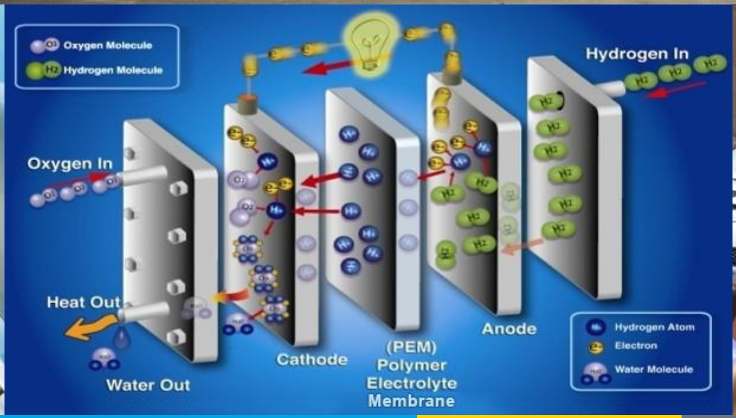
U.S. Department of Energy Fuel Cell Technologies Office

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



Program Overview

Stanford, CA
April 14th 2016

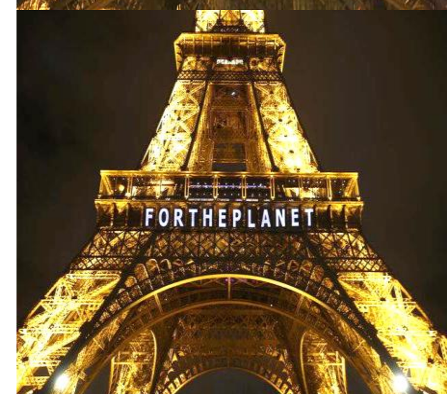
Dr. Sunita Satyapal

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

Key Driver- Paris Agreement at COP 21

"Let that be the common purpose here in Paris. A world that is worthy of our children. A world that is marked not by conflict, but **by cooperation**; and not by human suffering, but by human progress. A world that's safer, and more prosperous, and more secure, and more free than the one that we inherited. **Let's get to work**."

- President Barack Obama at the launch of COP21



PARIS2015
UN CLIMATE CHANGE CONFERENCE
COP21·CMP11

All-of-the-Above Energy Strategy

*"We've got to invest in a serious, sustained, **all-of-the-above energy strategy** that develops every resource available for the 21st century."*

- President Barack Obama

"As part of an all-of-the-above energy approach, fuel cell technologies are paving the way to competitiveness in the global clean energy market and to new jobs and business creation across the country."

- Secretary Moniz,
U.S. Department of Energy

Secretary Moniz at DC Auto Show

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.

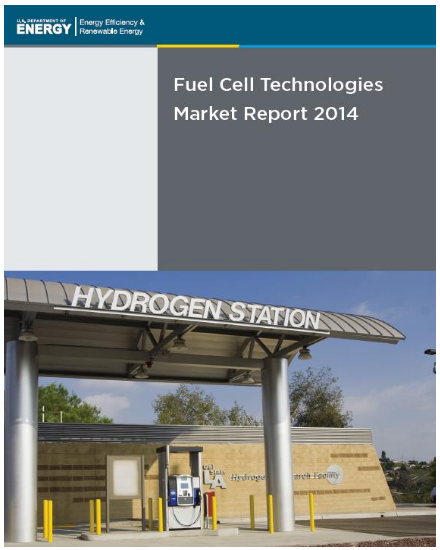


Photos courtesy of Spc. Jordan Huettl, U.S. Army; U.S. Environmental Protection Agency; and M. Studinger, NASA

It takes decades of sustained effort to turn over the fleet

Fuel Cells- Steady Market Growth

Market Report Just Published!



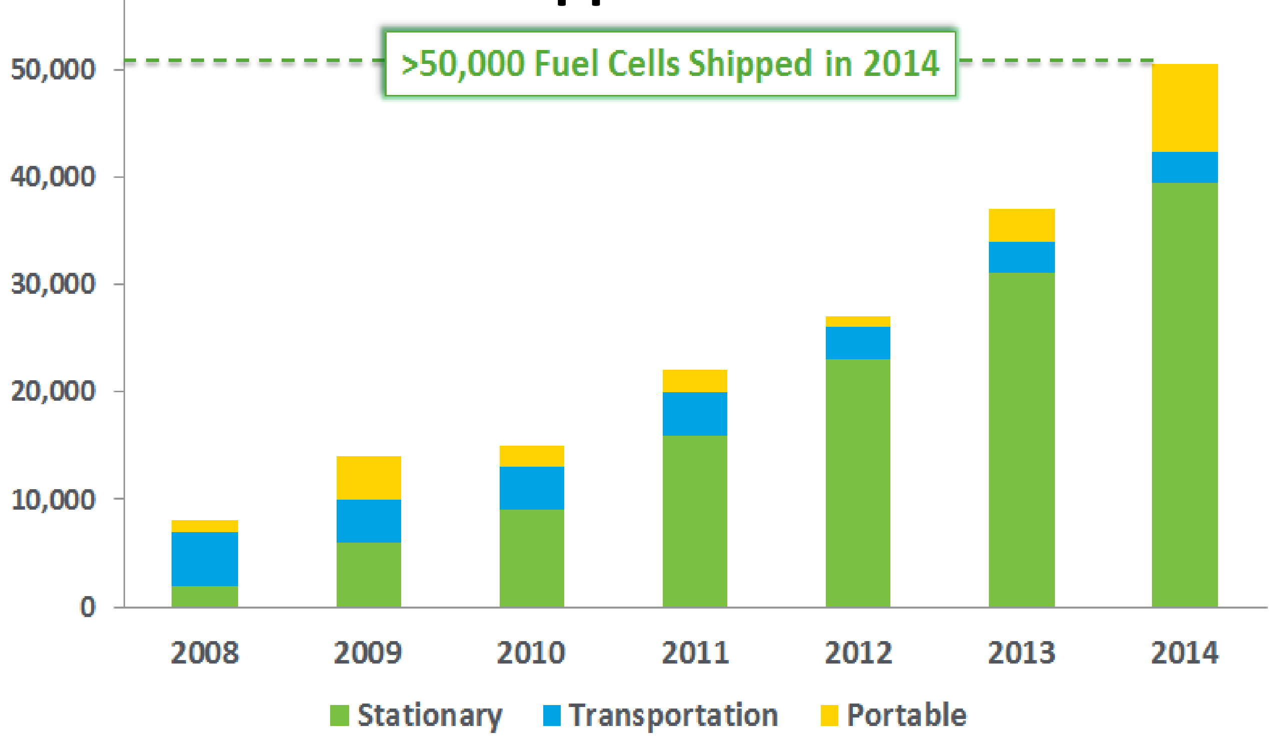
In 2014…

>$2B in revenues

>180 MW fuel cells shipped

Available at:
http://energy.gov/eere/fuelcells/downloads/2014-fuel-cell-technologies-market-report

Fuel Cell Systems Shipped Worldwide by Application



Source: Navigant & E4tech

- **Consistent ~30% annual growth since 2010**
- **Global Market Potential in 10- 20 year** →
  - **$14B – $31B/yr for stationary power**
  - **$11B /yr for portable power**
  - **$18B – $97B/yr for transportation**

FCEVs are on U.S. Roads Now!

Toyota Mirai Fuel Cell Vehicle

Available for Commercial Sale

- **$57,500 MSRP**
- 67 mi/gge
- 312 mi range, ~5 min refuel
- 114 kW stack
- US:200 2015, 3000 by 2017

Hyundai Tucson Fuel Cell SUV

Available for Lease

- **$499/month lease**
- 50 mi/gge
- 265 mi range
- 100 kW stack
- US: 70 thru May '15 (237 overall)

Honda Clarity Fuel Cell Vehicle

Just Announced at Auto Shows

- **$60,000 MSRP**
- **$500/month lease** for initial launch
- +300 mi range*
- 100 kW stack
- Initial launch planned for late 2016

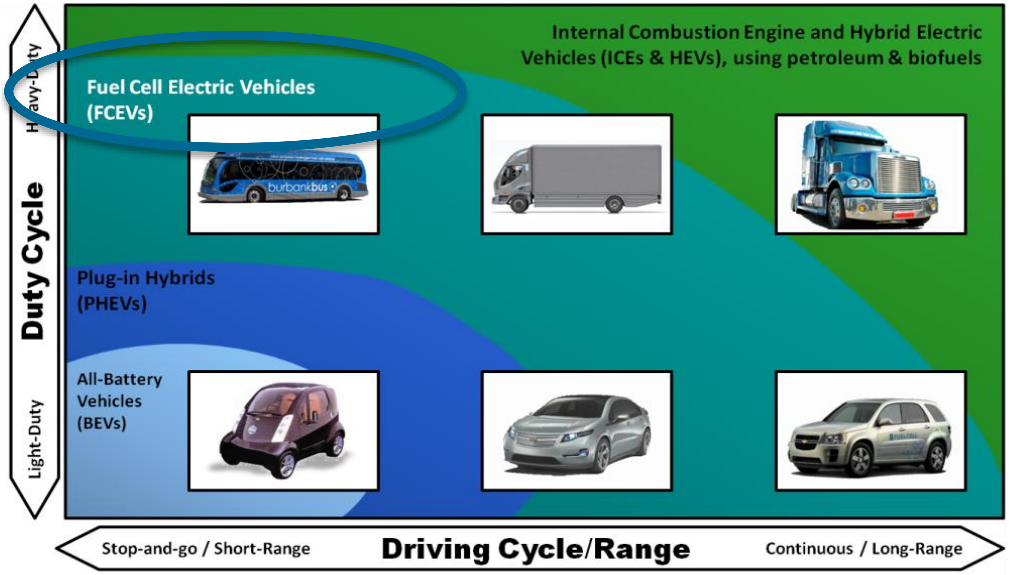
*Preliminary range estimate determined by Honda

Additional OEMs planning FCEVs in soon

A Portfolio of Technologies: Each has Pros and Cons

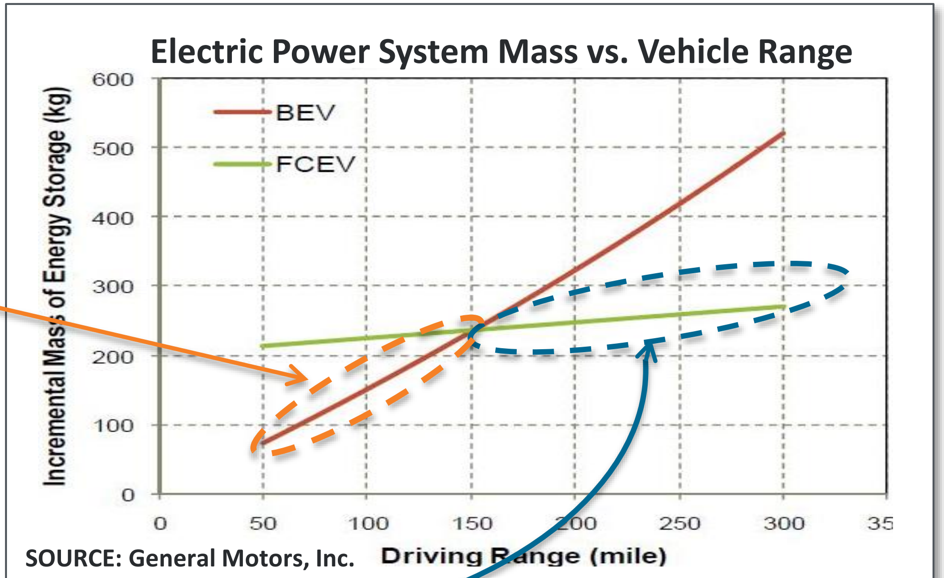
Fuel Cell Benefits: Can have ALL these attributes simultaneously

- Fast Filled
- Long Range
- Zero emissions
- Zero Criteria Pollutants
- Fueled by Renewables
- Uses domestic Sources
- Fewer Vehicle Trade-offs
- Diverse Uses (V2B, SUVs, APUs, range extenders, etc.

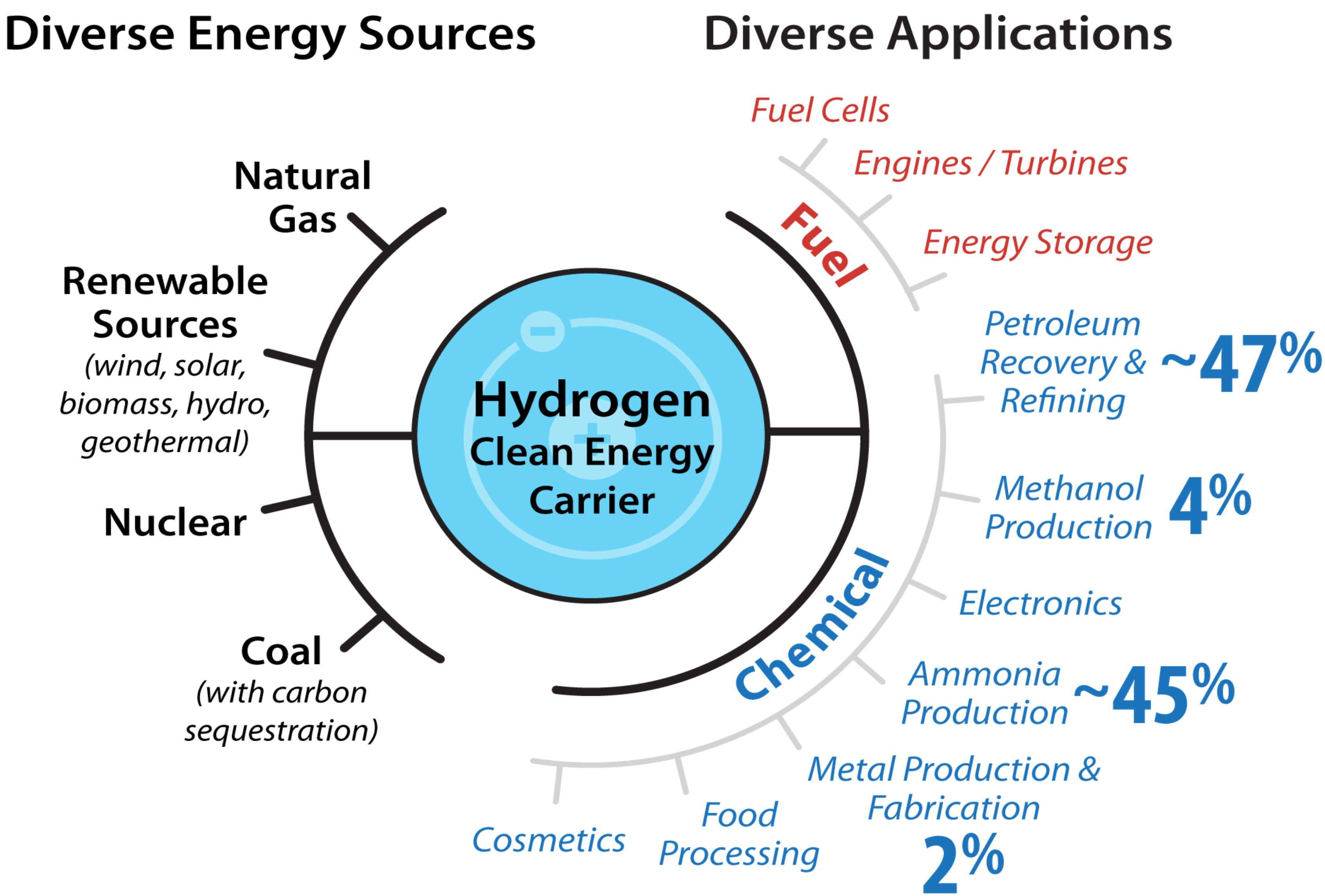


For shorter distances, batteries are more effective in terms of system mass

Fuel cells offer an advantage for longer driving range with less weight penalty



Hydrogen- A Clean, Flexible Energy Carrier



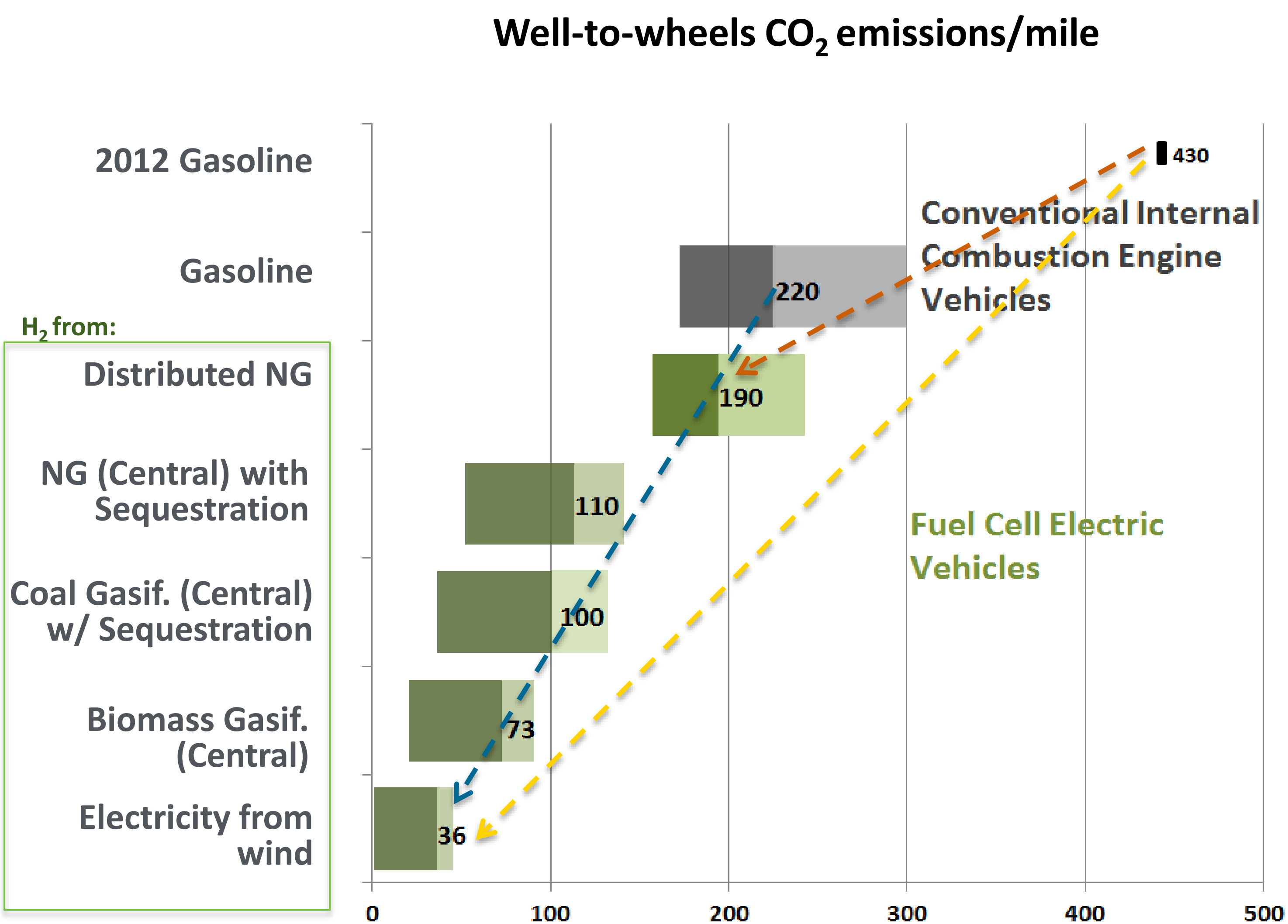
Source: DOE, NREL, Hydrogen and Fuel Cell Program

FCEVs Reduce Greenhouse Gas Emissions

>50% with H_2 from Distributed Natural Gas*

>80% with H_2 from Renewables* (Wind)

>90% with H_2 from Renewables** (Wind)



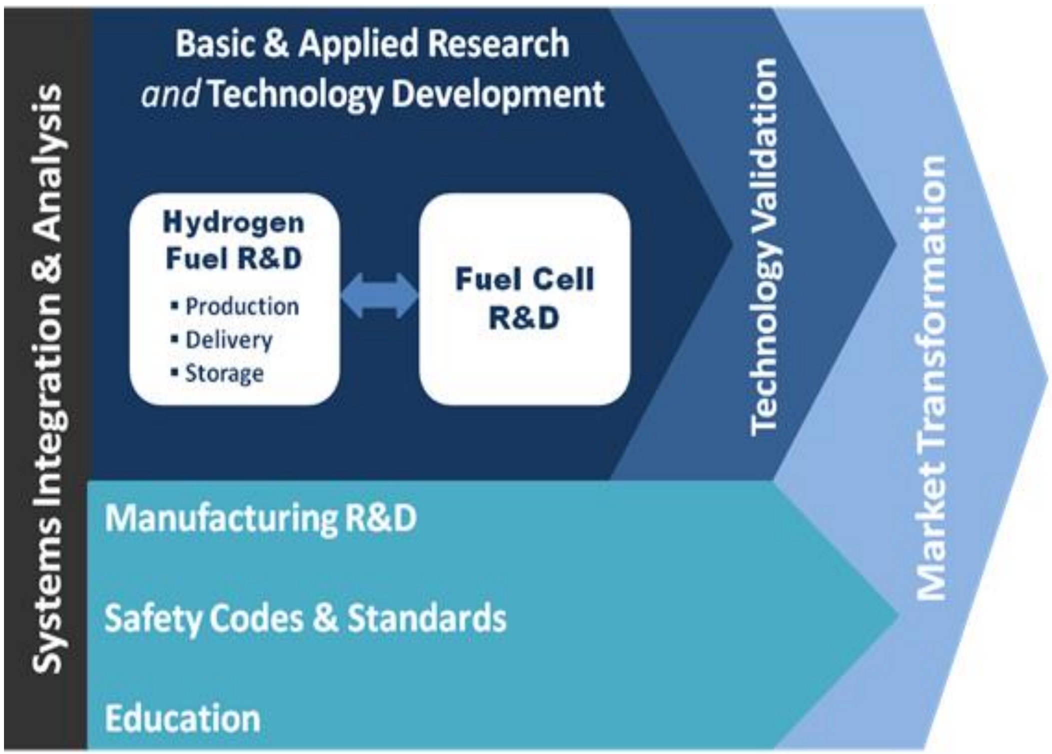
*Compared to 2035 gasoline vehicle
**Compared to 2012 gasoline vehicle

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

Substantial GHG reductions with H_2 produced from renewables

Mission

To enable the ***widespread commercialization of hydrogen and fuel cell technologies***, which will reduce petroleum use, greenhouse gas (GHG) emissions, and criteria air pollutants, and will contribute to a more diverse energy supply and more efficient use of energy.



2020 Targets by Application

Fuel Cell Cost	$40/kW	$1,000/kW* $1,500/kW**
Durability	5,000 hrs	80,000 hrs
H_2 Storage Cost (On-Board)	$10/kWh 1.8 kWh/L, 1.3 kWh/kg	
H_2 Cost at Pump	<$4/gge <$7/gge (early market)	

*For Natural Gas
**For Biogas

Integrated approach to widespread commercialization of H_2 and fuel cells

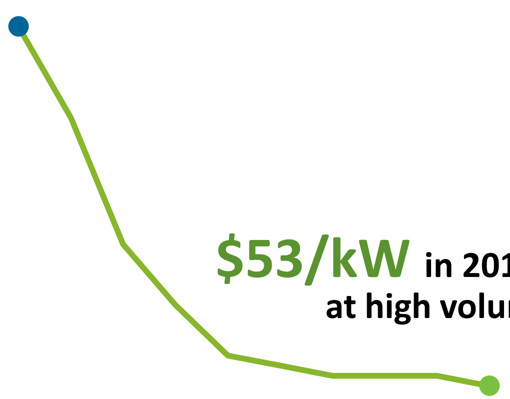
DOE Activities Span from R&D to Deployment

1. Research & Development

Fuel Cells

- **>50% decrease** in cost since 2006
- **5X less** platinum used
- **>4X increase** in durability

$124/kW in 2006



$53/kW in 2015*
at high volume

*$280/kW low volume

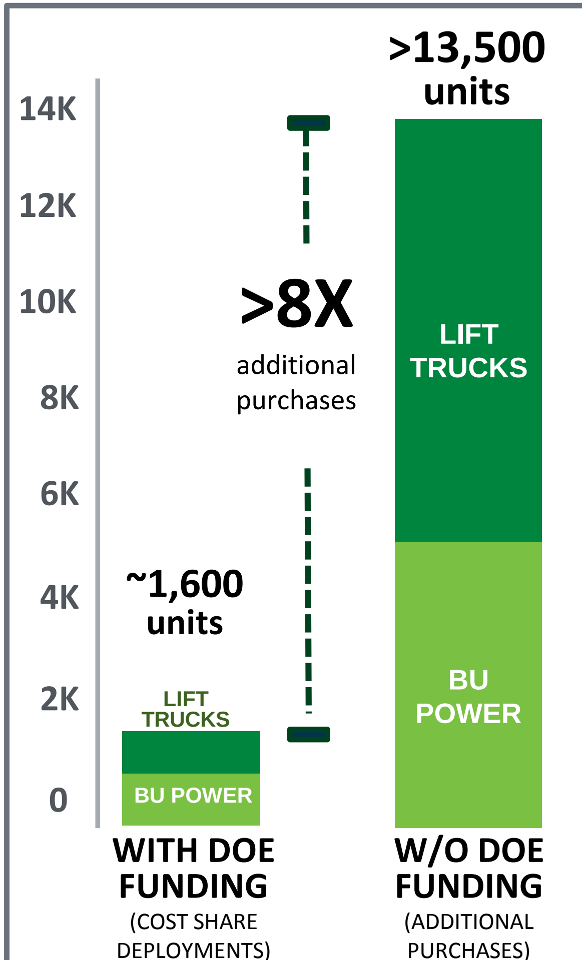
2. Demonstration

Forklifts, back-up power, airport cargo trucks, parcel delivery vans, marine APUs, buses, mobile lighting, refuse trucks

>220 FCEVs, 30 stations, 6M miles traveled

World's first tri-gen station

3. Deployment

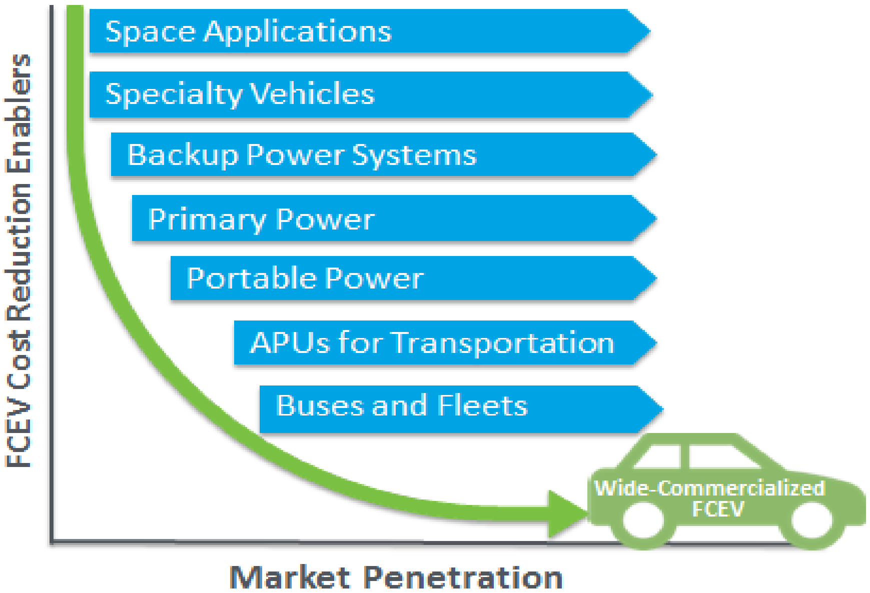


BU: Back Up Power

Early Market Strategies Increase Volume

Early Markets enable:

- Fuel cell **cost reduction**
- Robust **supply base**
- Emerging **infrastructure**
- Customer **acceptance**



Early Markets Applications Recently Deployed in the U.S.

Fuel Cell Tow Trucks

Fuel Cell Bus Fleets

Forklifts

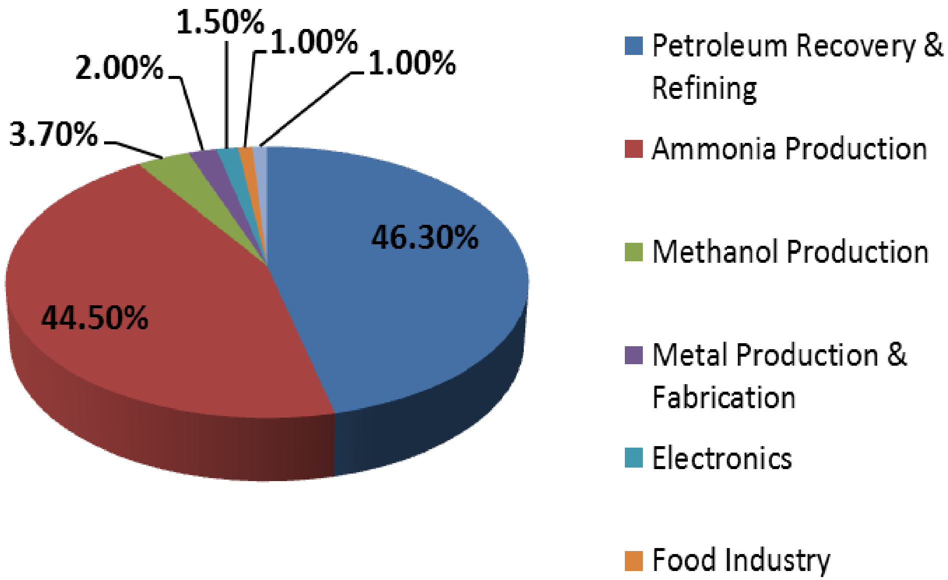
Backup Power

H_2 Production: Current Status

~10 million* metric tons of H_2

mostly from:

- **Steam methane reforming of natural gas (SMR)**

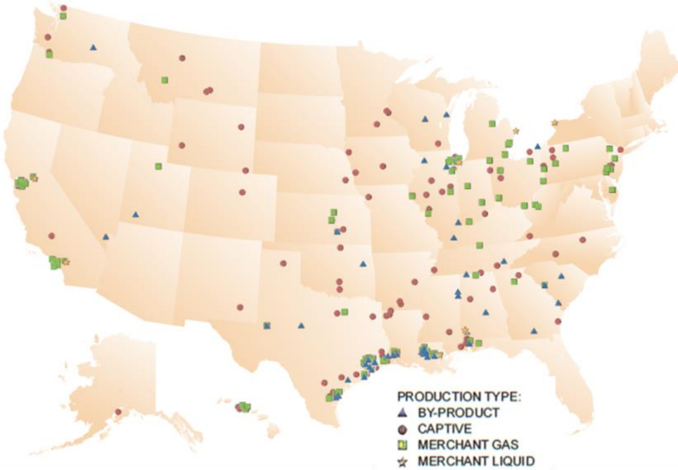


H_2 consumption market share by application

*CryoGas International. Hydrogen Production and Consumption in the US- the last 25 years (Sep 2015).

Near-term strategy for cost-competitive hydrogen fuel

- **H_2 from Natural Gas** through SMR
- **At-scale** production
- **<$2/gge produced** ($4.50/gge delivered)



Centralized H_2 production facilities

Early adoption of H_2 and fuel cell technologies can leverage production and delivery infrastructure associated with low cost NG reforming

Examples of Global Infrastructure Activities

Hydrogen Supply/Utilization Technology (HySUT)

- 18 companies (3 car companies) with plans to commercialize FCEVs and build infrastructure by 2015
- **FCEVs and H2 Stations- 40K & 160 by 2020, 200K and 320 by 225 and 800K & 900 by 2030**.

H2Mobility

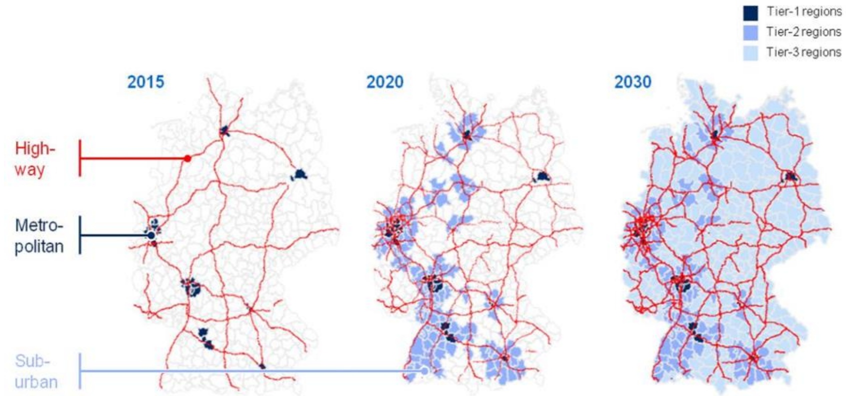
- Public-private initiative for nationwide H_2 infrastructure
- **50** H_2 stations and **5,000** FCEVs by 2015

UKH2Mobility

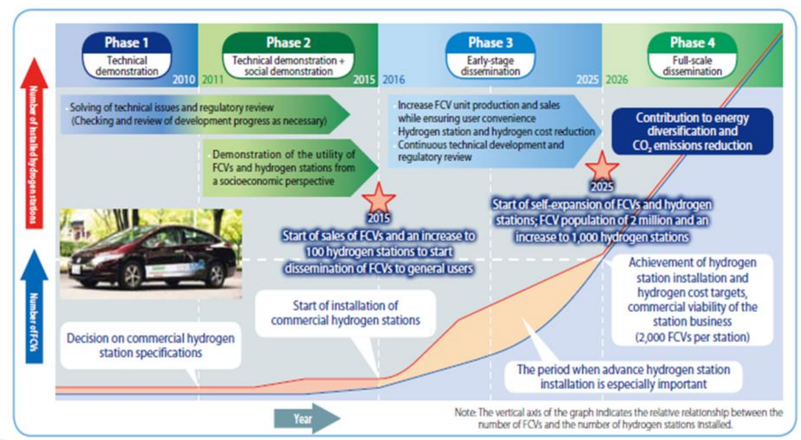
- Evaluating anticipated FCEV rollout in 2014-2015
- Will develop action plan to make UK a leading market for FCEVs

Scandinavian H2 Highway Partnership (SHHP)

- Denmark, Norway and Sweden
- **45** H_2 **stations** and a fleet of **~1K vehicles.** Projects include H2Moves Scandinavia and Next Move
- 2012 MOU with industry and NGOs for FCEVs and H_2 infrastructure introduction by 2015 timeframe



	2015	2020	2030
No. of FCEVs Thousands	~ 5	~ 150	~ 1,800
No. of HRS	~ 100	~ 400	~ 1,000
Total population covered by HRS Percent	~ 20	~ 60	~ 100



*Assumption: FCV user benefits (price, convenience, etc.) have been secured, and dissemination proceeds steadily.

Source: Fuel Cell Commercialization Conference of Japan

International partnerships established to accelerate hydrogen infrastructure

H_2USA: Public-Private Partnership

H_2 USA

Partners

~ 45 Partners in 2015

Mission

To address hurdles to **establishing hydrogen fueling infrastructure,** enabling the **large scale adoption of fuel cell electric vehicles**

Structure

4 Working Groups coordinated by the **Operations** Steering Committee

H_2FIRST Coordination panel

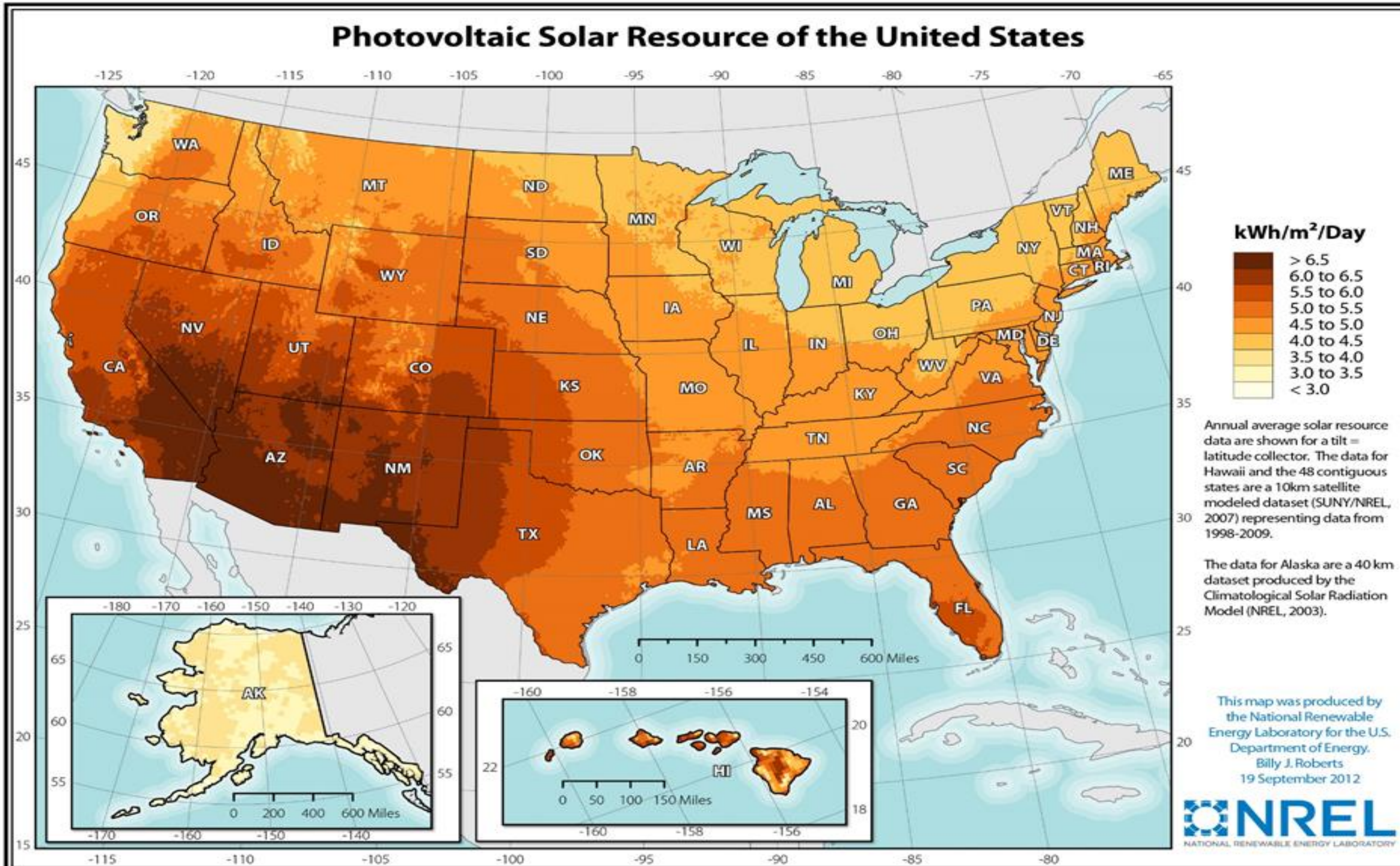
H_2FIRST

H_2USA's Working Groups

- Hydrogen Fueling Station
- Locations Roadmap
- Financing Infrastructure
- Market Support & Acceleration

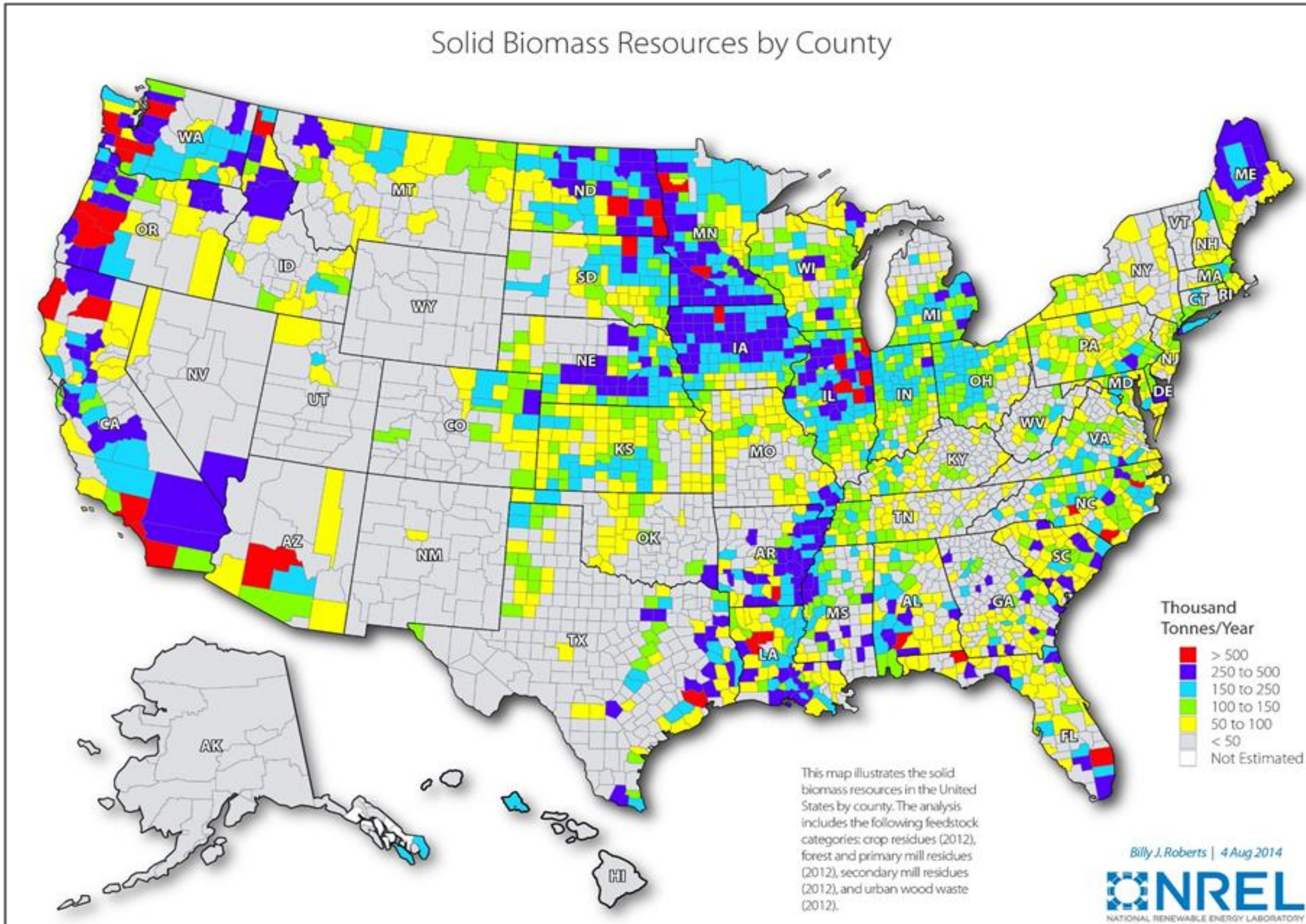
More than 45 partners working towards adoption of FCEVs and H_2

Solar Sources: Opportunity for Renewable H_2



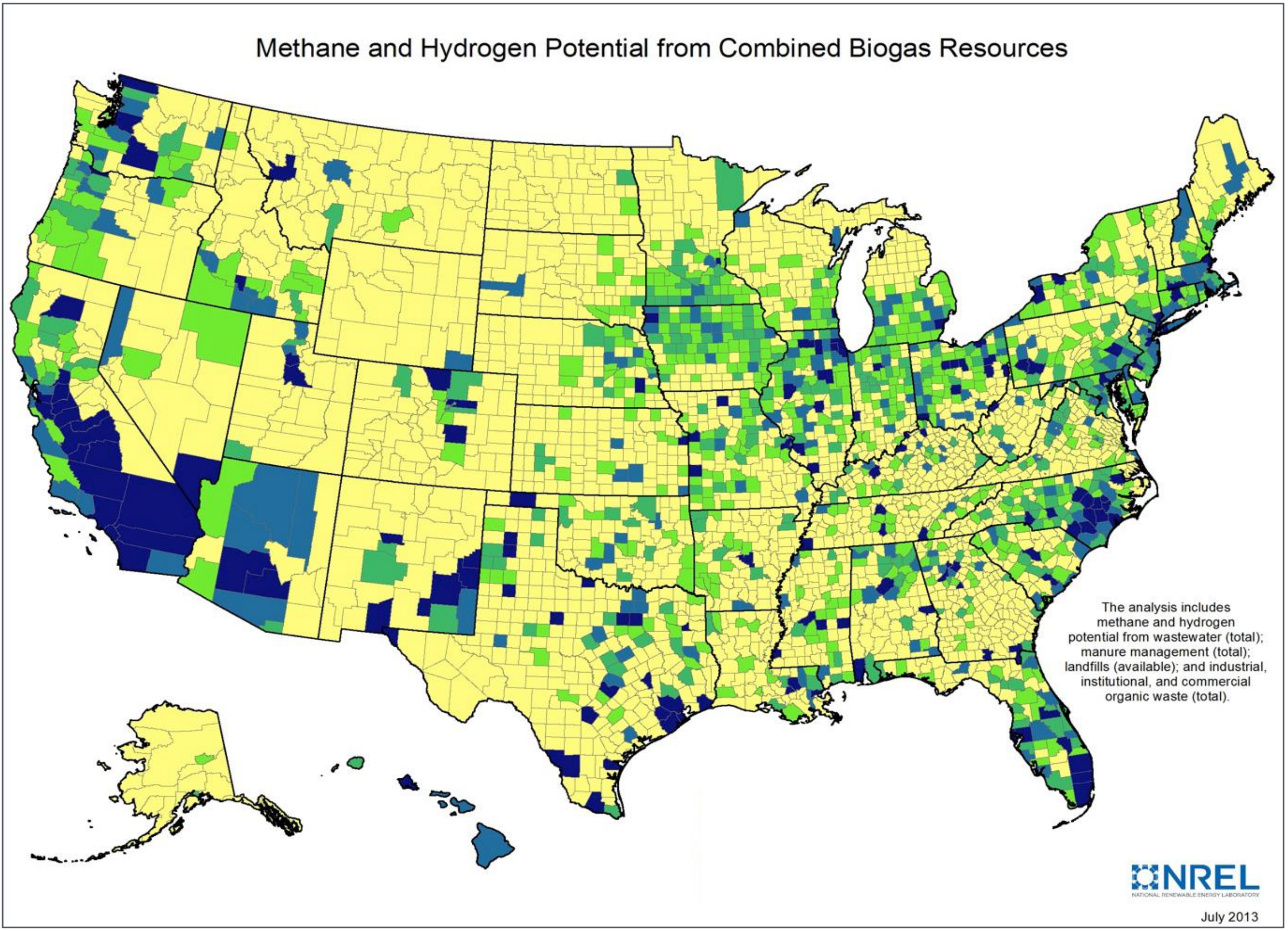
Solar water-splitting is an important longer term option

Biomass Resources: Opportunity for Renewable H_2



Bio-feedstock reforming is a near term option

Biogas Resources: Opportunity for Renewable H_2



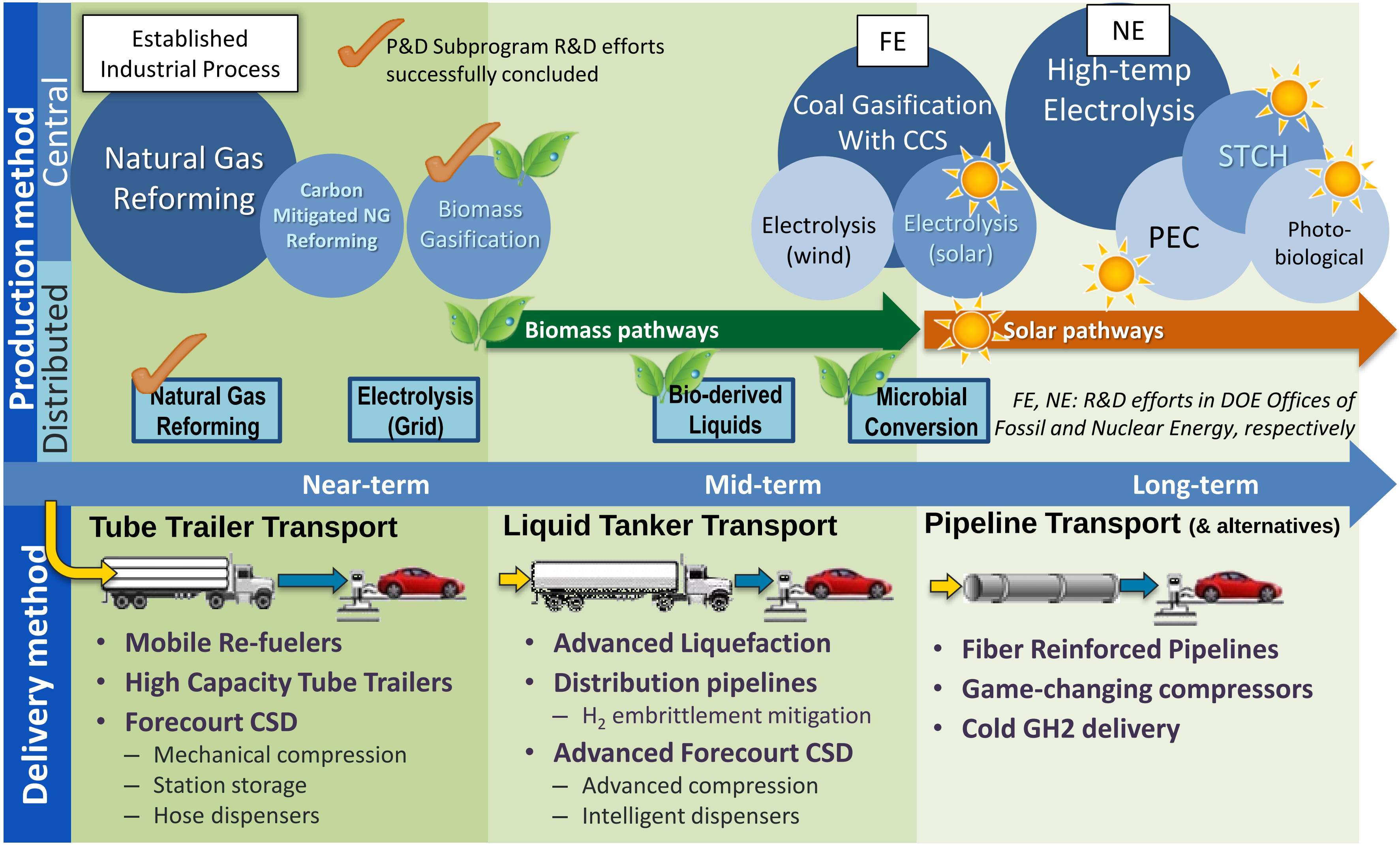
Methane potential in tonnes (Hydrogen potential in tonnes)

- > 10,000 (> 2,670)
- 5,000 - 10,000 (1,149 - 2,670)
- 2,500 - 5,000 (660 - 1,149)
- 1,000 - 2,500 (264 - 660)
- < 1,000 (< 264)

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

H_2 Production and Delivery Broad Technology Portfolio



Goal to develop technologies to produce H_2 from clean, domestic resources at a delivered & dispensed cost <$4/gge by 2020 (<$2 production,<$2 delivery)

H_2 Production Pathways Cost Status

Current Technology

- Natural Gas (D/C)
- Electrolysis (D)

Near to Mid-Term:

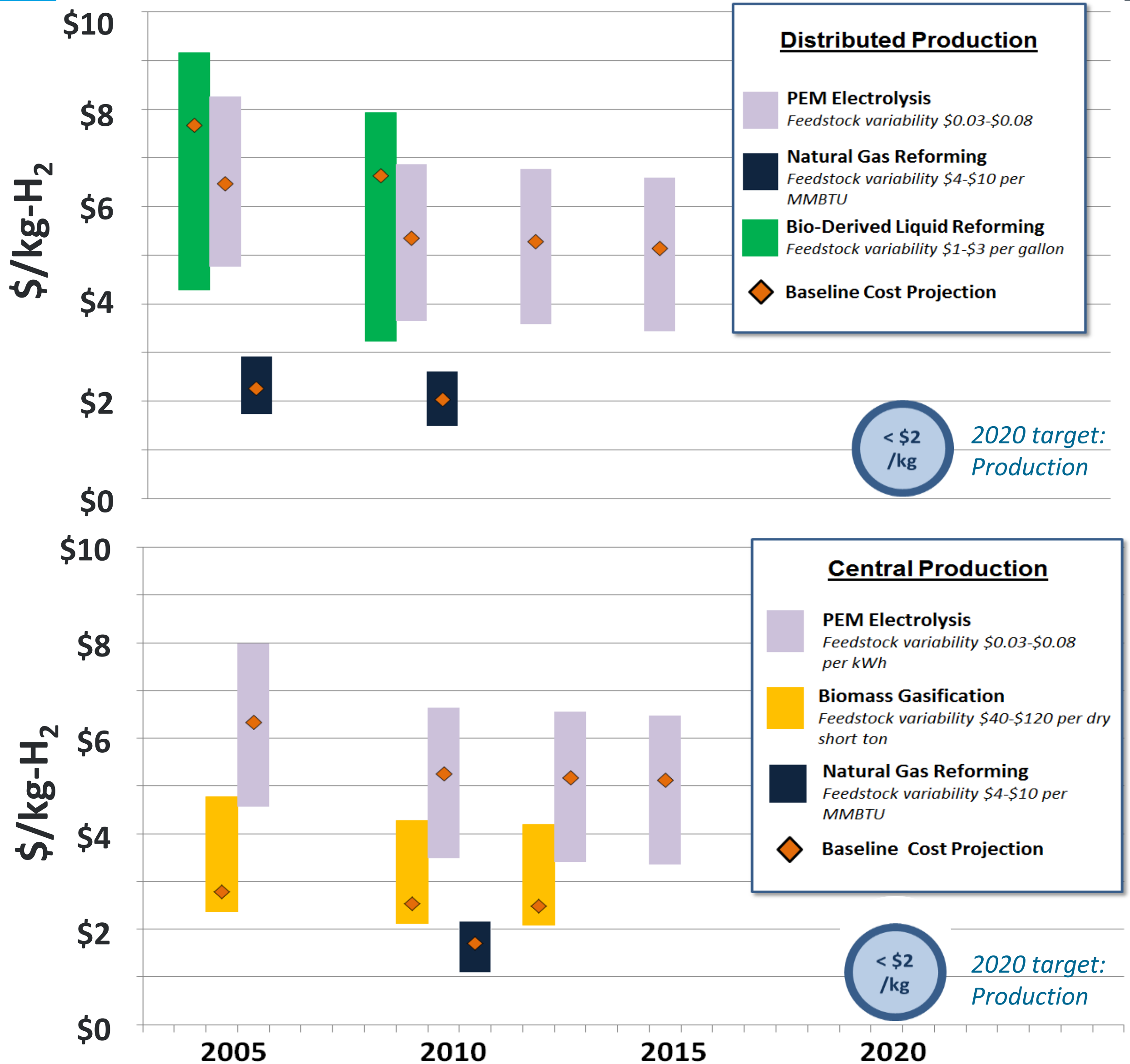
- Electrolysis- Wind and Solar Powered (D/C)
- Bio-derived Liquids (D/C)
- Fermentation (D/C)

Long-Term (not shown):

Central Renewable H_2

- Solar-based water splitting
- Photolytic Bio-hydrogen

D- Distributed **C- Central**



H_2 from NG can be competitive today - renewables is a longer-term focus

The hardest problems of pure and applied science can only be solved by the open collaboration of the world-wide scientific community

Kenneth G. Wilson

Nobel Prize, 1982 in Physics

Renewable Hydrogen- Materials Challenges

Production Pathways using Renewable Feedstock

Photoelectrochemical

Thermochemical

Advanced Electrolysis

Requiring

Efficient, durable and cost effective materials:

Catalysts for Conversion of renewable feedstocks
(e.g., H_2O and bio-feedstocks) to H_2

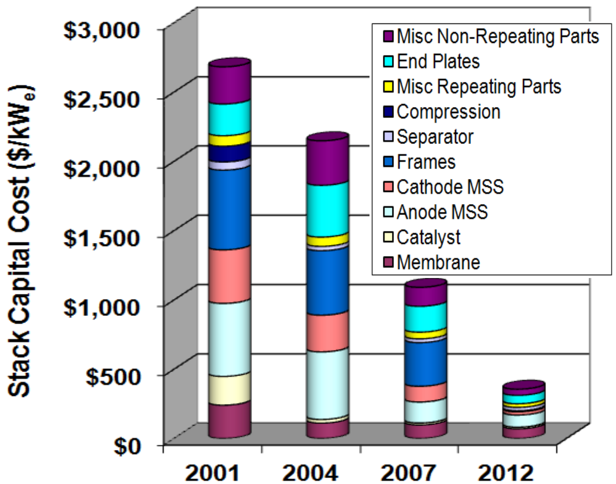
Solar conversion
for PEC and STCH production pathways

Membrane separator
for electrolytic, PEC and hybrid STCH processes

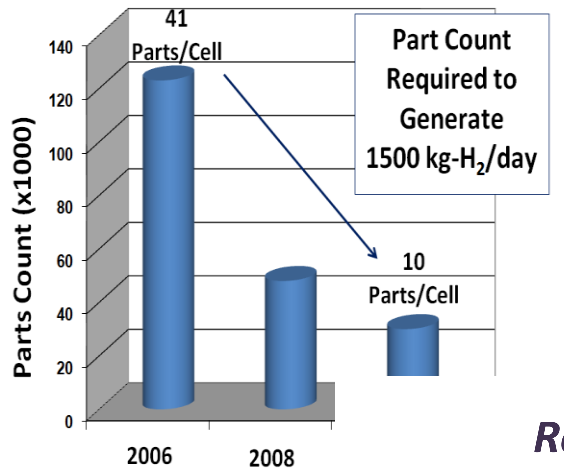
Integrated theory and experiments: Efficient approach to renewable H_2 R&D

PEM Electrolysis Achievements

Major Reduction in Electrolyzer Capital Costs:



Source: Giner Inc



Innovations continue to improve advanced water splitting technologies and reduce costs

- **2001-2011: >80% reduction in electrolyzer stack cost** through design optimization and manufacturing innovations since 2001 to less than $400/kW
- **2011- present: > 40% reduction in cell stack cost** for a large active area (>500 cm^2) electrolysis cell design compared to 2011 baseline with bipolar plate innovations

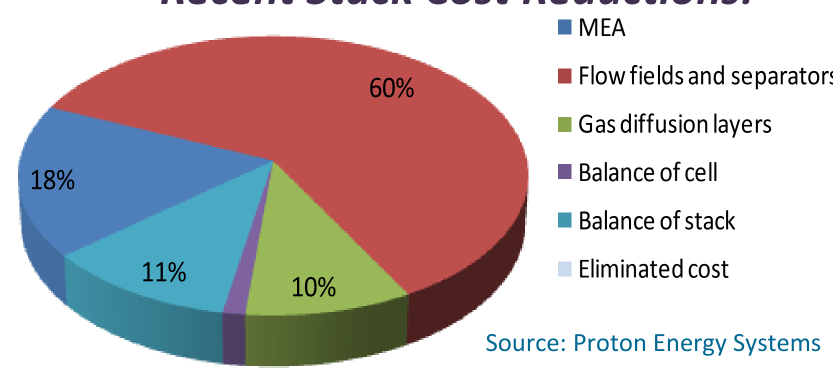
18%

11%

10%

1%

Recent Stack Cost Reductions:



Source: Proton Energy Systems

2011 Baseline (~$1.00/kg H_2)

~40% reduction

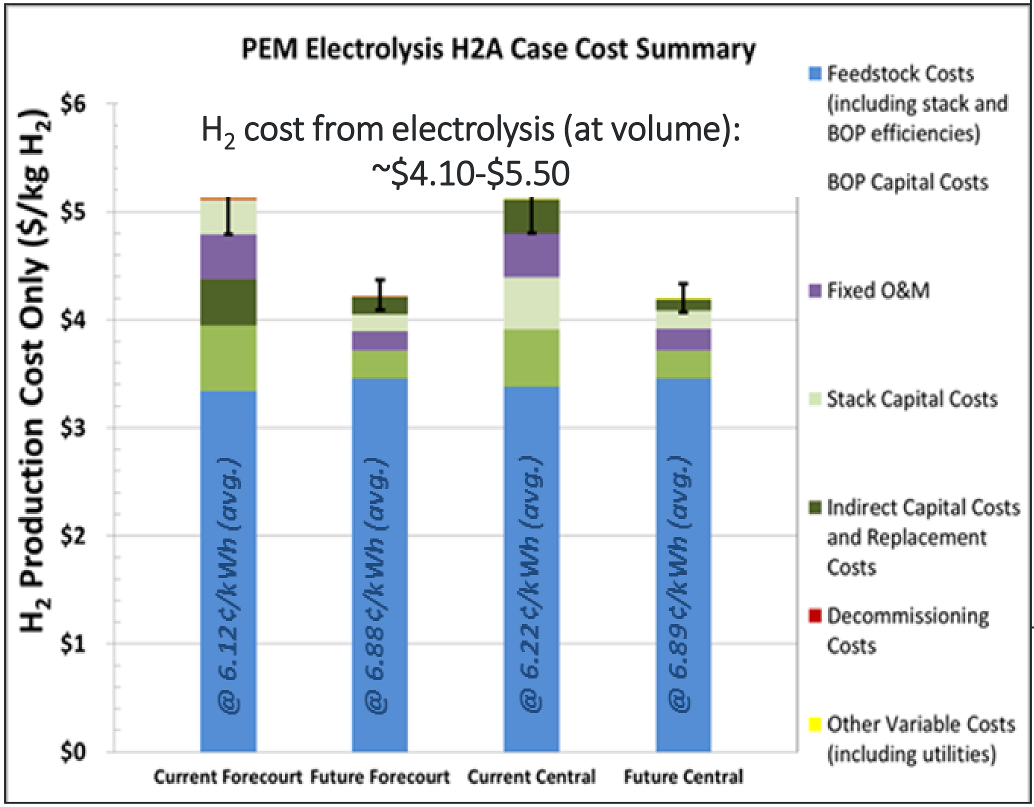
Balance of stack

Eliminated cost

Current Status (~$0.60/kg H_2)

Hydrogen Production & Delivery

Goal: Hydrogen from diverse domestic resources for < $4/gge by 2020 (delivered, dispensed, untaxed)



Examples of Focus Areas

Near Term:

- Minimize cost of 700 bar hydrogen at refueling stations

Long Term:

- Improve performance and durability of materials and systems for production from renewable & low carbon sources.
- E.g., Hybrid/High T Electrolysis, Bio-Derived Liquids, Solar Water Splitting: PEC, STCH, Biological, Microbial Biomass Conversion

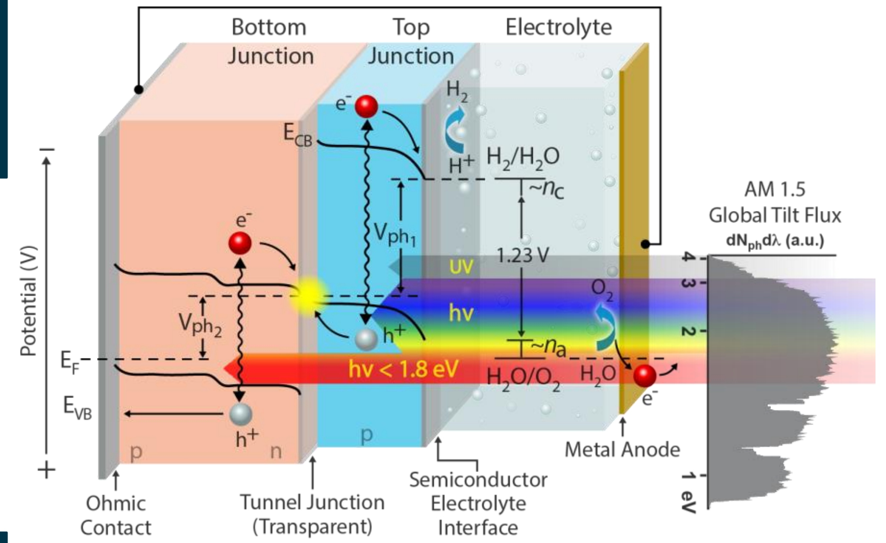
http://www.hydrogen.energy.gov/pdfs/h2a_pem_electrolysis_case_study_documentation.pdf

Photoelectrochemical (PEC) Hydrogen- Highlights

World record for III/V PEC photoelectrode

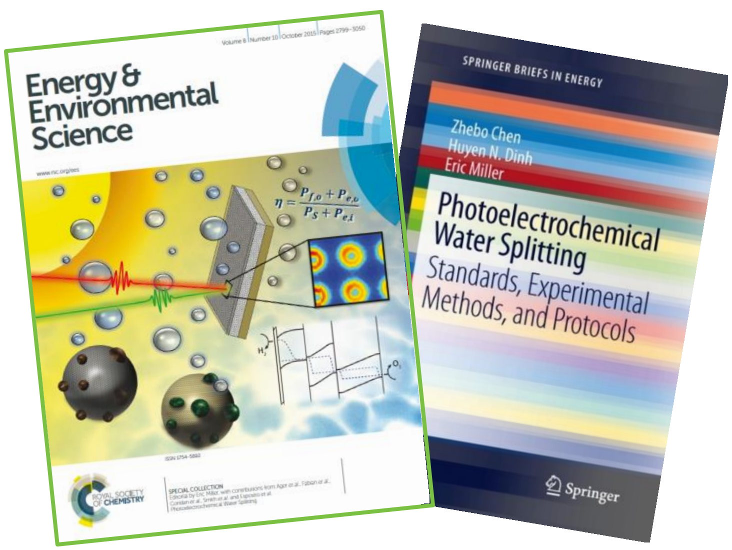
- **~15% efficient $GaInP_2$/InGaAs tandem cell**
- Developed by NREL through incorporating:
  - an Inverted Metamorphic Multi - junction (IMM)
  - a "p-n" junction

PI: Todd Deutsch , NREL:
https://www.hydrogen.energy.gov/pdfs/review15/pd115_deutsch_2015_o.pdf



Information Resources with High Impact

- **Detailed experimental protocols and reporting standards vetted** by national and international experts with **> 16,800 chapter downloads**
- **6 PEC papers published** in a special edition in *Energy & Environmental Science* titled 'Status of Photoelectrochemical Water Splitting: Past, Present, and Future'



Semiconductor materials and devices for direct solar water splitting

JCAP: Electro- and Photo- Catalytic Materials

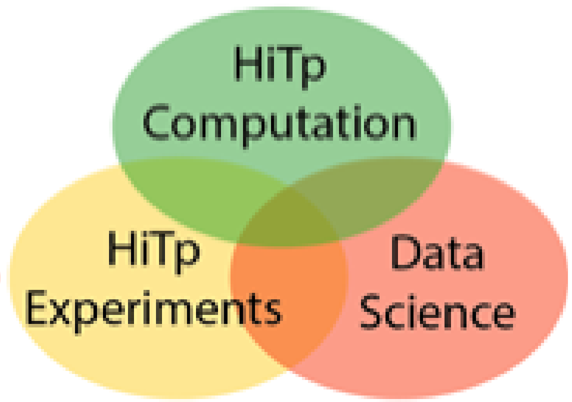
The JCAP "Sunlight to Fuels" Energy Innovation Hub is supported by the DOE Office of Science

Technical Objectives

- **Discover electrocatalysts, light absorbers and interfaces** to advance solar fuels technology
- Identify non-precious functional materials. The electrochemical conditions are relevant to fuel cells.

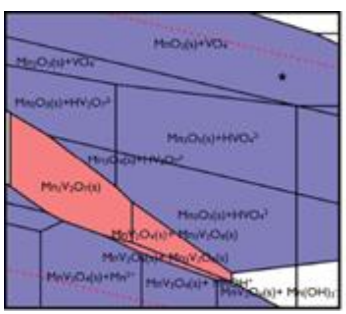
MGI Elements Incorporated

- Advancement of **high throughput experimental and computational methods**, and their mutual integration
- **Data analytics** and access via custom user interface
- Development of composition-property **informatics**

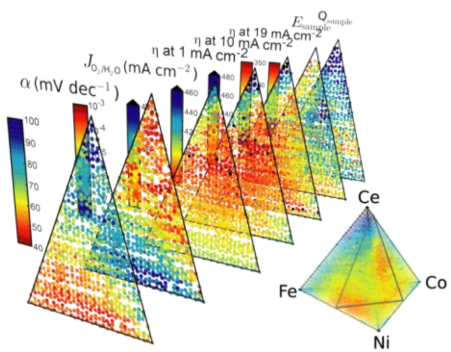


Approach and Outcomes

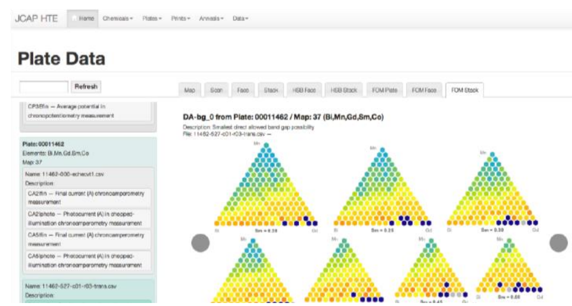
- **Theory-guided HiTp** evaluation of material libraries synthesized using scalable manufacturing techniques
- **High throughput experiments** with requisite data quality to enable robust data informatics
- Recent discoveries include **new classes of electrocatalysts** and illuminating data relationships



theory



experiment



data informatics

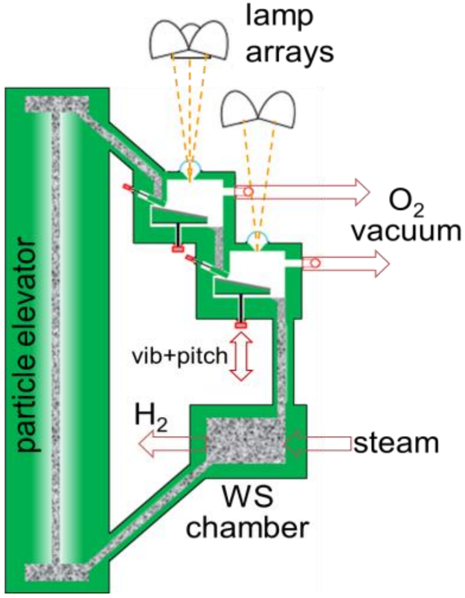
Courtesy of J.M. Gregoire, Caltech; J. Jin, J.B. Neaton and K.A. Persson, LBNL

Innovative high throughput (HiTp) approaches accelerate materials RD&D

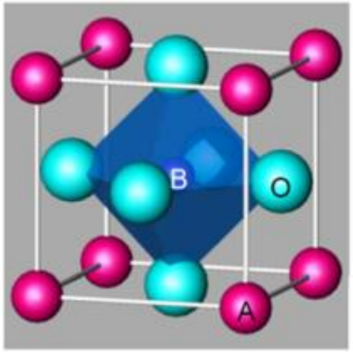
Solar Thermochemical Hydrogen (STCH)

SNL: High Efficiency Redox STCH Reactor

- Designed and started building prototype 3kW cascading pressure reactor/receiver
- Extended approach to material discovery and engineering of thermochemical properties



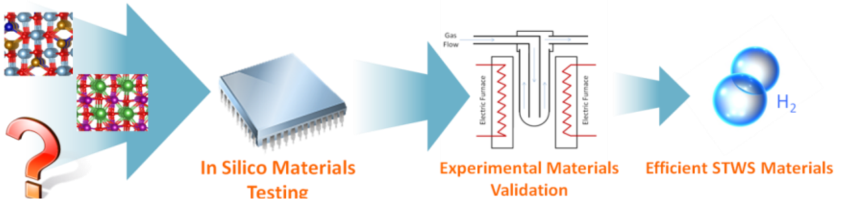
STCH reactor and redox material innovations



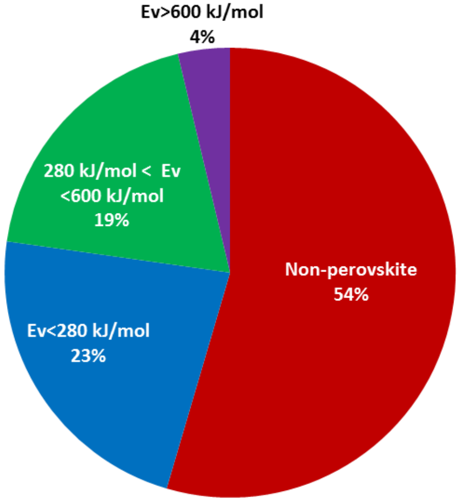
Perovskite cycle: 9x > H_2 than CeO_2 at 150 °C lower temp

PI: Tony McDaniel, SNL:
https://www.hydrogen.energy.gov/pdfs/review15/pd113_mcdaniel_2015_o.pdf

CU: Accelerated Redox Materials Discovery



>1045 materials screened since April 2015



- Use state-of-the-art electronic structure theory to develop design rules for new materials
- Developing digital data base for material screening to down-select candidate redox materials with the best performance

PIs: Al Weimer, Charles Musgrave, CU Boulder:
https://www.hydrogen.energy.gov/pdfs/review15/pd114_weimer_2015_o.pdf

STCH Redox materials RD&D is focused by reactor performance requirements

Lab Consortia Approach

Activities

Consortia Core

- **Fuel Cells: FC-PAD** (Fuel Cell Performance and Durability)
- **Storage: HyMARC** (Hydrogen Storage Materials Advanced Research Consortium)
- **ElectroCat – Just Launched!**
- **Renewable H2 Production (planned)**

Projects added through FOAs

- Companies, universities, labs
- 2-4 yrs/project
- May include seedling projects

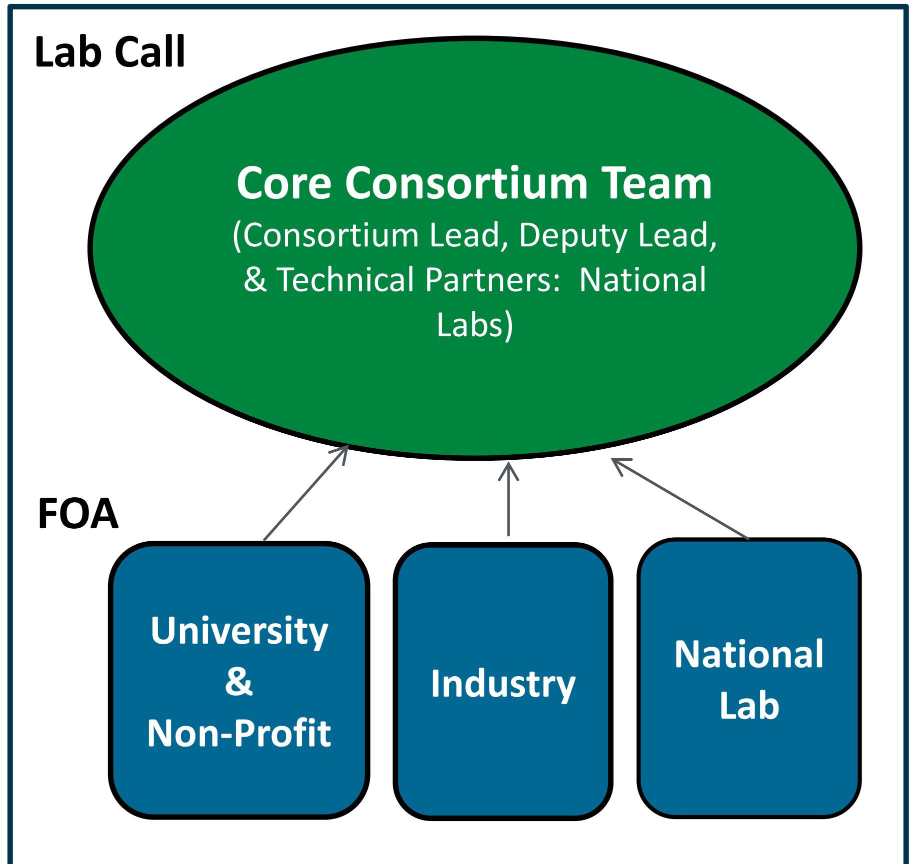
* Subject to appropriations

Potential Future Collaborations

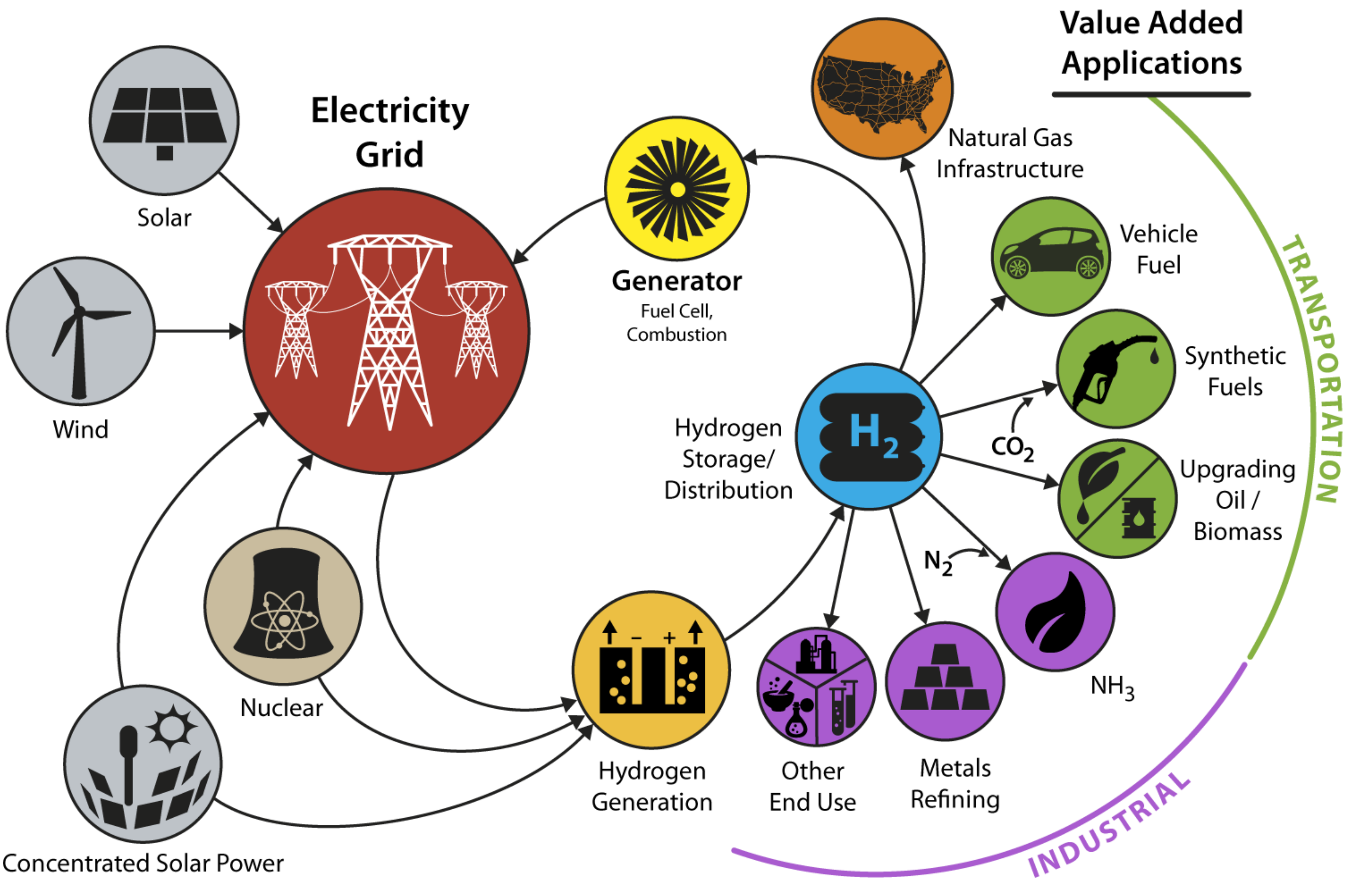
Relevant Offices and other Agencies (e.g. Office of Science , Advanced Manufacturing Office, etc.)

Strategy and Structure

Multi-Lab team with Lab Call to competitively select core team



H_2 at Scale as Key Part of Solution



Source: NREL; Lab Big Idea Summit

Going Forward

- **Continue to strengthen R&D activities and accelerate Tech to Market (Lab impact)**
  - **Continued emphasis on safety, H_2 production, delivery, storage and fuel cells**
  - **Key Focus: Renewable H_2**
  - **Consortia and high throughput + computational approaches**
- **Continue to conduct key analyses to guide RD&D and path forward**
  - **Life cycle cost; infrastructure, economic & environmental analyses, sustainability for various pathways, cradle to grave, jobs, etc.**
- **Leverage activities to maximize impact**
  - **U.S. and global partnerships, H2USA, States**

Save the date: Annual Merit Review (AMR)
June 6-10, 2016- Washington DC

Outreach and Communication Efforts

- **Publications- ~100/yr**
  - Monthly Newsletter
  - Success Stories
  - News Alerts, Blogs
- **Educated:**
  - **>12,000** teachers
  - **>35,000** code officials & first responders
- **Investor Days**
- **Congressional Caucus Events**
- **Annual Merit Review**

June 2015- >1,800 attendees

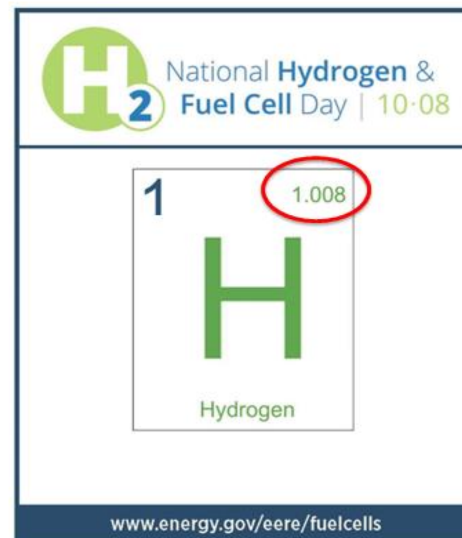
Save the Date: 2016 AMR- June 6-10

- **Ride & Drives**

U.S Department of Energy Secretary Ernest Moniz test driving the Toyota Mirai

- **Events**

2015: 1st year the U.S. **to celebrate Hydrogen and Fuel Cells Day**



Increasing public awareness and understanding about fuel cells and H_2

Thank You

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