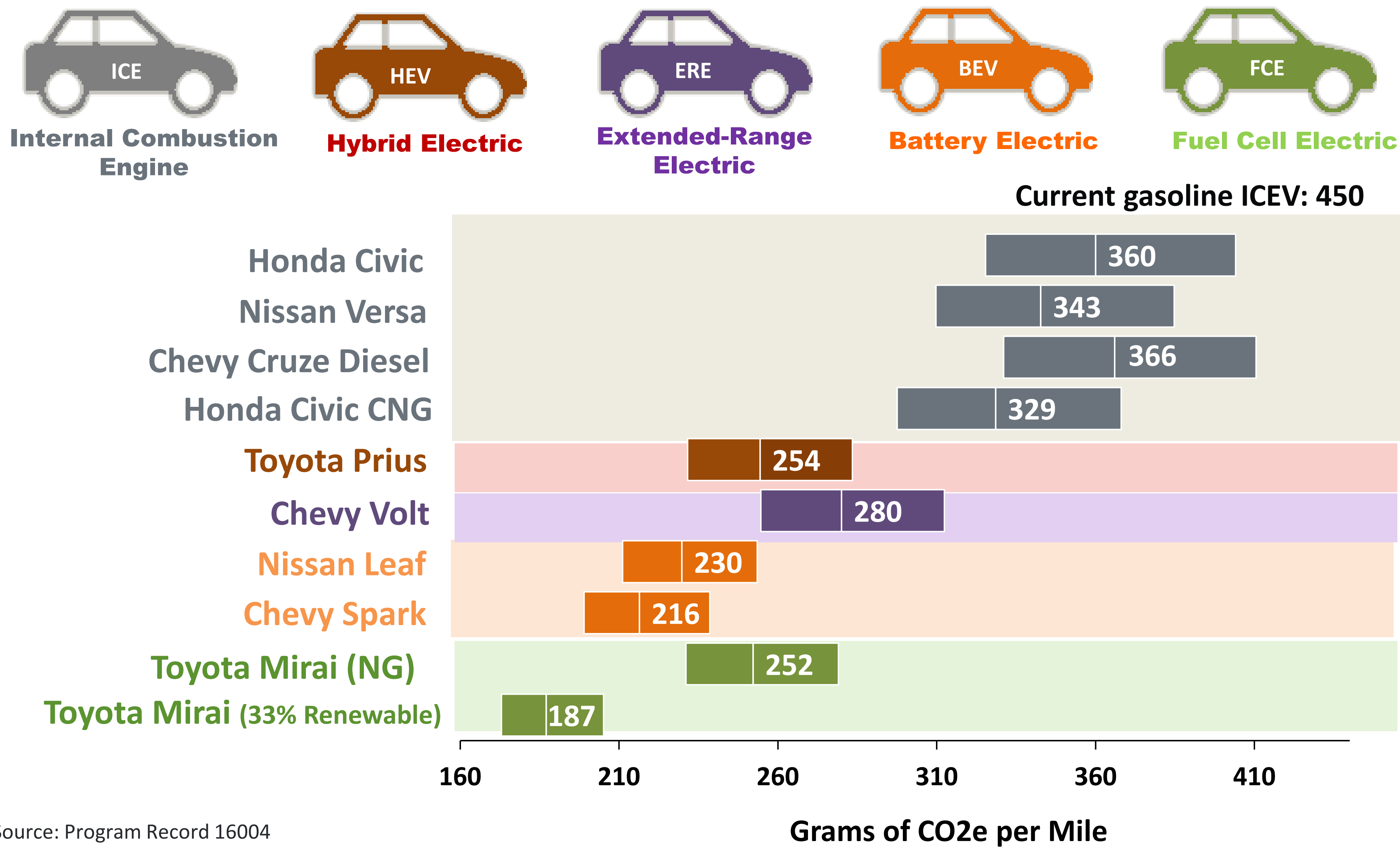
23 H_2 stations in California **open**

20 H_2 stations in development in California

12 H_2 stations **planned** for Northeast

> 17,000 kg/day fueling capacity expected by 2022.

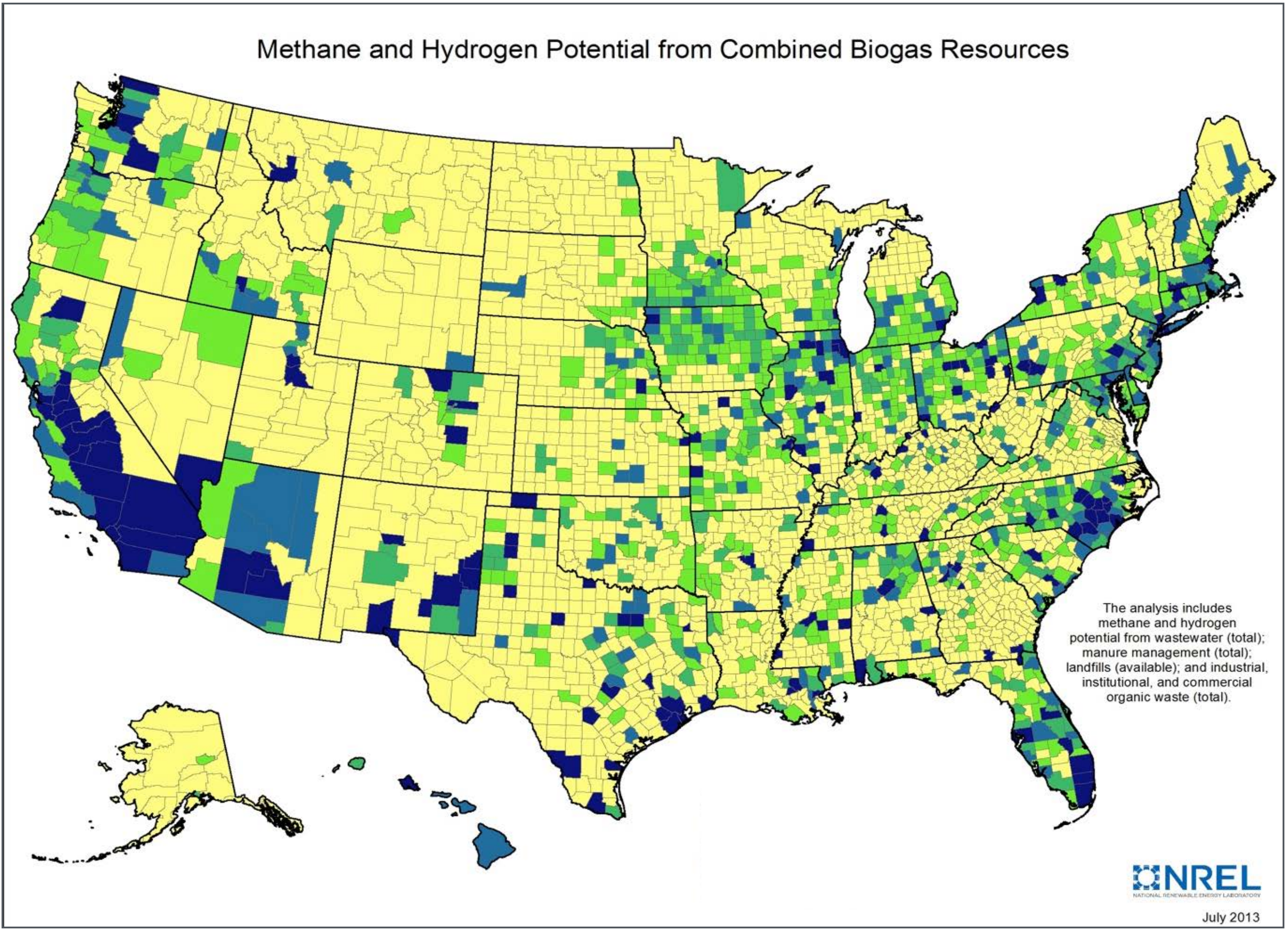
Life-Cycle GHG Emissions- Today's Cars



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.

Biogas Resources: Opportunity for Renewable H_2



Hydrogen from biogas already **available in some California fueling stations**

Wastewater treatment plants alone have the potential to provide enough hydrogen to support over ~1-3M FCEVs/year