Fuel Cells and Hydrogen Enabling Large Scale Renewable Energy

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IPHE Hydrogen for Energy Storage Workshop in Seville Spain,

15-16 November, 2012

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Fuel Cell Technologies Program

Outline

- Exponential Renewable Energy Growth
  - Faster than HV Transmission Lines can be Built
- Hydrogen as an Energy Carrier
  - Multiple Production Sources and Applications
- High Efficiency Fuel Cells
  - Longer Runtimes for Equivalent Energy Use
- Hydrogen for Energy Storage
  - Low Cost for Large Storage Requirements to Manage Intermittency of Renewable Energy

Exponential Renewable Energy Growth

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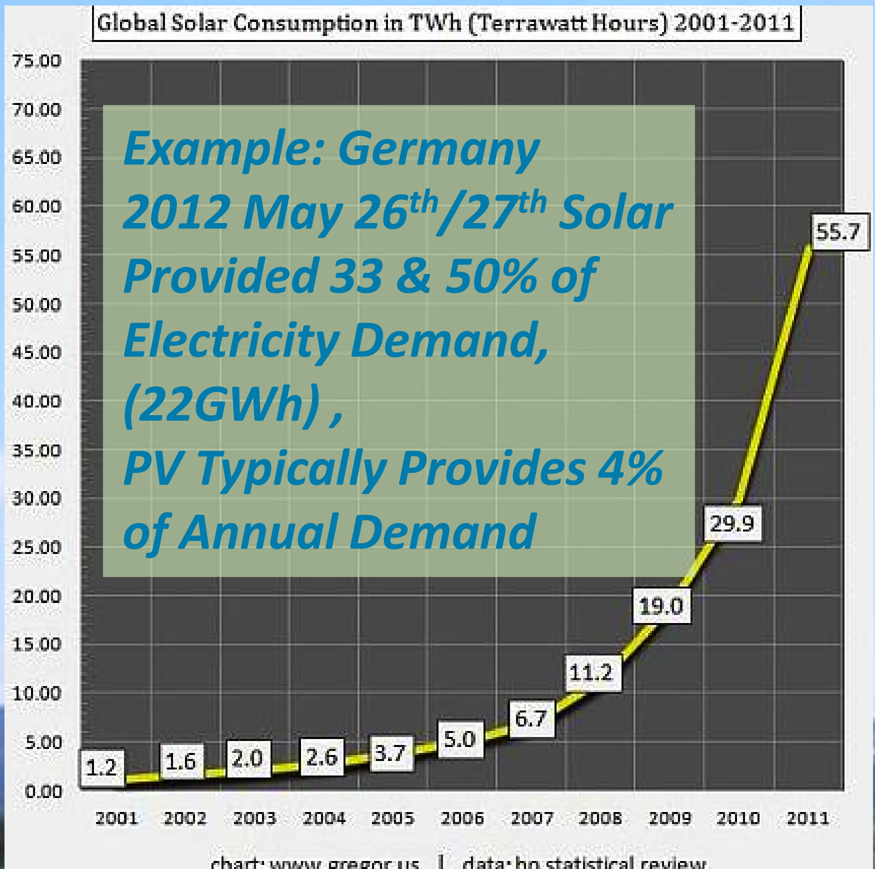


Example: Germany
2012 May 26th/27th Solar Provided 33 & 50% of Electricity Demand, (22GWh) ,
PV Typically Provides 4% of Annual Demand

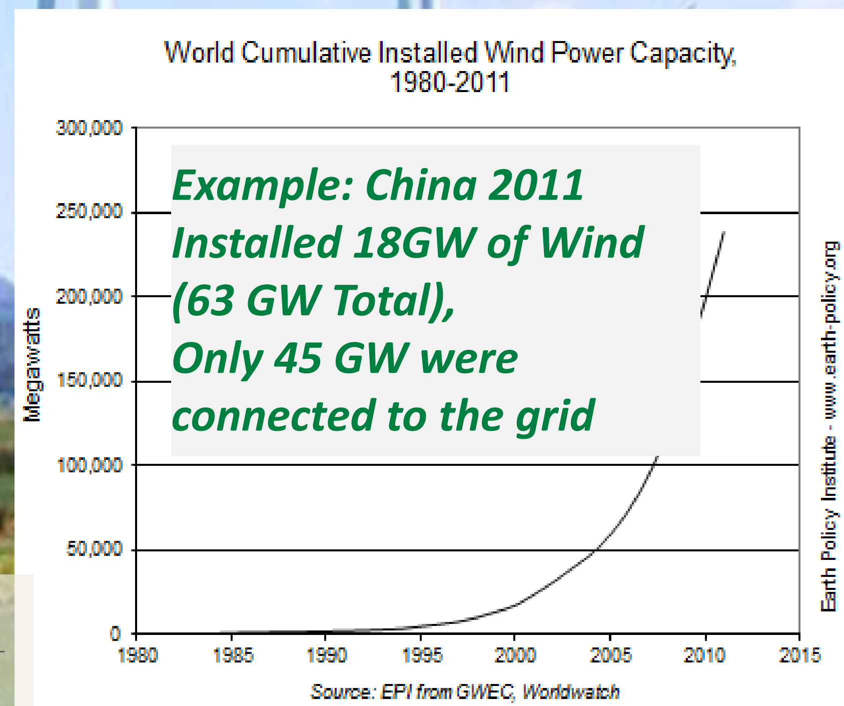
Stronger Electricity Grids Needed Everywhere

2012 Spanish Wind & Electricity

***February-provided 20% of consumption**

***April 16th-briefly provided 60% of demand**

***Long Distance Transmission can take 5 to 10+ years to build out, resulting in a tremendous Opportunity Cost**



Example: China 2011 Installed 18GW of Wind (63 GW Total),
Only 45 GW were connected to the grid

www.green-blog.org/2012/03/28/china-helped-wind-power-climb-to-new-record-levels-in-2011/
www.reuters.com/article/2012/04/16/markets-iberia-power-idUSL6E8FG8NH20120416

http://cleantechnica.com/2012/02/29/wind-energy-output-hit-record-high-in-spain-kept-electricity-prices-lower-than-neighbors/

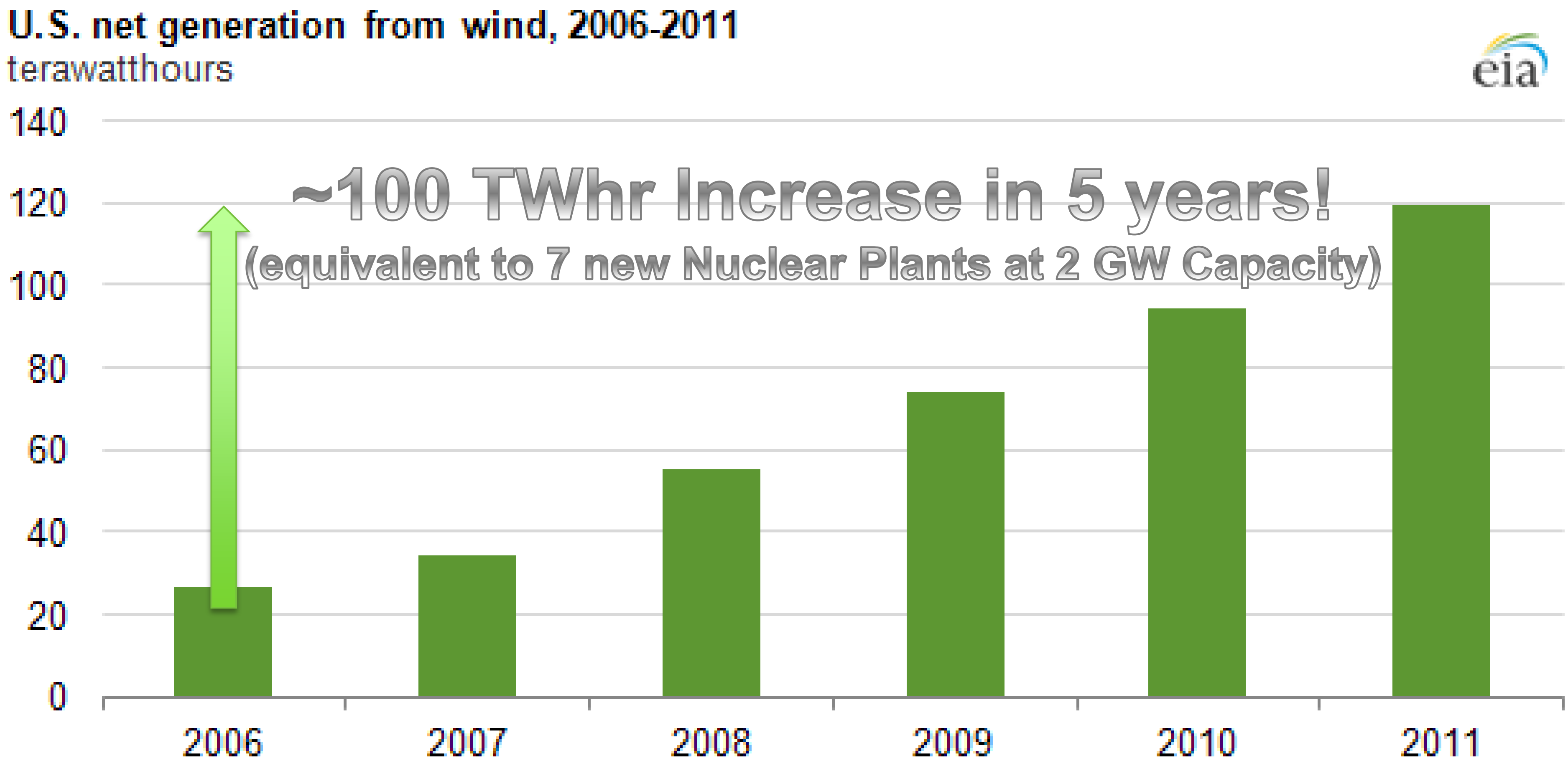
http://www.pv-tech.org/news/germany_breaks_world_record_for_solar_power_generation_with_22gw

http://reneweconomy.com.au/2012/solar-showdown-us-china-tensions-simmer-92222

Transmission can take 10- 20 years to build and cost ~$2M/ mile

~100 Net TWhr production increase over 5 years (~20 TWhr/Yr average growth)

(1 GW Nuclear power plant produces ~7 TWhr in a year at 80% capacity factor)



http://www.eia.gov/todayinenergy/detail.cfm?id=5350

http://www.csmonitor.com/Business/Consumer-Energy-Report/2012/0413/Wind-power-America-s-future

Visualizing the U.S. Grid and Wind

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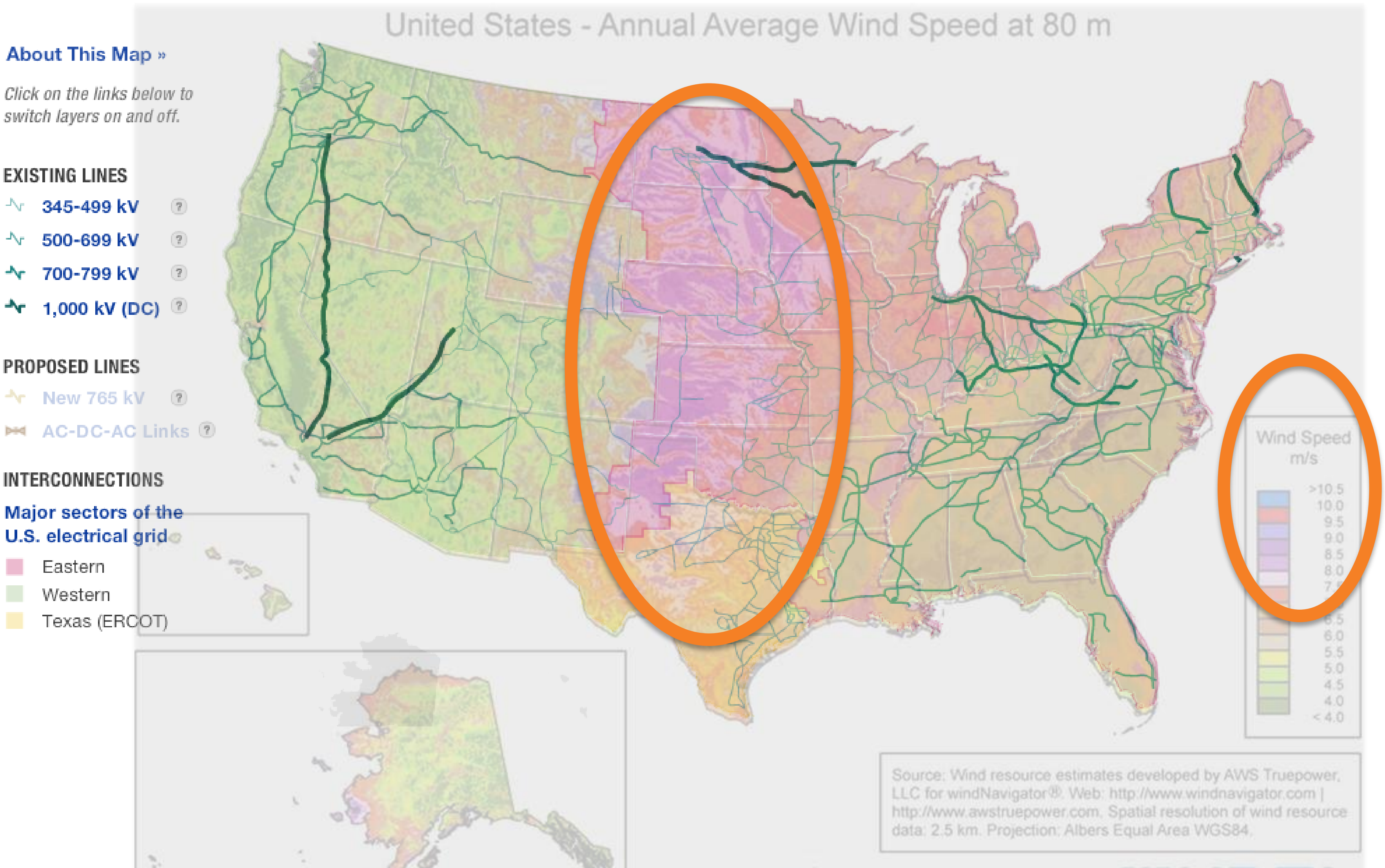
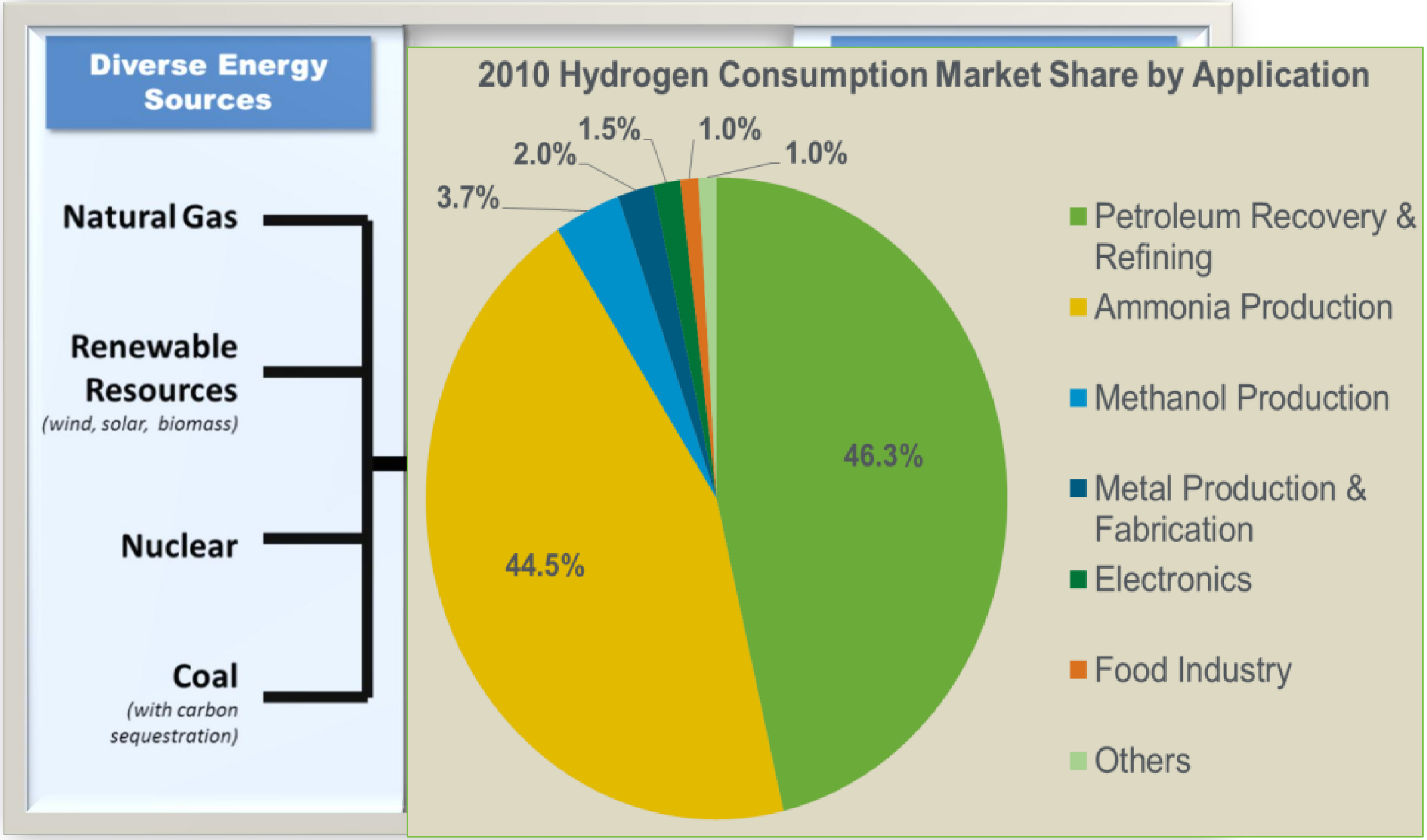


Source: American Electric Power, American Wind Energy Association, Center for American Progress, Department of Energy, Edison Electric Institute, Energy Information Administration, Electric Power Research Institute, Federal Energy Regulatory Commission, National Renewable Energy Laboratory, U.S. Environmental Protection Agency, Western Resource Advocates
Credit: Producer: Andrew Prince; Designer: Alyson Hurt; Editors: Avie Schneider and Vikki Valentine; Supervising Editors: Anne Gudenkauf and Quinn O'Toole; Additional Research: Jenny Gold; Database and GIS Analysis: Robert Benincasa Per National Public Radio http://www.npr.org/templates/story/story.php?storyId=110997398

Hydrogen: A Diverse Energy Carrier



Hydrogen Production

- Natural Gas: ~95% of U.S. H_2 production –baseline efficiency 65-80%
- Electrolysis: baseline efficiency 50-60% efficient (~50-60 kWh/kg H_2)
  - Alkaline w/liquid KOH electrolyte, polymer electrolyte, high temperature ceramic electrolyte

Steam-Reforming Reactions

Methane:

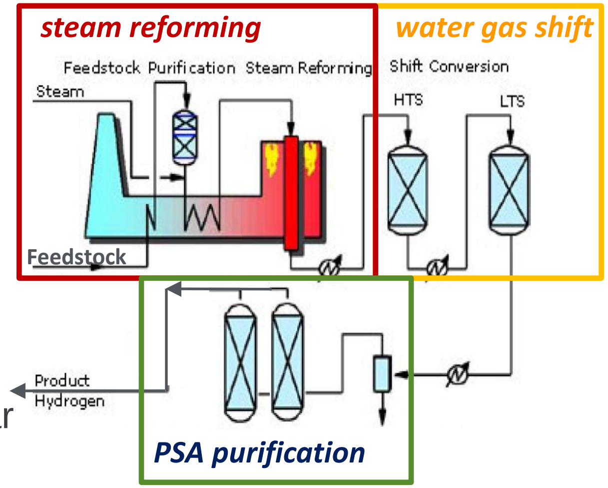
$CH_4 + H_2O$ (+heat) $\rightarrow CO + 3H_2$

Water-Gas Shift Reaction

$CO + H2O \rightarrow CO_2 + H_2$

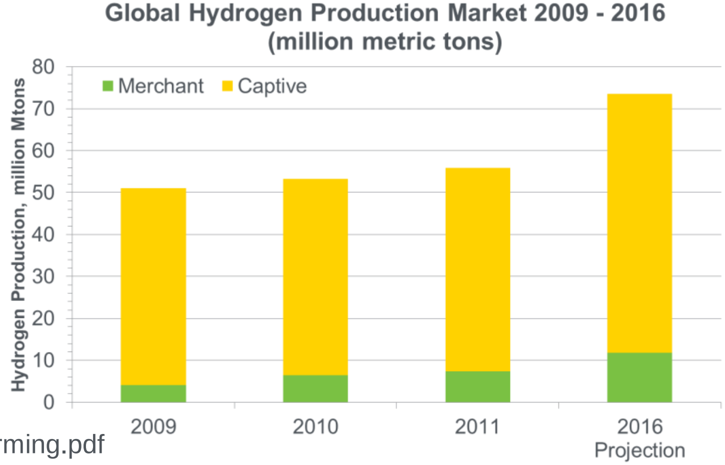
Pressure-Swing Adsorption (PSA)

Purifies H_2 to >99.99% using molecular sieves



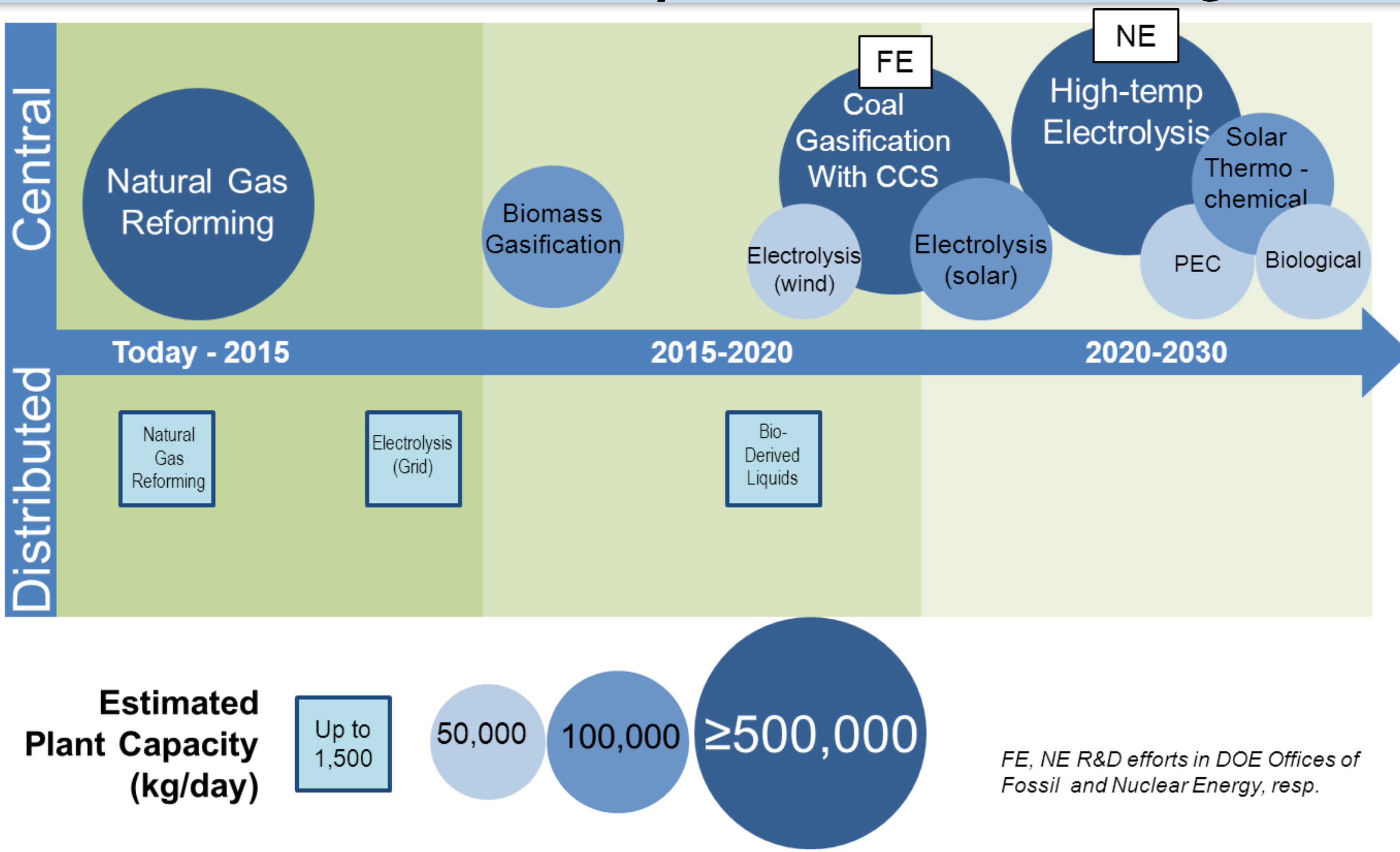
Norsk Hydro Large Electrolysis Stack (975 kg/day)

The global hydrogen market is robust with over 55 Mtons produced in 2011 and over 70 Mtons projected in 2016, a > 30% increase.



http://www1.eere.energy.gov/hydrogenandfuelcells/production/natural_gas.html
http://www.getenergysmart.org/files/hydrogeneducation/6hydrogenproductionsteammethanereforming.pdf

Hydrogen can be produced from numerous diverse domestic resources via large central production and smaller distributed scale production technologies



High Efficiency:
Potential of Fuel Cell Technology

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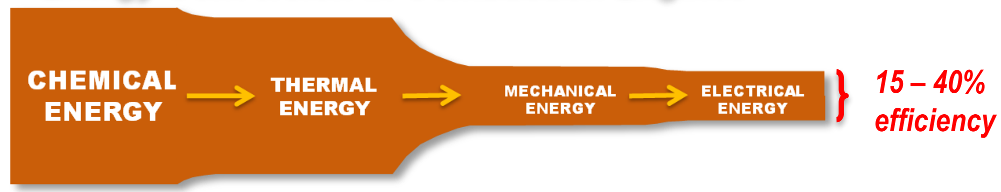
Fuel cells convert chemical energy directly to electrical energy — with very high efficiency — and without PM,CO, SOx, NOx, etc, emissions

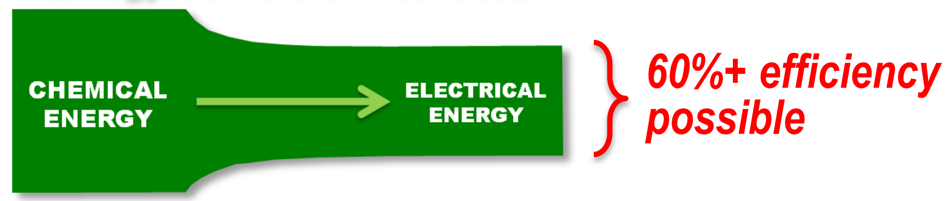
Combustion Engines — convert chemical energy into thermal energy and mechanical energy, and then into electrical energy.

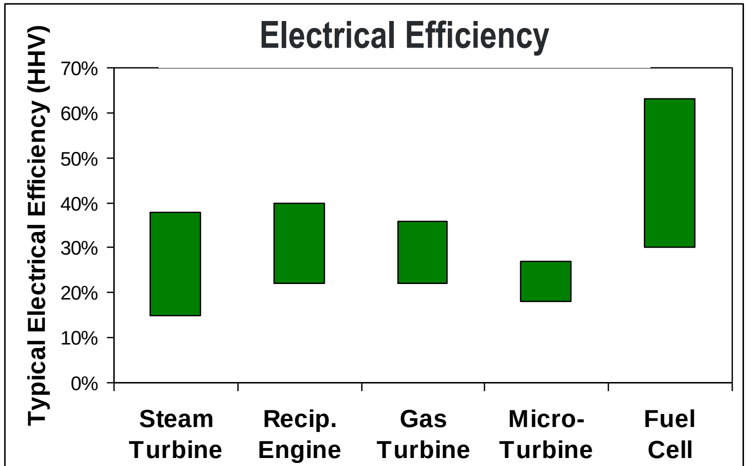
Fuel cells — convert chemical energy directly into electrical energy, bypassing inefficiencies associated with thermal energy conversion. Available energy is equal to the Gibbs free energy.

Energy Conversion in Combustion Engines



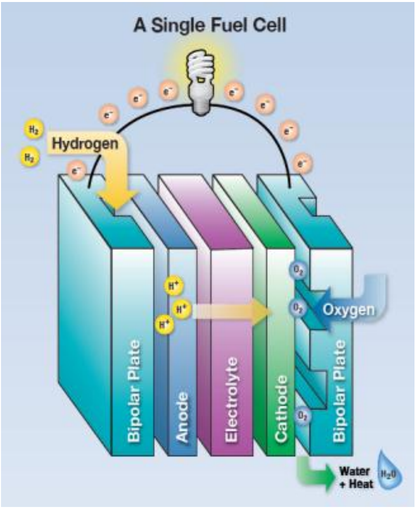
Energy Conversion Fuel Cells





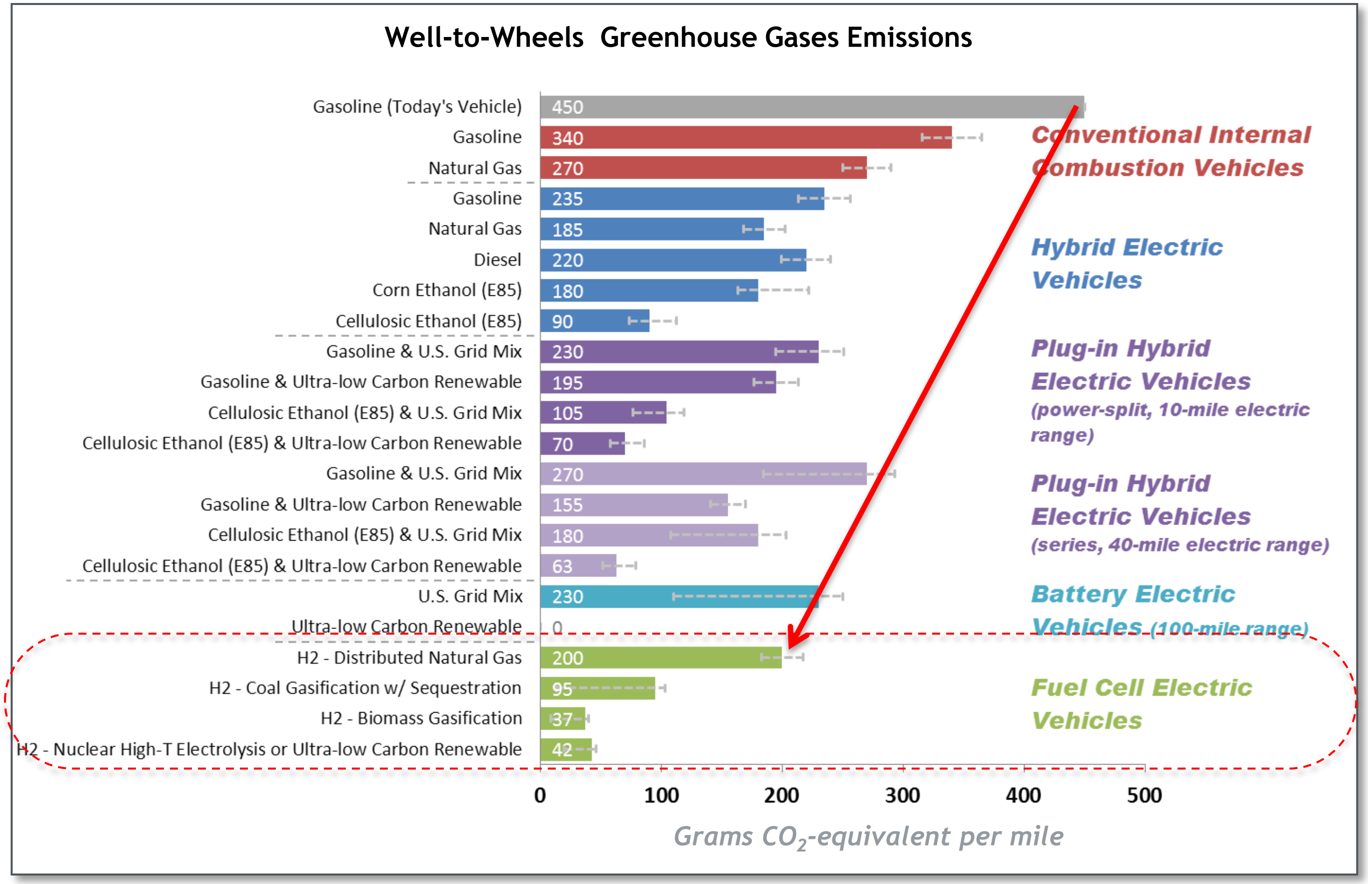
Source: EPA, Catalog of CHP Technologies, December 2008

Fuel cells convert chemical energy directly into electrical energy, bypassing inefficiencies associated with thermal energy conversion



Benefits: Well-to-Wheels CO_2 Analysis

Analysis by Argonne National Lab, DOE Vehicle Technologies Program, and FCT Program shows benefits from a portfolio of options



H_2 from Natural Gas

Even FCEVs fueled by H_2 from distributed NG can result in a **>50% reduction in GHG emissions** from today's vehicles.

Use of H_2 from NG decouples carbon from energy use—i.e., it allows carbon to be managed at point of production vs at the tailpipe.

Even greater emissions reductions are possible as hydrogen from renewables enter the market.

Notes:
For a projected state of technologies in 2035-2045. Ultra-low carbon renewable electricity includes wind, solar, etc. Does not include the lifecycle effects of vehicle manufacturing and infrastructure construction/decommissioning.
Analysis & Assumptions at: http://hydrogen.energy.gov/pdfs/10001_well_to_wheels_gge_petroleum_use.pdf

Fuel Cells (Fuel Sources & Applications)

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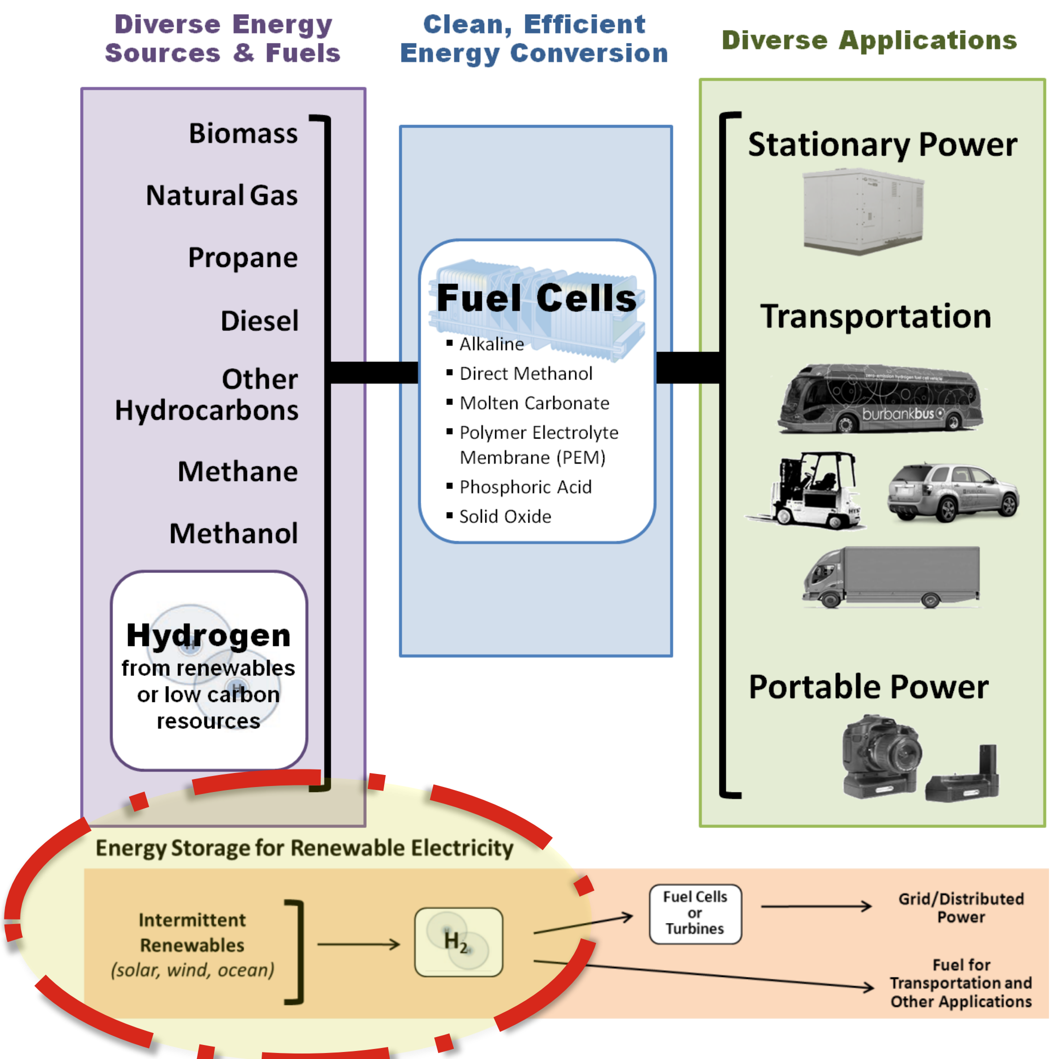

Key Benefits

Very High Efficiency

- **> 60%** *(electrical)*
- **> 70%** *(electrical, hybrid fuel cell / turbine)*
- **> 80%** *(with CHP)*

Reduced CO_2 Emissions

- **35–50%+ reductions** *for CHP systems (>80% with biogas)*
- **55–90% reductions** *for light-duty vehicles*

Reduced Oil Use

- **>95% reduction** *for FCEVs (vs. today's gasoline ICEVs)*
- **>80% reduction** *for FCEVs (vs. advanced PHEVs)*

Reduced Air Pollution

- **up to 90% reduction in criteria pollutants** *for CHP systems*

Fuel Flexibility

- **Clean fuels** — *including biogas, methanol, H_2*
- **Hydrogen** — *can be produced cleanly using sunlight or biomass directly, or through electrolysis, using renewable electricity*
- **Conventional fuels** — *including natural gas, propane, diesel*

Hydrogen can play important role in the transport, storage and efficient conversion of renewable energy in the President's "all of the above" energy strategy.

Fuel Cell Comparison

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Fuel Cell Type	Common Electrolyte	Operating Temperature	Typical Stack Size	Efficiency
Polymer Electrolyte Membrane (PEM)	Perfluoro sulfonic acid	50 - 100°C Typically 80°C	< 1kW– 100kW	60% transportation 35% stationary
Alkaline (AFC)	Aqueous solution of potassium hydroxide soaked in a matrix	25 - 75°C	10 – 100 kW	60%
Phosphoric Acid (PAFC)	Phosphoric acid soaked in a matrix	150 - 200°C	400 kW 100 kW module	40%
Molten Carbonate (MCFC)	Solution of lithium, sodium, and/or potassium carbonates, soaked in a matrix	600 - 700°C	300 kW-3 MW 300 kW module	50%
Solid Oxide (SOFC)	Yttria stabilized zirconia	700 - 1000°C	1 kW – 2 MW	60%

High Profile CHP Installation Underscores Benefits

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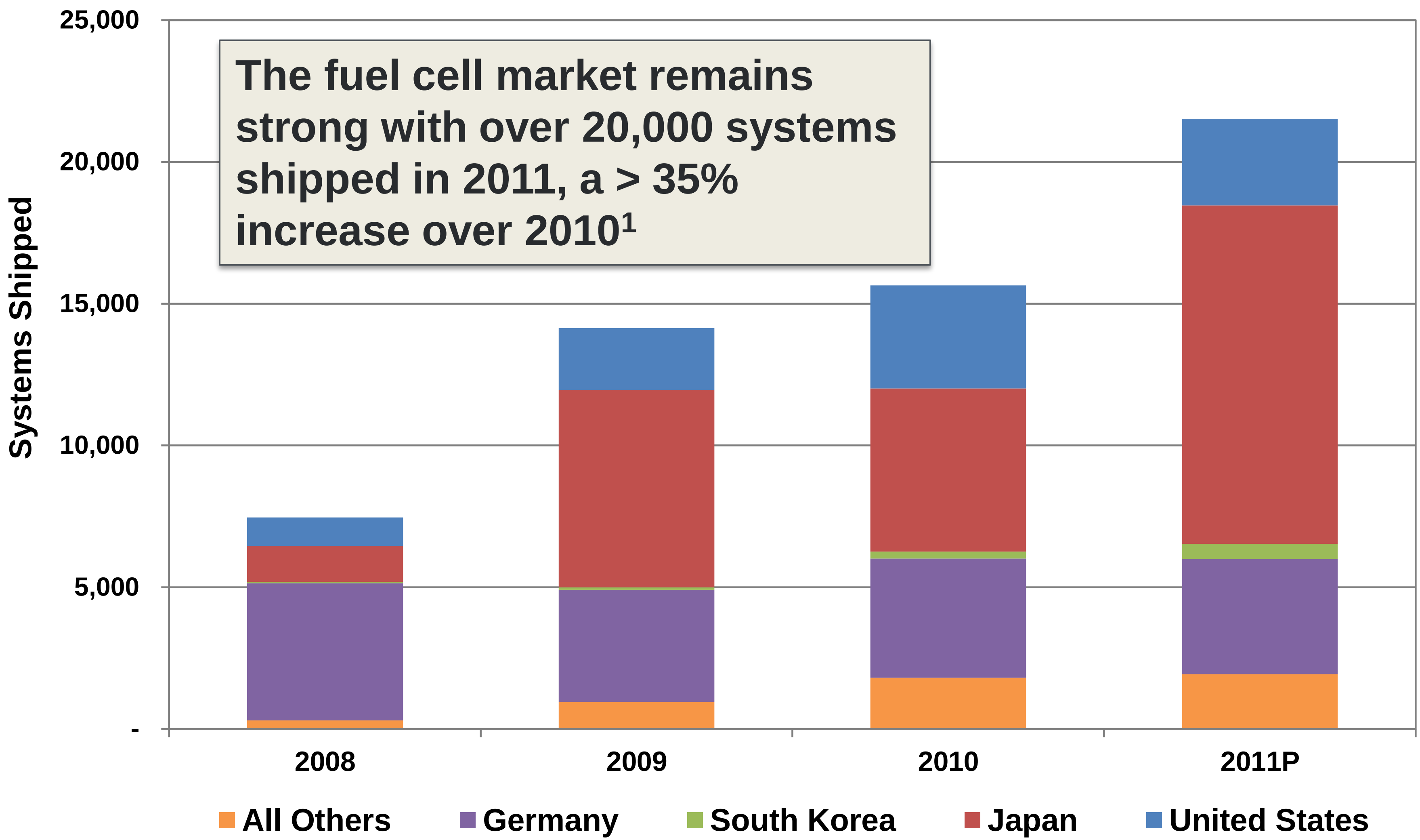
Freedom Tower to tap green fuel cell power:

Low emission fuel cells to provide onsite heat and power for landmark project

"New York's Freedom Tower, the skyscraper being constructed on the site of the World Trade Center, is to use fuel cells to power its heating and cooling systems.

UTC Power, the fuel cell division of engineering conglomerate United Technologies, announced that it has received orders from the ***New York Power Authority (NYPA)*** *for 12 fuel cells totaling 4.8MW of power to serve the Freedom Tower and three other new towers under construction at the site in Manhattan."*

System Shipments by Key Countries: 2008-2011



Sources: FuelCells2000, Pike Research, Markets & Markets

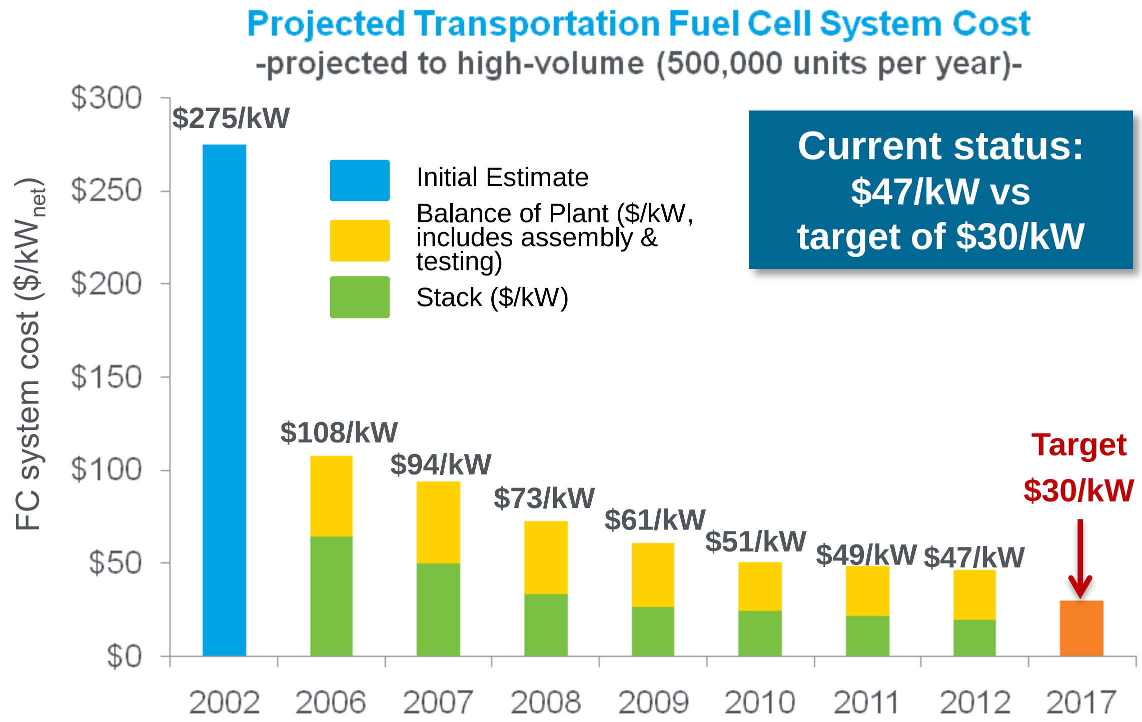
[1]FCT Market Report to be published in June 2012.

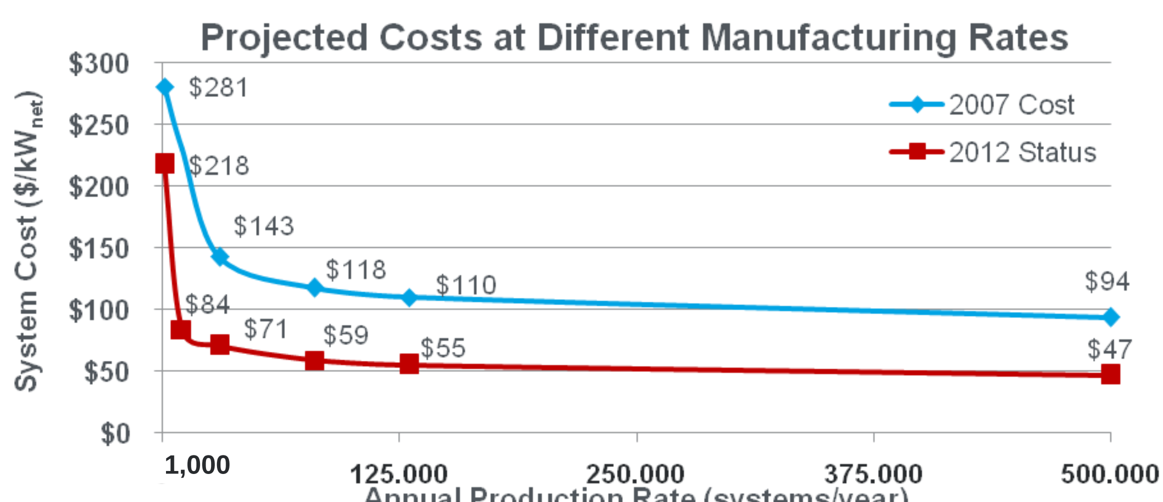
*by Top 10 Investors

Projected high-volume cost of fuel cells has been reduced to $47/kW (2012)*

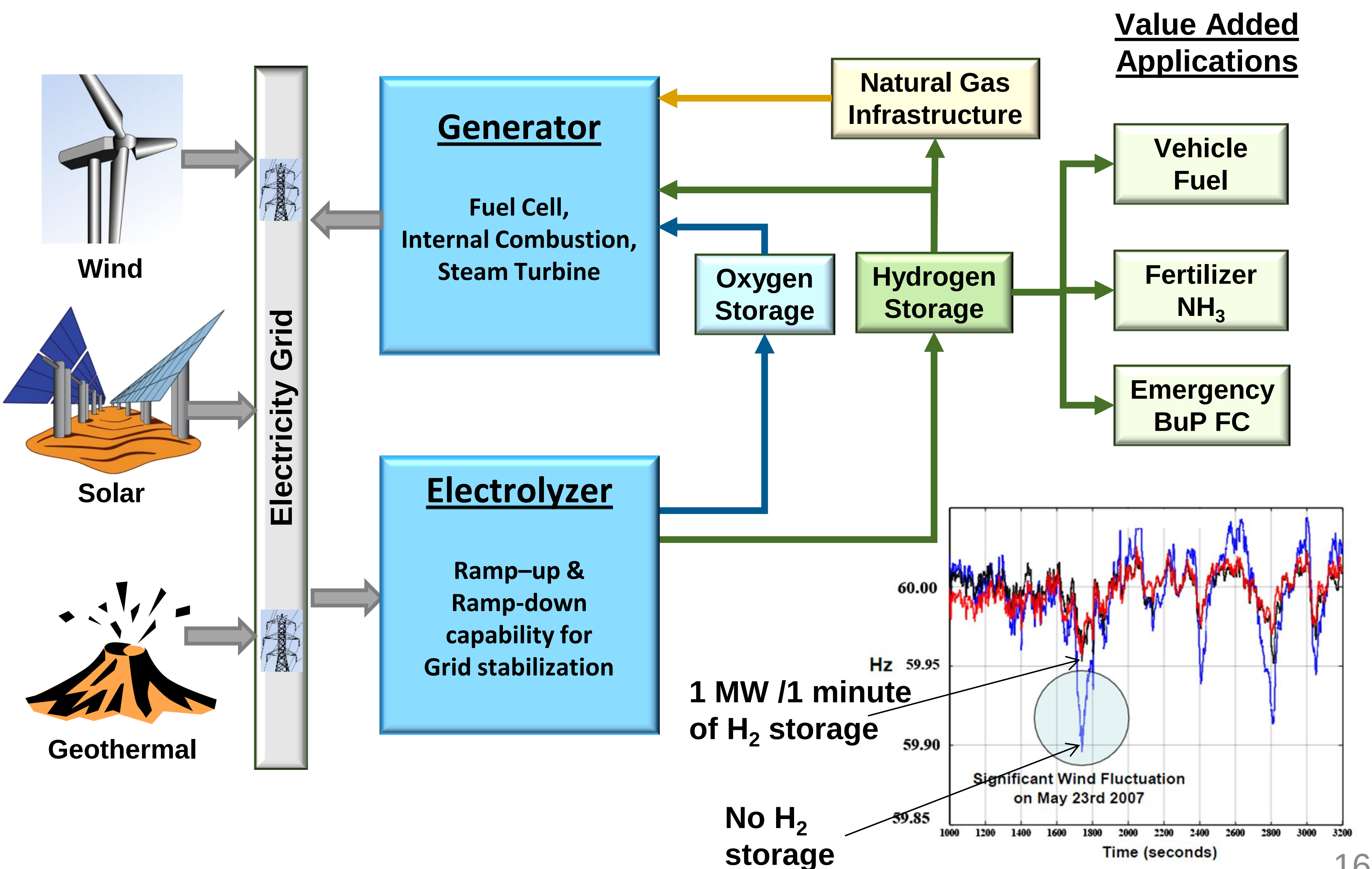
- ***More than 35% reduction since 2008***
- ***More than 80% reduction since 2002***

***Based on projection to high-volume manufacturing (500,000 units/year).** The projected cost status is based on an analysis of state-of-the-art components that have been developed and demonstrated through the DOE Program at the laboratory scale. Additional efforts would be needed for integration of components into a complete automotive system that meets durability requirements in real-world conditions.*





H_2 for Energy Storage



Energy Storage & Hydrogen

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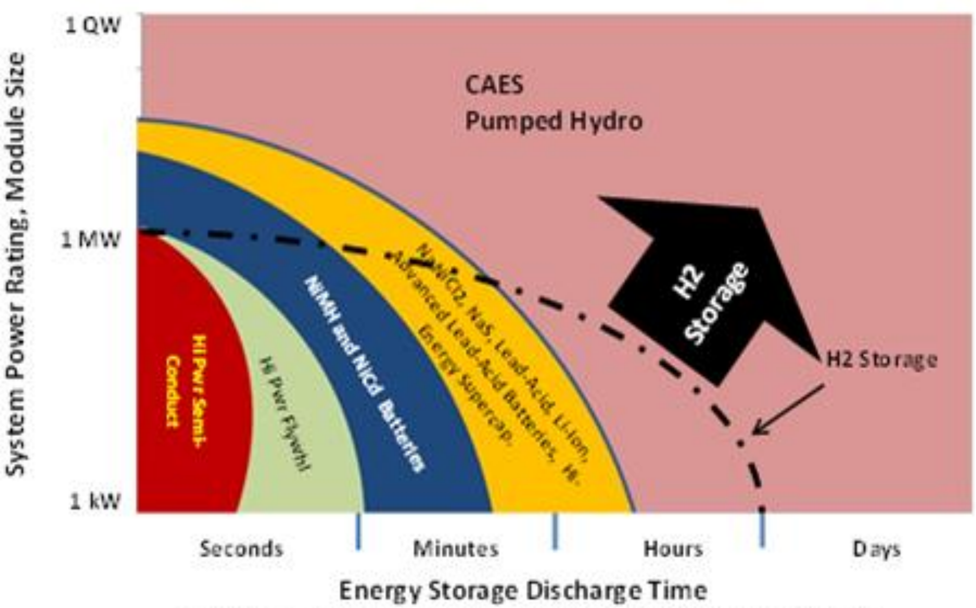
Hydrogen can be used to store electrical energy and meet fluctuating demand which will improve electricity distribution and help enable renewable power generation.

Energy storage requirements can range from a few watt-hours to a kilowatt-hour.

Hydrogen technologies can be competitive with battery systems for this application and could be a viable alternative to pumped hydro and CAES at sites where those technologies are not feasible.

Stored hydrogen energy can be used for other high-value applications—such as CHP systems, passenger vehicles, and buses—or it can be converted back into grid electricity, using fuel cells or turbines, for "peak-power" when demand exceeds generation.

Energy Storage Technologies Power Rating and Capacity



Source: The data for the figure was obtained from EPRI's **Electricity Energy Storage Technology Options** A White Paper Primer on Applications, Costs, and Benefits

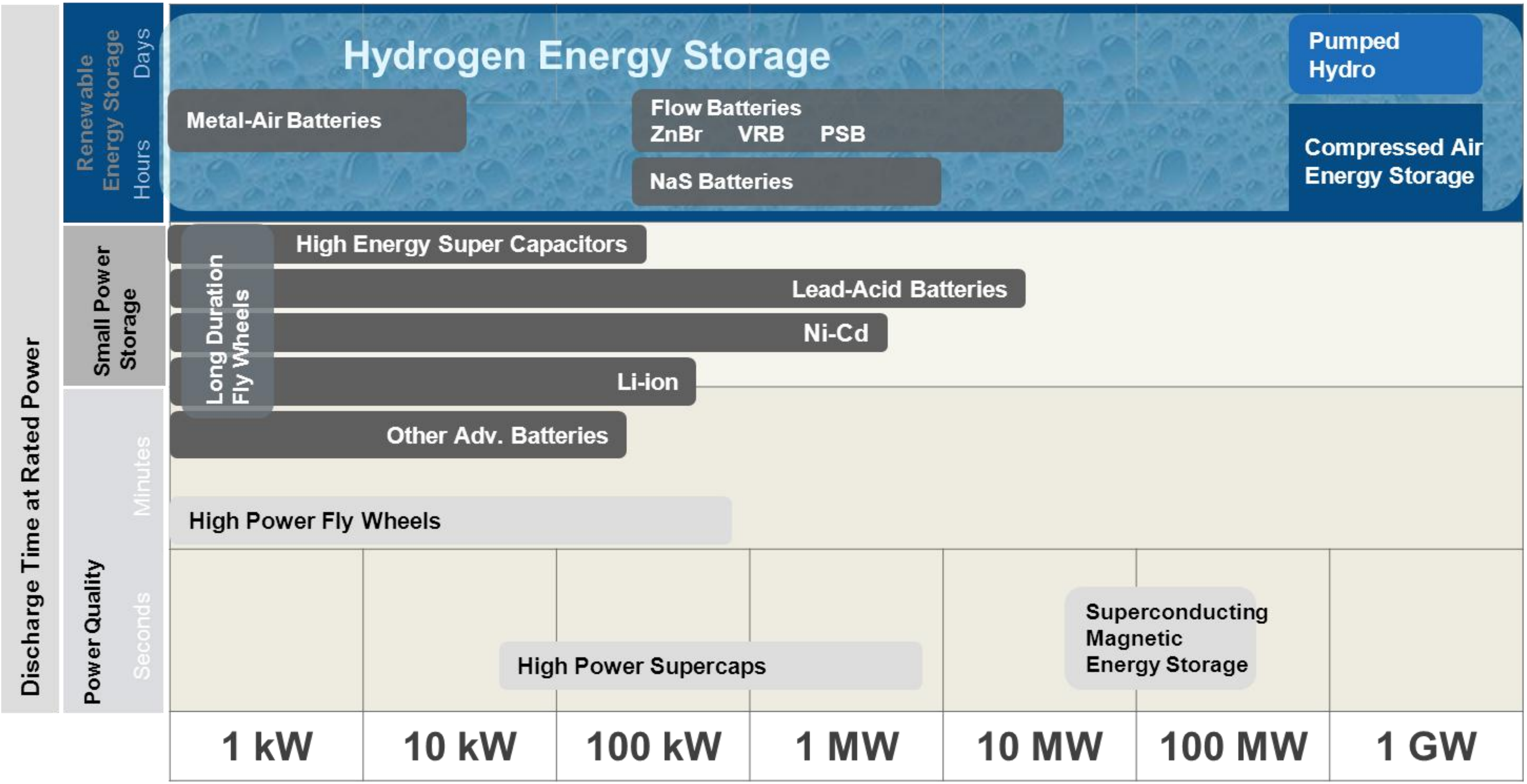
H_2 Storage Has Unique Competitive Characteristics That Can Add Value

- **Scalable** energy storage can be deployed wherever needed (not limited to cavern)
- **Greater flexibility** for discharging stored energy
  - As clean power
  - As low carbon heat
  - As hydrogen fuel for transport
- If hydrogen injected into the natural gas system
  - **Seasonal** storage potential
  - The energy can be **discharged anywhere** on the gas or electric network

Key Barriers to hydrogen grid implementation: Cost, overall efficiency, and durability

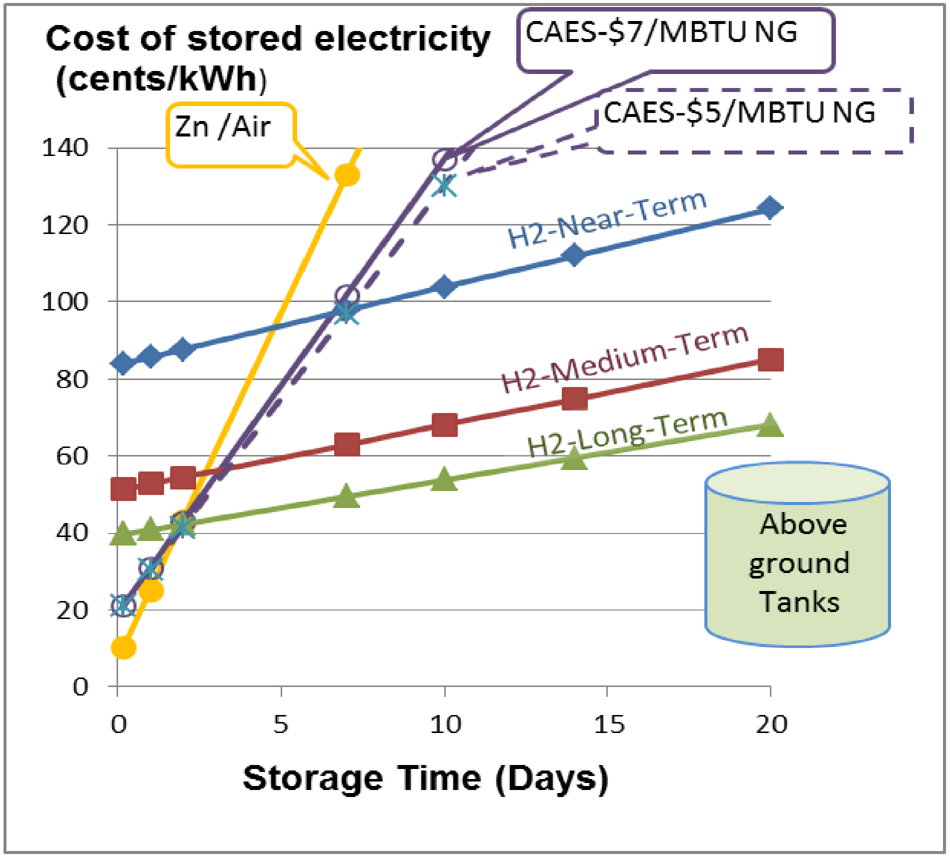
Hydrogen is a flexible energy storage option and spans the range from 1kW to GWs of Power Generation, and Hours to Months of Capacity

Low emission fuel cells to provide onsite heat and power for landmark project



Source: Electricity Storage Association

Source: Hydrogenics



Need to understand when there is economic value for longer storage times under high penetration renewables scenarios

Source: Sandy Thomas

Long-Term H_2 Storage competes in single day cycling

But multi-day energy storage will likely be necessary in a high renewables penetration scenario, if there is more value placed on otherwise curtailed renewable resources due to:

- Higher Renewable Portfolio Standards
- Carbon Dioxide Emission Controls

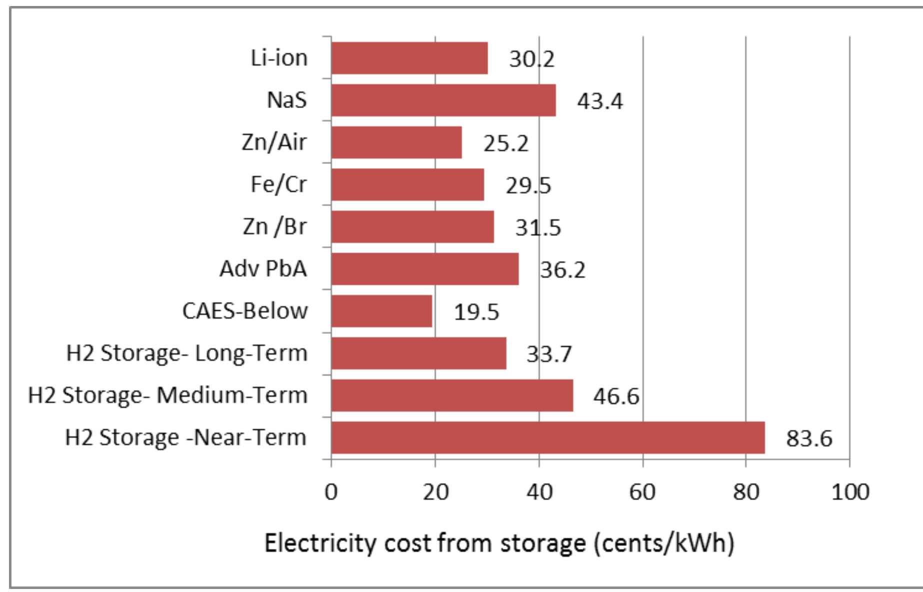
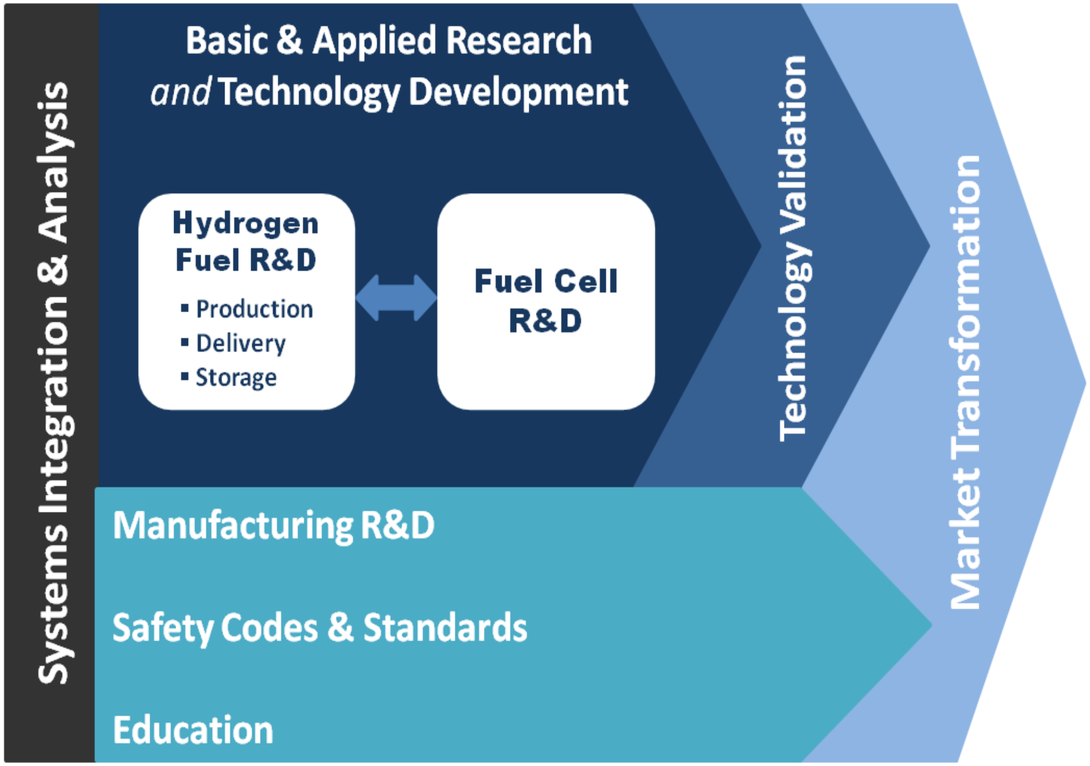


Figure 1. Price of on-Peak electricity for various below-ground H2 & CAES storage and battery storage options with one-day storage and 10% "free" (stranded) energy for a 10MW output over 4 hours (40MWh/day) & NG = $5/MBTU (for CAES) [All battery & CAES costs are based on the lower EPRI estimates.]

DOE Hydrogen Program Overview

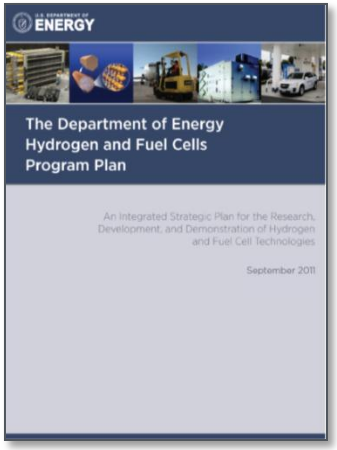
The Program is an integrated effort, structured to address all the key challenges and obstacles facing widespread commercialization.



WIDESPREAD COMMERCIALIZATION ACROSS ALL SECTORS

- Transportation
- Stationary Power
- Auxiliary Power
- Backup Power
- Portable Power

http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/program_plan2011.pdf



Released September 2011 Update to the Hydrogen Posture Plan (2006) Includes Four DOE Offices EERE, FE, NE and Science

Nearly 300 projects currently funded

at companies, national labs, and universities/institutes

More than $1B DOE funds spent from FY 2007 to FY 2011

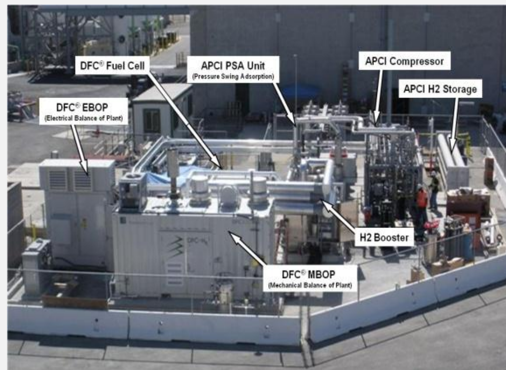
Released September 2011

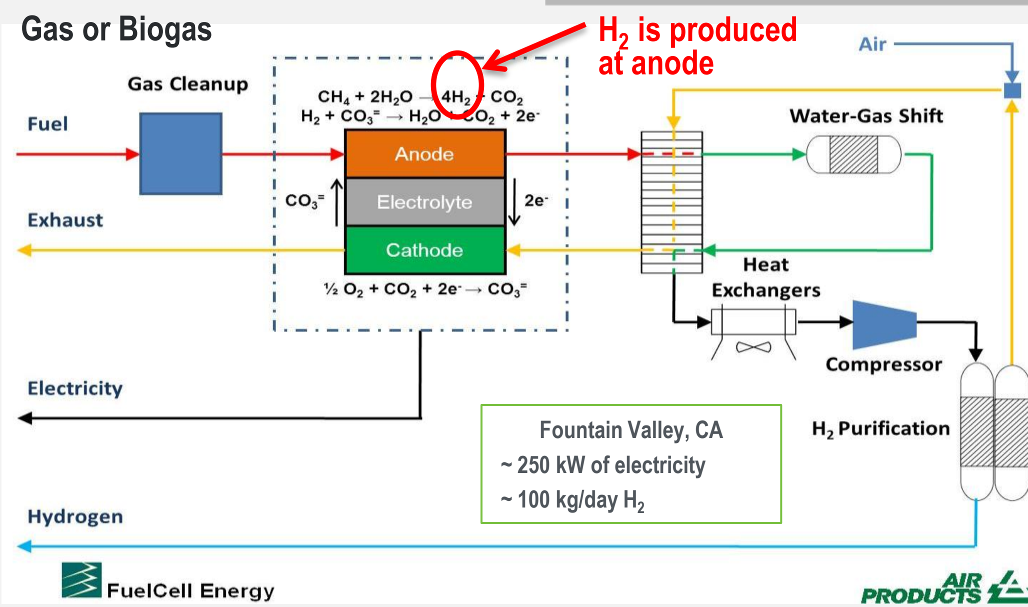
Tri-Generation of Heat, Hydrogen, and Power

Potential Opportunity
Does a synergy exist between stationary and transportation sectors?

Demonstrated world's first Tri-generation station (54% efficiency – H_2 and power)

-Anaerobic digestion of municipal wastewater-





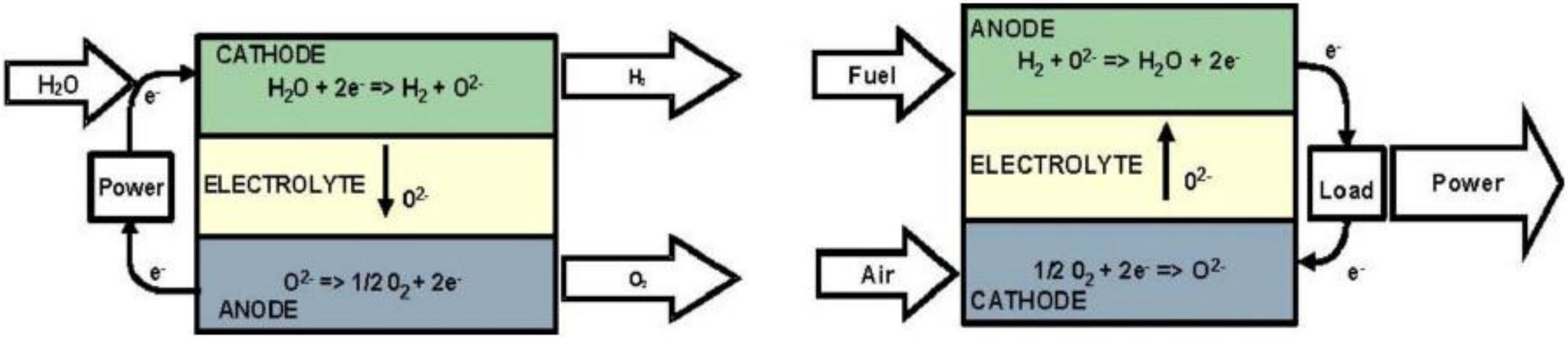
Is tri-generation a viable option for H_2 production:

- Co-produce H_2, power, and heat for multiple applications?
- More efficient use of natural gas?
- Use a renewable resource in anaerobic digester gas?
- Use off-gas from other waste material processing (e.g., gasifiers)?
- Establish an early market infrastructure?

R&D on Reversible Solid Oxide Fuel Cells for Grid Energy Storage

•Reversible solid oxide fuel cells are capable of operating in **both** power generation (SOFC) and electrolysis (SOEC) mode and have the potential to operate at increased round trip efficiency (due to high electrical efficiency from HT operation).

- Cost and durability are still key challenges



Conclusions

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- **Large-scale renewable energy will eventually *require* energy carriers/storage**

- **Hydrogen is an *extremely flexible* energy carrier/storage option**

- **Fuel cells provide *high efficiency* conversion with multiple end use opportunities**

- **More work is needed to *reduce cost* and *address performance***

Program Contact Information

https://www1.eere.energy.gov/hydrogenandfuelcells/

http://www1.eere.energy.gov/hydrogenandfuelcells/organization.html#contacts

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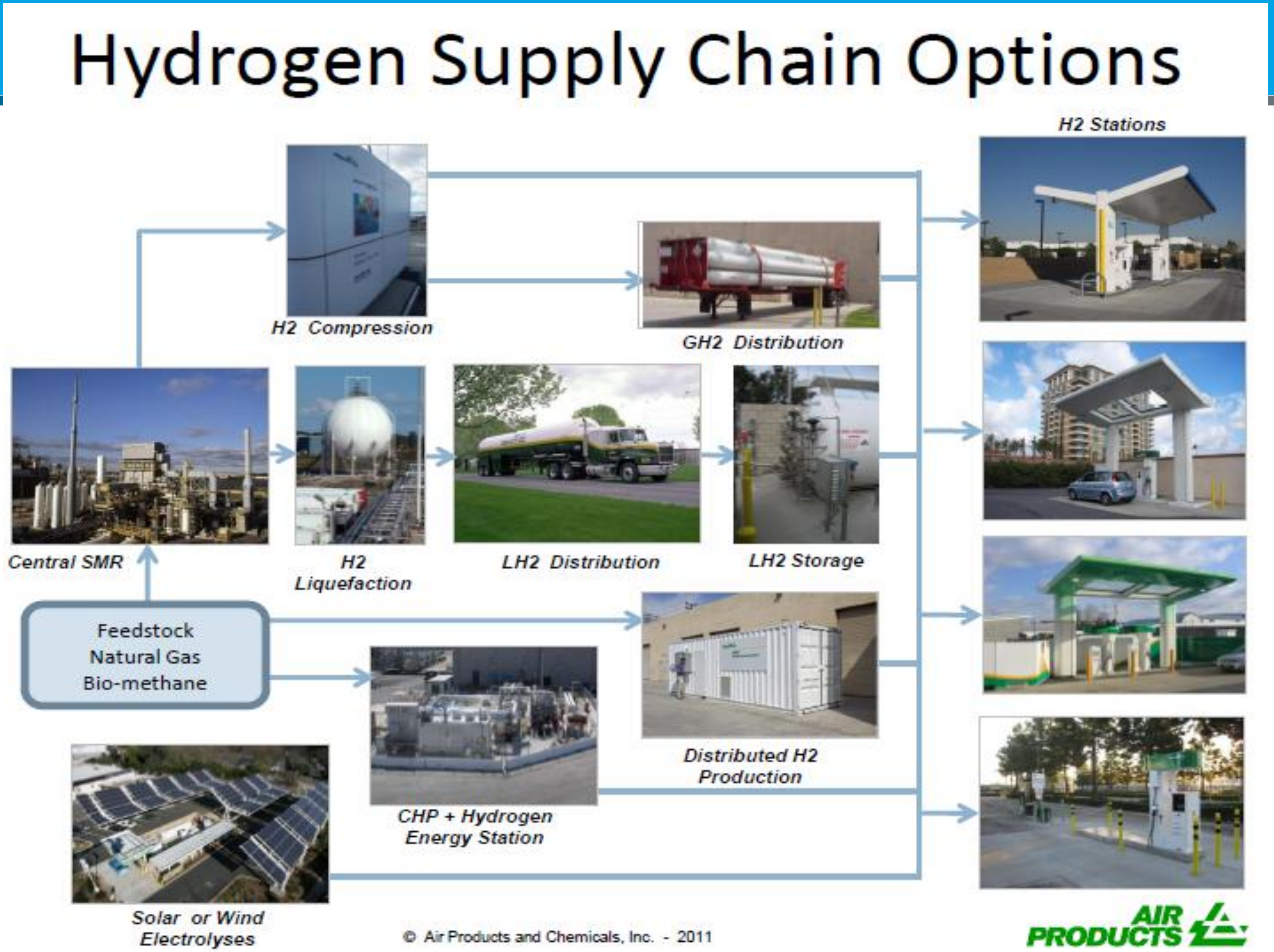
Backup Slides



Hydrogen Supply Chain Options
H2 Stations
H2 Compression
GH2 Distribution
Central SMR
H2 Liquefaction
LH2 Distribution
LH2 Storage
Feedstock
Natural Gas
Bio-methane
Distributed H2 Production
CHP + Hydrogen Energy Station
Solar or Wind Electrolyses
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AIR PRODUCTS

Current Hydrogen Infrastructure

Current Status

- Over **9 million metrics tons** of hydrogen produced per year
- Over **1,200 miles** of hydrogen pipelines in use (CA, TX, LA, IL, and IN)
- Hydrogen is delivered via liquid tank truck and gas tube trailer.
- There are more than **50 fueling stations** in the U.S.

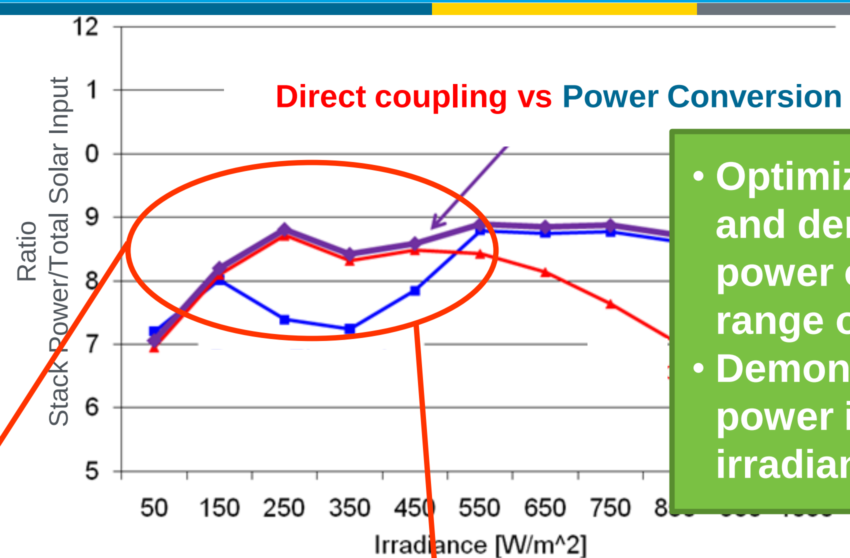
Existing Hydrogen Production Facilities

- ***Significant hydrogen supply infrastructure is already located near most major U.S. cities.***
- **Hydrogen can be delivered from central production facilities to fueling stations by liquid truck, tube trailer or new drop-tank system (Air Products).**

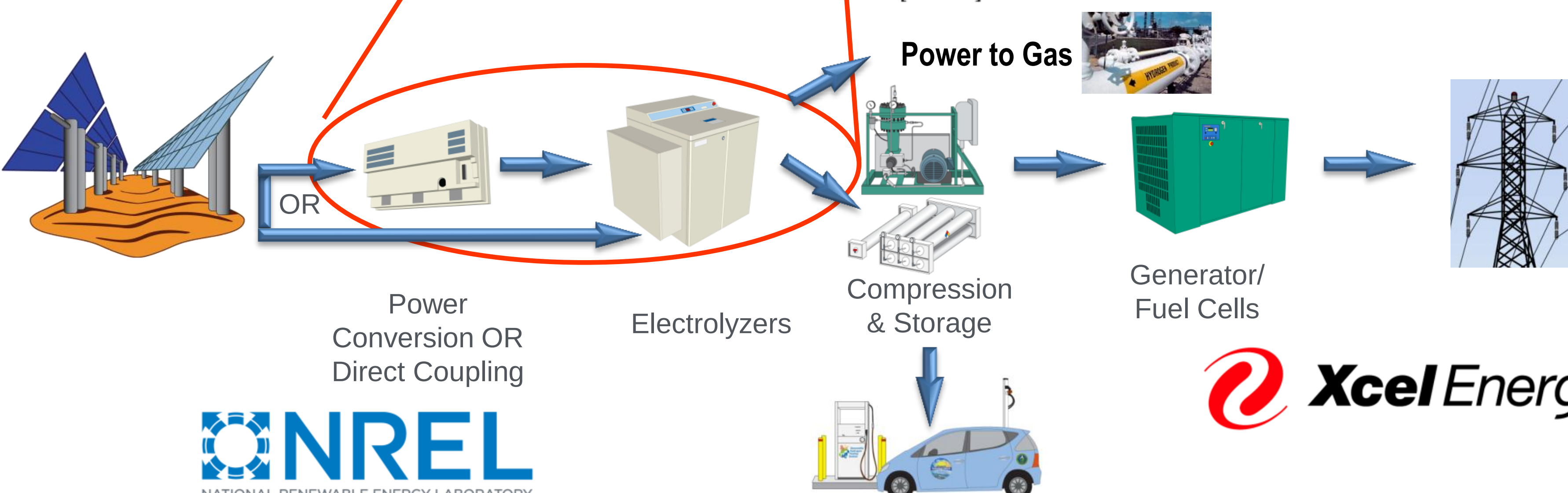
Hydrogen & Fuel Cells for Energy Storage

Improved efficiency of renewable H_2 production by matching the polarization curves of PV & electrolyzers to enable direct coupling.

Expanded Facility to test multiple technologies (wind, solar, electrolyzers, fuel cells/ generators, plus H_2 refueling)



- **Optimized power conversion and demonstrated consistent power output across larger range of solar input**
- **Demonstrated up to nearly 20% power improvement at low irradiance**



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Xcel Energy®

Fuel Cell Comparison Chart, part 2

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Fuel Cell Type	Applications	Advantages	Disadvantages
Polymer Electrolyte Membrane (PEM)	• Backup power • Portable power • Distributed generation • Highway transportation • Specialty vehicles	• Solid electrolyte reduces corrosion & electrolyte management problems • Low temperature • Quick start-up	• Expensive catalysts • Sensitive to fuel impurities
Alkaline (AFC)	• Military • Space • Supermarkets • Hospitals • Hotels	• Cathode reaction faster in alkaline electrolyte, leads to high performance • Low cost components	• Sensitive to CO_2 in fuel & air • Electrolyte management due to high pH
Phosphoric Acid (PAFC)	• Distributed generation	• Higher temperature enables CHP • Increased tolerance to fuel impurities	• Pt catalyst • Long start up time • S sensitivity
Molten Carbonate (MCFC)	• Electric utility • Distributed generation	• High efficiency • Fuel flexibility • Can use a variety of catalysts • Suitable for CHP & CHHP	• High temperature (HT) corrosion and breakdown of cell components • Long start up time • Low power density
Solid Oxide (SOFC)	• Auxiliary power • Electric utility • Distributed generation	• High efficiency • Fuel flexibility • Can use a variety of catalysts • Solid electrolyte • Suitable for CHP & CHHP • Hybrid/GT cycle	• HT corrosion and breakdown of cell components • HT operation requires long start up time and limits shutdowns

Early Market Cost Reduction Analysis

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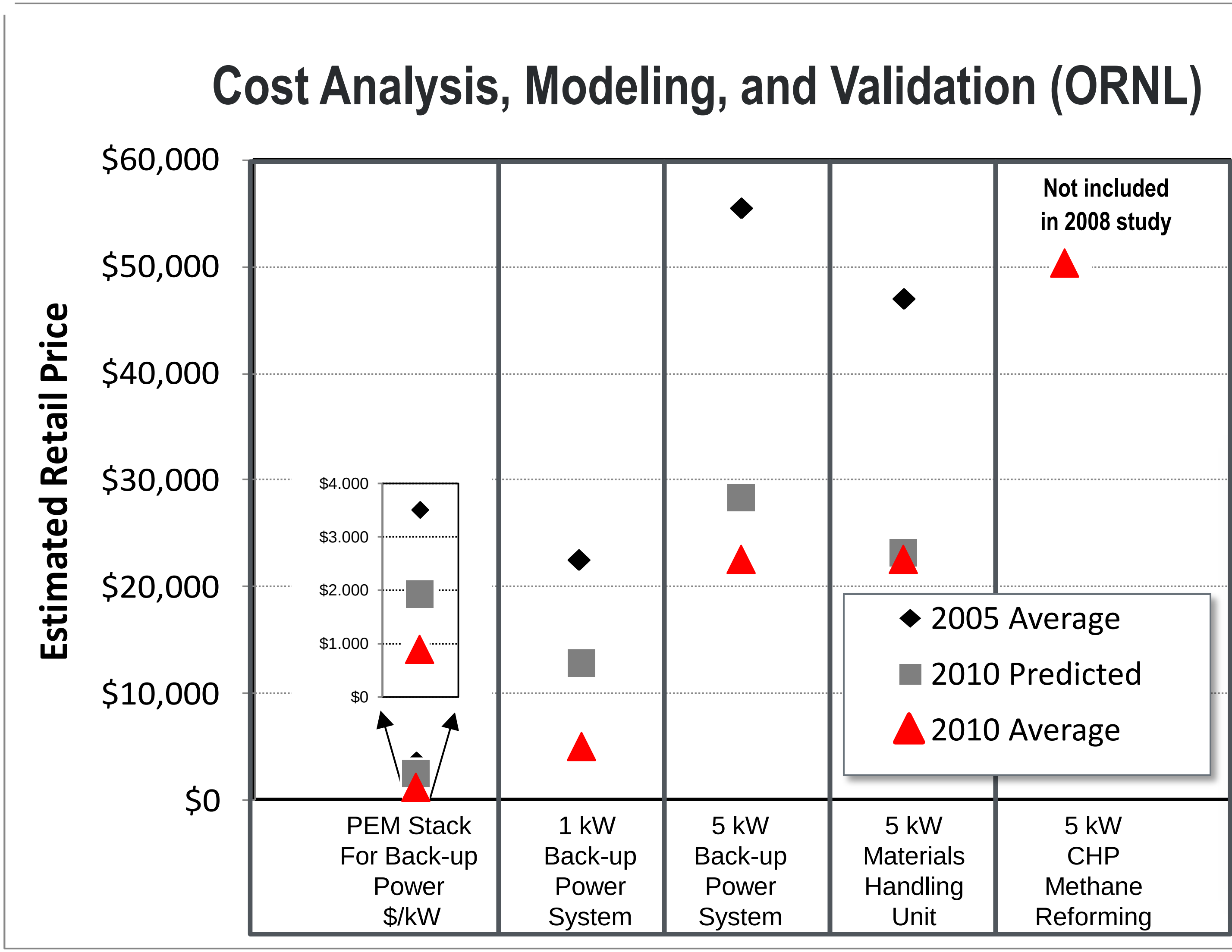
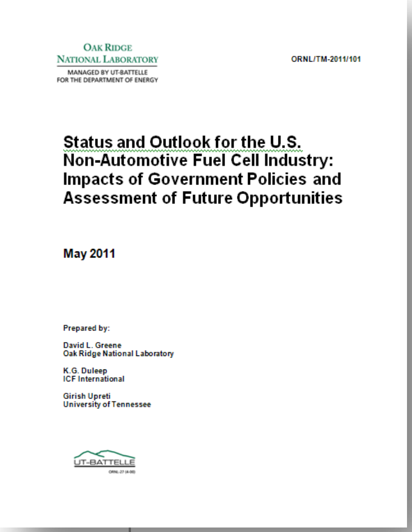


- 50% or greater reduction in costs
- 2008 model generally underestimated cost reductions



http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/ornl_non_automotive_fuelcell.pdf

2005 and 2010 averages based on estimates supplied by OEMs. 2010 predicted assumed government procurements of 2,175 units per year, total for all market segments. Predictions assumed a progress ratio of 0.9 and scale elasticity of -0.2.

ORNL

Challenges and Strategy: Stationary Applications

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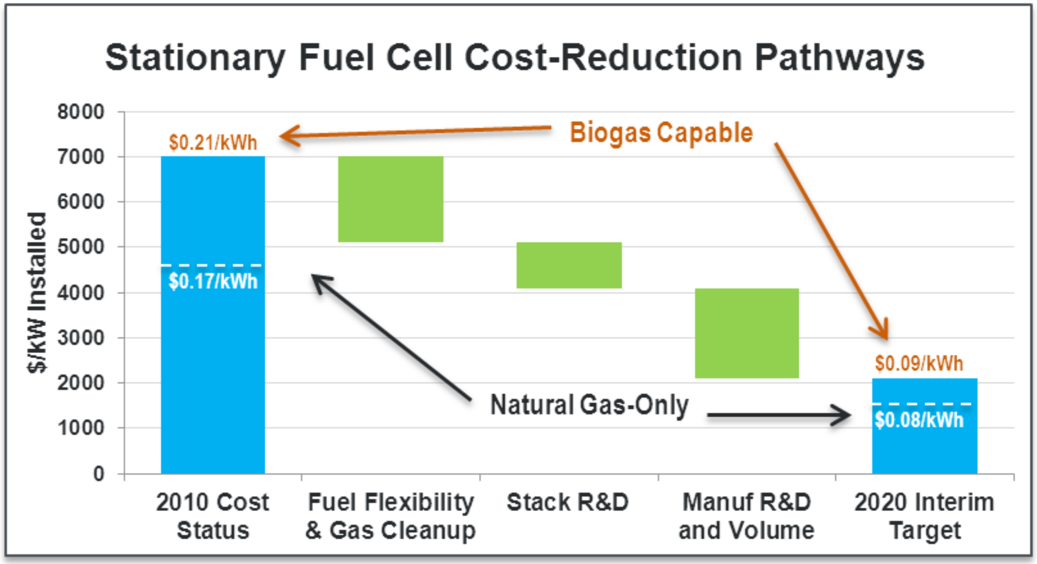
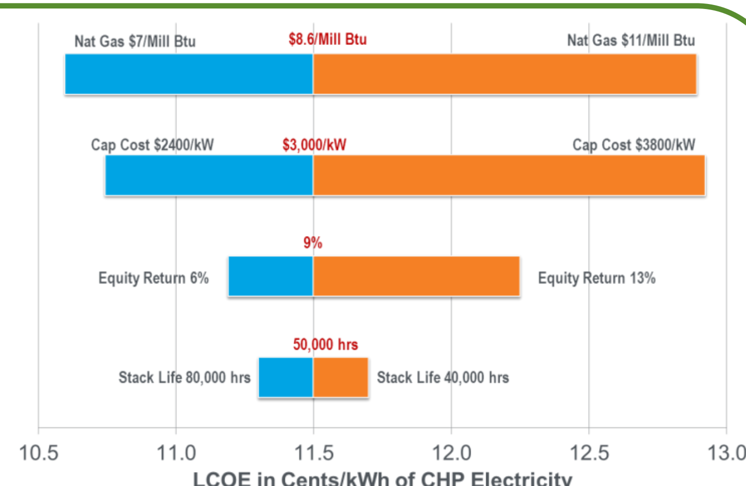
Further reduction in capital cost of medium scale distributed generation/CHP (100 kW – 3 MW) need to be pursued to facilitate widespread commercialization



- Further reduction of fuel cell system cost required to expedite commercialization
- Natural gas availability and fuel cell performance (efficiency) gains will enhance the technology's market attractiveness
- Development of a cost-effective process for removing fuel contaminants would allow for fuel flexibility
- Also applicable for tri-gen (H_2 production)

Sensitivity analysis around 2015 targets assesses impact of fuel cell system cost and durability on commercialization prospects

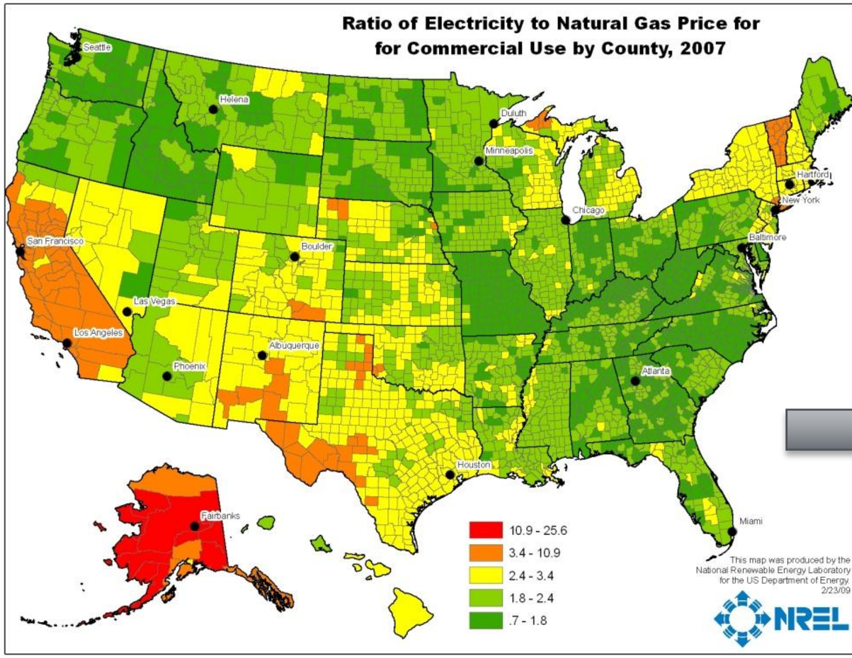
Technical Parameters (2015)	
Electric Efficiency (LHV)	45.0%
Combined Effic.(LHV)	87.5%
Size, MWe	1
Operating Life, years	20
Equipment, $/kWe	2,300
Engineering& Installation, $/kWe	700
Fixed O&M, $/MWh	13
Variable O&M, $/MWh	8.0



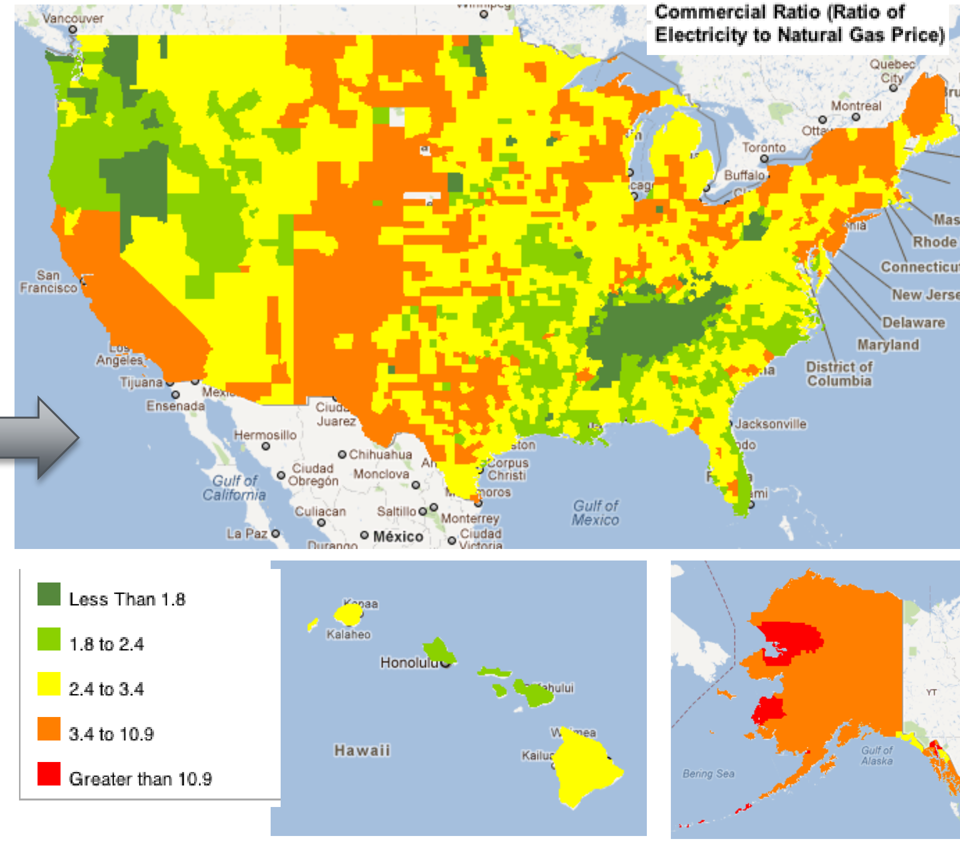
Spark-Spread Determines Regional Opportunities for DG from Natural Gas

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

2007



2010



Spark spread determines regions for favorable use of natural gas

Red/orange regions: High electricity cost, low natural gas cost- favorable for DG

Lower natural gas prices offer increased opportunities for CHP and distributed generation- current vs. 2007

Source: NREL

Stationary Fuel Cell Applications

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Assured Power

First National Bank of Omaha
Omaha, Nebraska

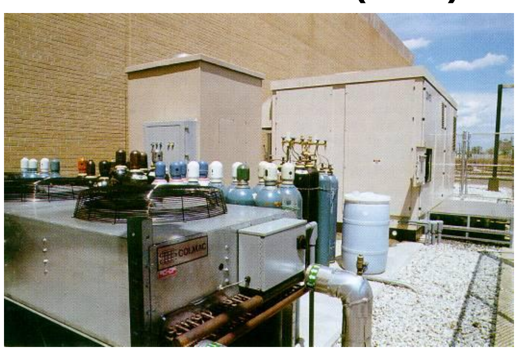
On-Line Emergency Power

Verizon
Garden City, New York

Indoor Green Power / Cogeneration

4 Times Square
New York, New York

Renewable Fuel (ADG)



Wastewater treatment plants
New York, New York

Off-Grid Power

Central Park Police Station,
New York, New York

Bloom Energy

- Estimated to have raised $800M in venture capital
- Selling 200 kW solid oxide fuel cell systems
  - Systems run on NG and biogas and have >60% electrical efficiency
  - Customers include Google, Apple, Coca-Cola, FedEx, Walmart, AT&T, eBay
  - Has division focused on setting up PPAs
- Constructing manufacturing facility in Delaware
  - Delmarva Power & Light will purchase 30 MW of fuel cells
  - Delaware PSC approved an average of ~$1.34/mo surcharge on customer's utility bills to subsidize these activities

Partnerships & Collaboration

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Federal Agencies

- DOC
- DOD
- DOE
- DOT
- EPA
- GSA
- DOI
- DHS
- NASA
- NSF
- USDA
- USPS

– *Interagency coordination through staff-level Interagency Working Group (meets monthly)*

– *Assistant Secretary-level Interagency Task Force mandated by EPACT 2005.*

External Input

- Annual Merit Review & Peer Evaluation
- H2 & Fuel Cell Technical Advisory Committee
- National Academies, GAO, etc.

Industry Partnerships & Stakeholder Assn's.

- Tech Teams (USCAR, energy companies- U.S. DRIVE)
- Fuel Cell and Hydrogen Energy Association (FCHEA)
- Hydrogen Utility Group
- ~ 65 projects with 50 companies

Universities

~ 50 projects with 40 universities

DOE Hydrogen & Fuel Cells Program

State & Regional Partnerships

- California Fuel Cell Partnership
- California Stationary Fuel Cell Collaborative
- SC H_2 & Fuel Cell Alliance
- Upper Midwest Hydrogen Initiative
- Ohio Fuel Coalition
- Connecticut Center for Advanced Technology

International

- IEA Implementing agreements – 25 countries
- International Partnership for Hydrogen & Fuel Cells in the Economy – 17 countries & EC, 30 projects

National Laboratories

National Renewable Energy Laboratory P&D, S, FC, A, SC&S, TV, MN

Argonne A, FC, P&D, SC&S

Los Alamos S, FC, SC&S

Sandia P&D, S, SC&S

Pacific Northwest P&D, S, FC, SC&S, A

Oak Ridge P&D, S, FC, A, SC&S

Lawrence Berkeley FC, A

Lawrence Livermore P&D, S, SC&S

Savannah River S, P&D

Brookhaven S, FC

Idaho National Lab P&D

Other Federal Labs: Jet Propulsion Lab, National Institute of Standards & Technology, National Energy Technology Lab (NETL)

P&D = Production & Delivery; S = Storage; FC = Fuel Cells; A = Analysis; SC&S = Safety, Codes & Standards; TV = Technology Validation, MN = Manufacturing