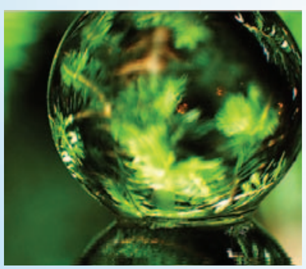
Hydrogen Production and Storage for Fuel Cells: Current Status



Timothy E. Lipman, PhD

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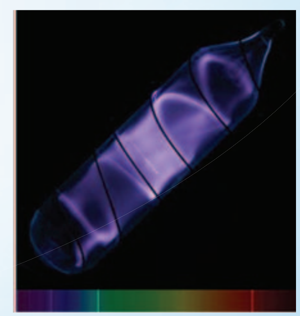
February 2, 2011

Prepared For:

Clean Energy States Alliance and

U.S. Department of Energy



Outline of Webinar

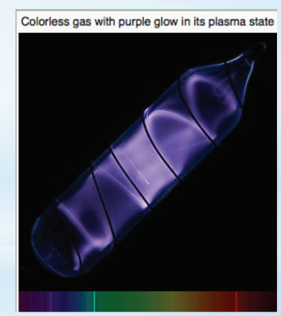
- Introduction
- Hydrogen Basics
- Hydrogen Production
- Hydrogen Storage and Distribution
- Conclusions
- Appendix: Overview of Hydrogen Applications

Introduction

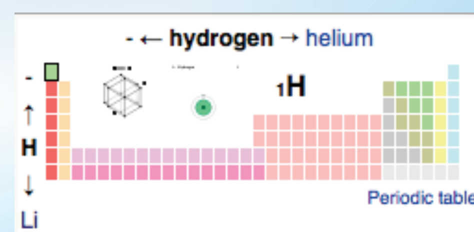
- Tim Lipman, PhD
- Current Appointments
  - Director, U.S. Dept. of Energy Pacific Region Clean Energy Application Center (PCEAC or "Pacific RAC")
  - Co-Director, Transp. Sustainability Research Center (TSRC)
  - Lecturer, Dept. of Civil and Envt'l Engineering (CEE)
- 10 Years at UC Berkeley
  - Post-Doc - Energy and Resources Group (2000-2003)
  - Asst. Research Engr. – Inst. of Transp. Studies (2004-pres)
- Previously
  - Hometown: Golden, Colorado
  - BA – Stanford University (1990)
  - NASA-Ames Research Center (1990-1992)
  - MS and PhD - UC Davis (1998/99)

Hydrogen Basics

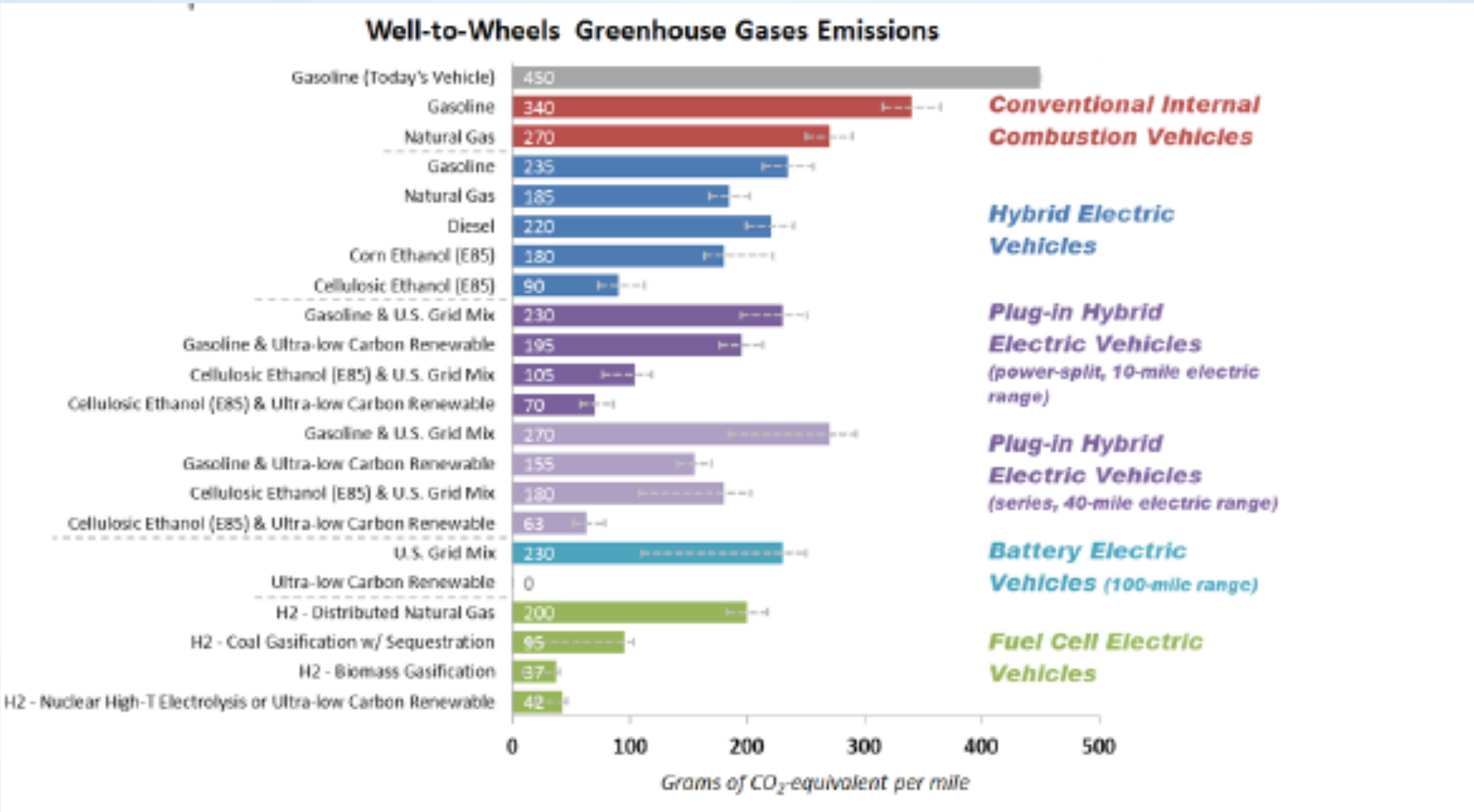
- Hydrogen is a Light Molecule Existing as a Gas at Room Temp. and Liquid at Cold (-253°C/-423°F) Temps.
  - It is not “found” but rather “made” from natural gas, biogas, water, and other substances containing elemental hydrogen
  - Small and light molecule is highly bouyant (1/15th the density of air), easily “fugitive” and odorless/colorless
  - Ignites readily and in wide range of fuel/air mixes but also has some off-setting safety advantages



- Hydrogen is Widely Used in Global Industry
  - Approx. 50 million tonnes used globally each year and ~11 million tonnes in U.S.
  - Major uses include petroleum refining, fertilizer manuf., food hydrogenation, methanol prod., and metallurgy

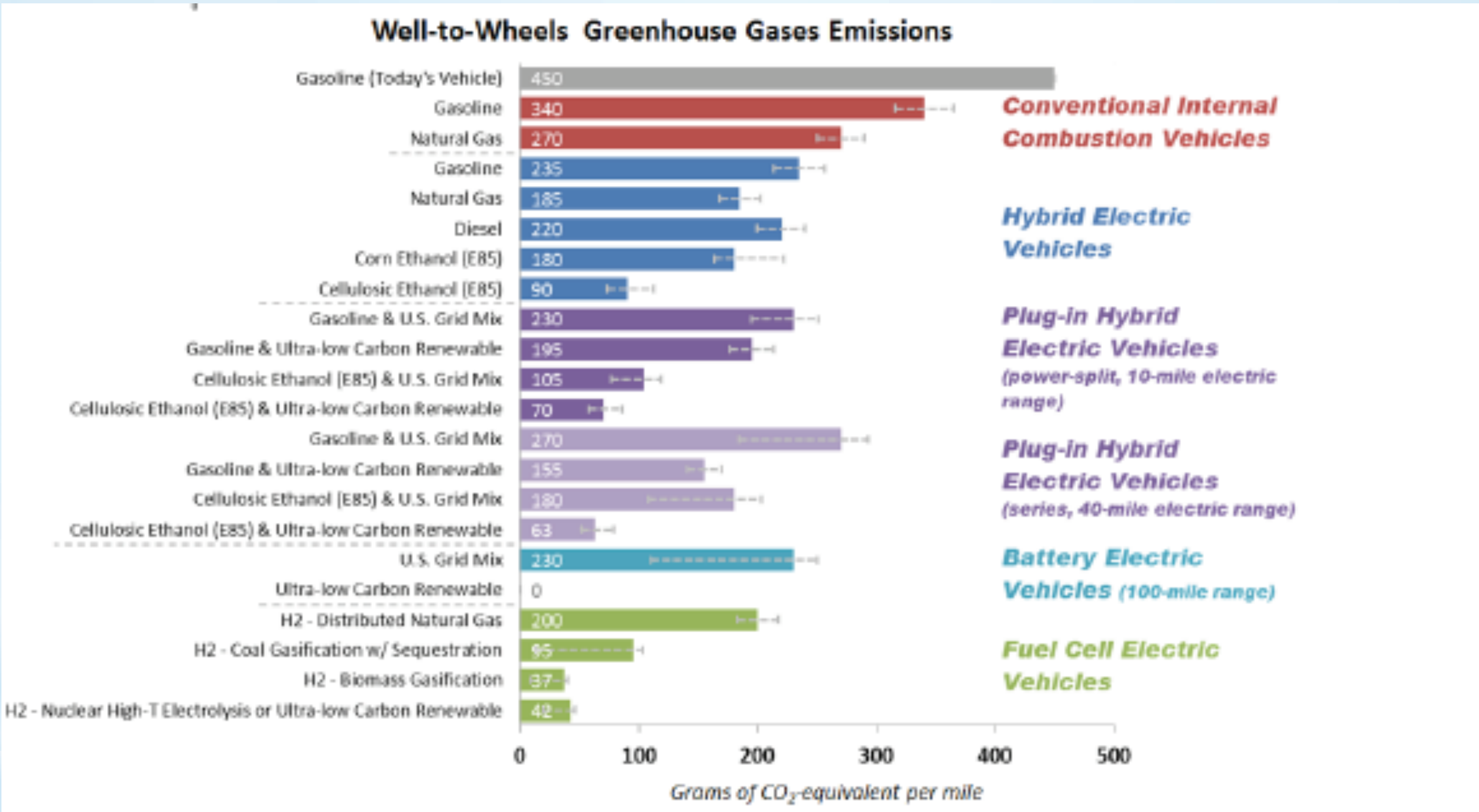


Hydrogen Basics – Emissions



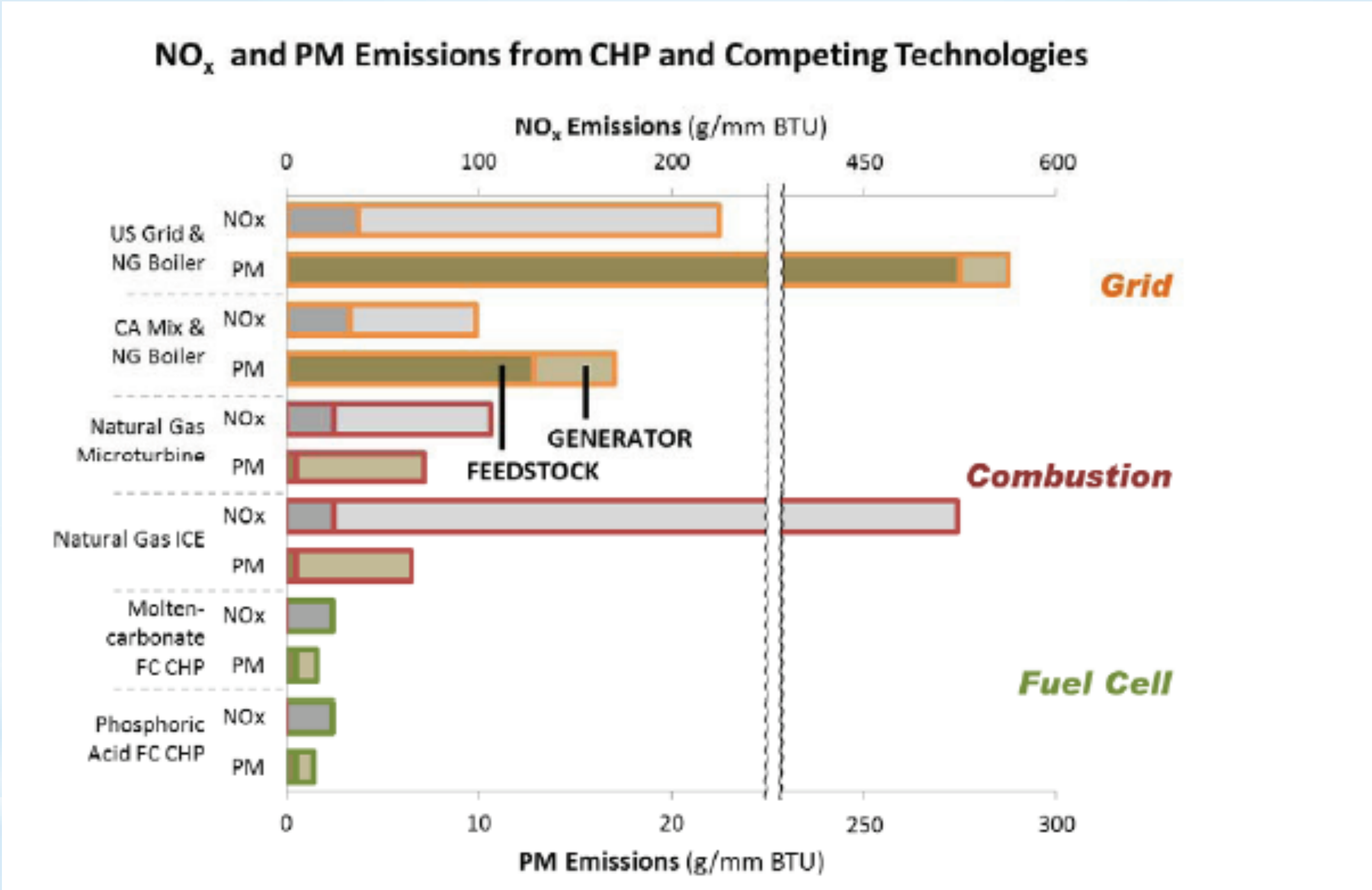
Source: U.S. DOE, 2010 draft

Hydrogen Basics – Emissions



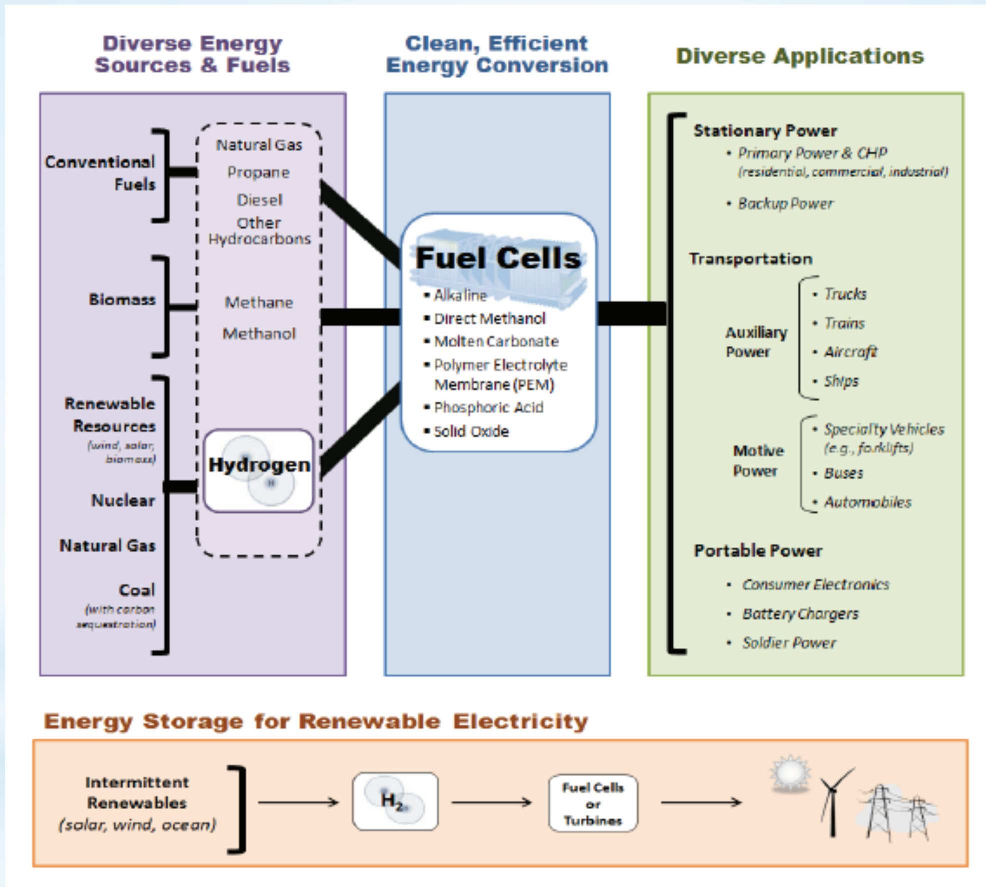
Source: U.S. DOE, 2010 draft

Hydrogen Basics – Emissions



Source: U.S. DOE, 2010 draft

Hydrogen Basics – Diverse Sources and Applications



Source: U.S. DOE, 2010 draft

Hydrogen Basics

- Hydrogen Applications Are Spreading
  - Stationary power using fuel cells or gen-sets
  - Transportation applications: heavy duty, light-duty, materials handling
  - Backup power e.g, for telecommunications
  - Educational teaching tools

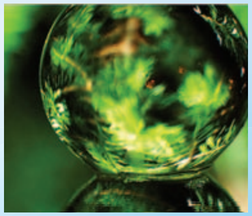
- Key Remaining Issues
  - Proving desired levels of stack and system durability for hydrogen fuel cells and electrolyzers (40,000+ hours stationary, 4,000 hours transportation)
  - Cost reduction in hydrogen and other fuel cell and electrolyzer systems (goal: $1000/kW stationary and $30-40/kW transportation)
  - Hydrogen storage – no ideal solution yet
  - Assuring hydrogen purity from esp. biogas and natural gas sources for “pure H_2” apps.

Hydrogen Production

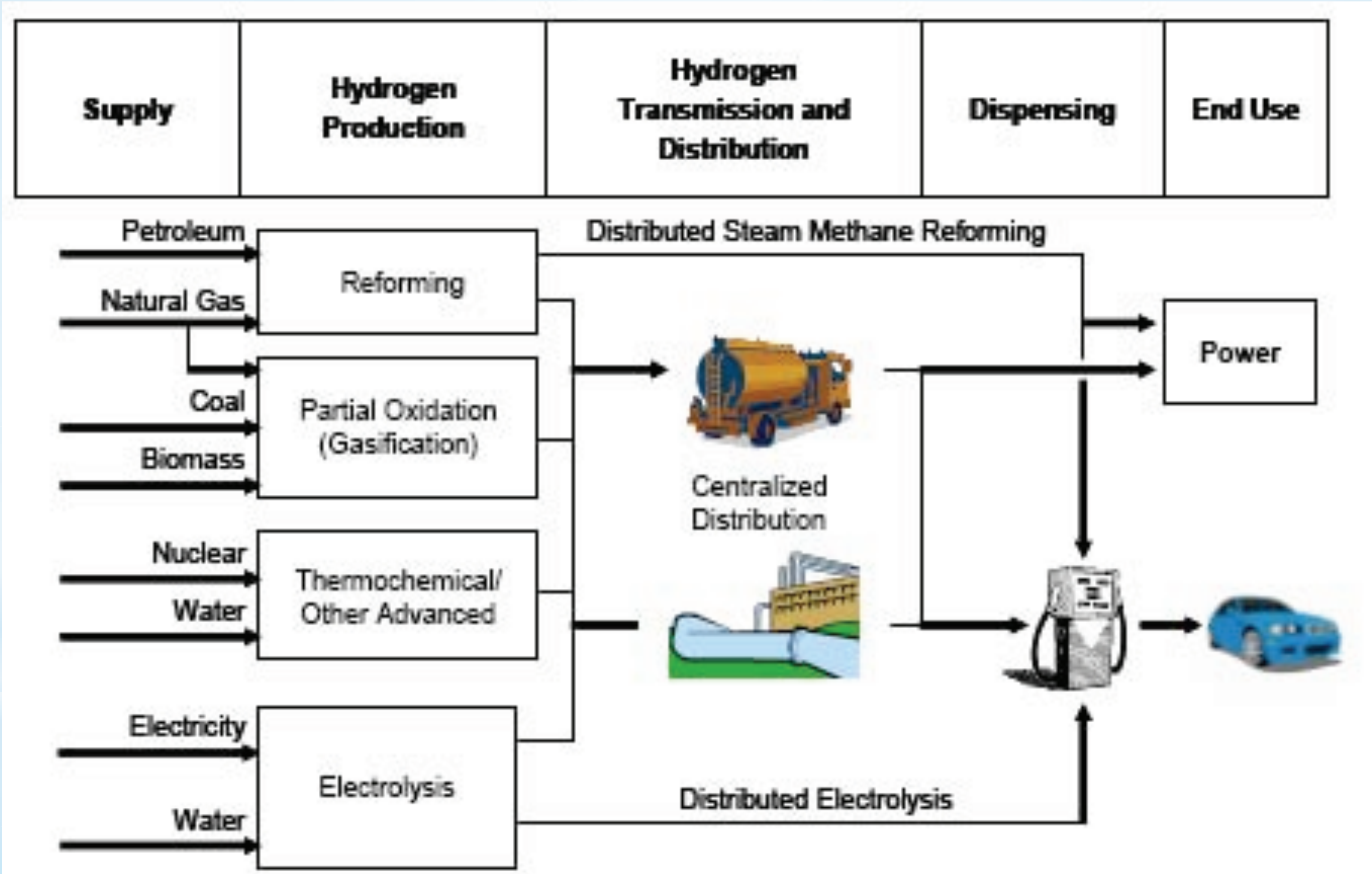
- Major Means of Industrial Hydrogen Production
  - Steam methane reforming: CH_4+H_2O->CO+3H_2(then WGS adds H_2O to the "syngas" to yield 4 H_2 plus CO_2)
  - Partial oxidation of hydrocarbons: 2CH_4+O_2->2CO+4H_2
  - Syngas from coal: C+H_2O->CO+H_2
  - Electrolysis: electricity plus water using "electrolyzer" devices
    - Low temperature
    - High temperature
  - "By-product": catalytic reforming at refineries, other off-gas recovery, and chlor-alkali process

Hydrogen Production

- Advanced Production Methods
  - Thermo-chemical
    - Over 200 cycles have been investigated to split water (though most have been found to be not viable)
    - Conversion of biomass
  - Photolytic and fermentative micro-organism systems
  - Photo-electrochemical – direct water splitting using semiconductor materials and sunlight
  - Many nuclear cycle-related pathways
    - High temperature thermo-chemical
    - High temperature electrolysis
    - Other nuclear process-interface pathways
  - Myriad other experimental methods using nano- and other finely structured materials



Multitude of Hydrogen Pathways
(near term pathways)

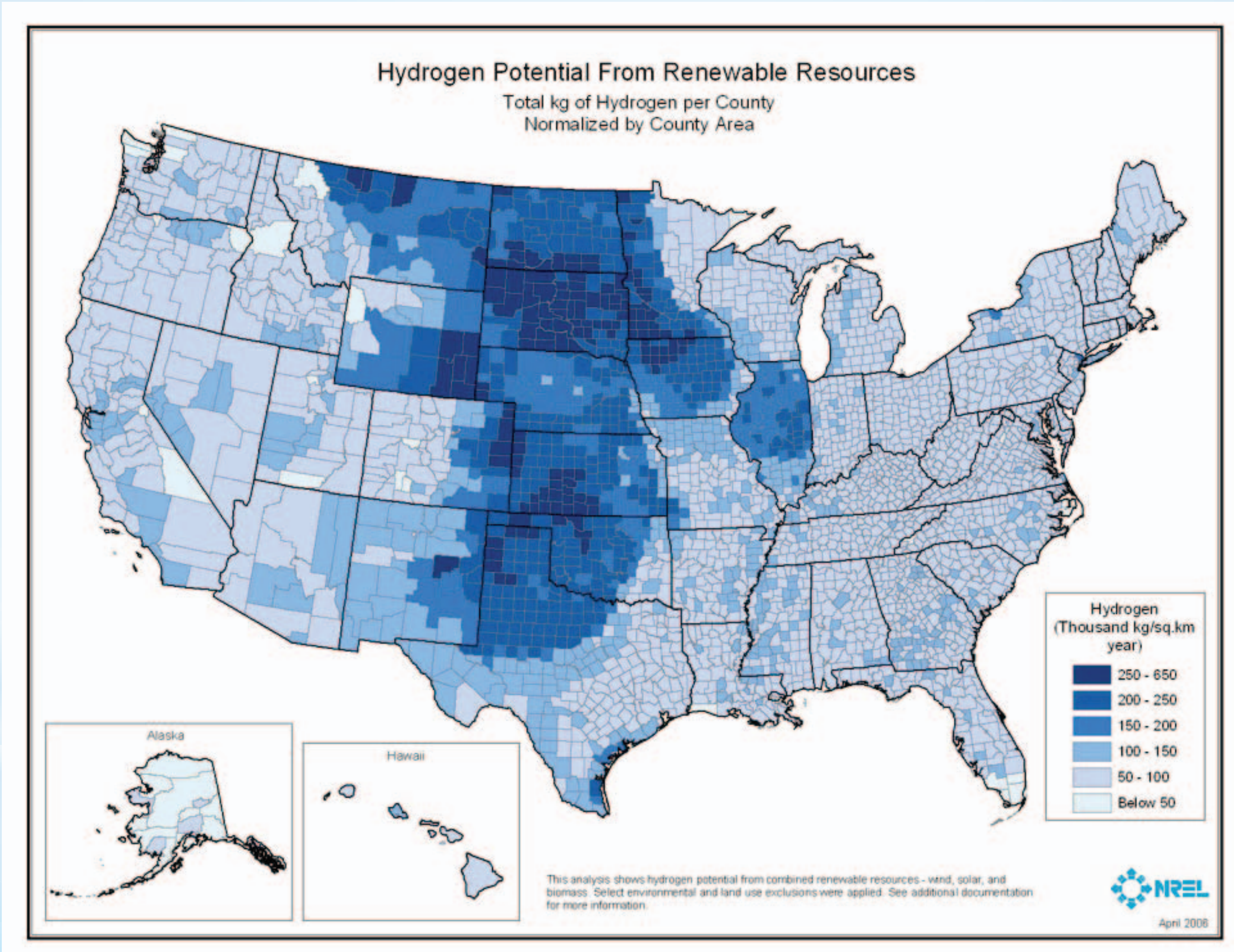


Source: EIA, 2008

U.S. Industrial Hydrogen Facilities

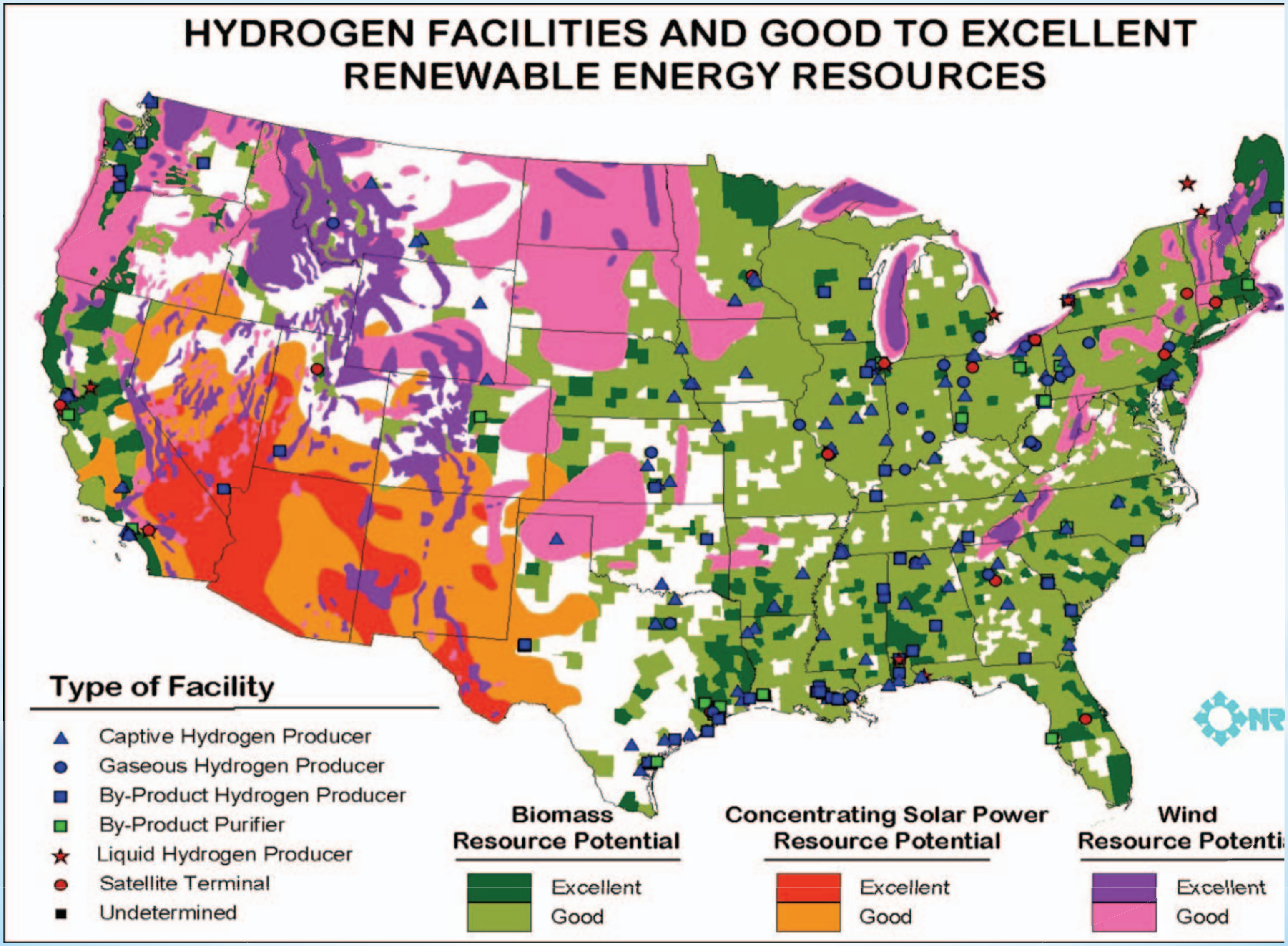
Source: NREL, 2006

Diverse Renewables Base in U.S.



Source: NREL, 2006

Diverse Renewables Base in U.S.



Hydrogen Production in U.S.

Capacity Type	Production Capacity (Thousand Metric Tons per Year)	
	2003	2006
On-Purpose Captive[a]		
Oil Refinery	2,870	2,723
Ammonia	2,592	2,271
Methanol	393	189
Other	18	19
On-Purpose Merchant[a]		
Off-Site Refinery	976	1,264
Non-Refinery Compressed Gas (Cylinder and Bulk)	2	2
Compressed Gas (Pipeline)	201	313
Liquid Hydrogen	43	58
Small Reformers and Electrolyzers	<1	<1
Total On-Purpose[a]	**7,095**	**6,839**
Byproduct		
Catalytic Reforming at Oil Refineries	2,977	2,977
Other Off-Gas Recovery[b]	462	478
Chlor-Alkali Processes	NA	389
Total Byproduct	**3,439**	**3,844**
Total Hydrogen Production Capacity	**10,534**	**10,683**

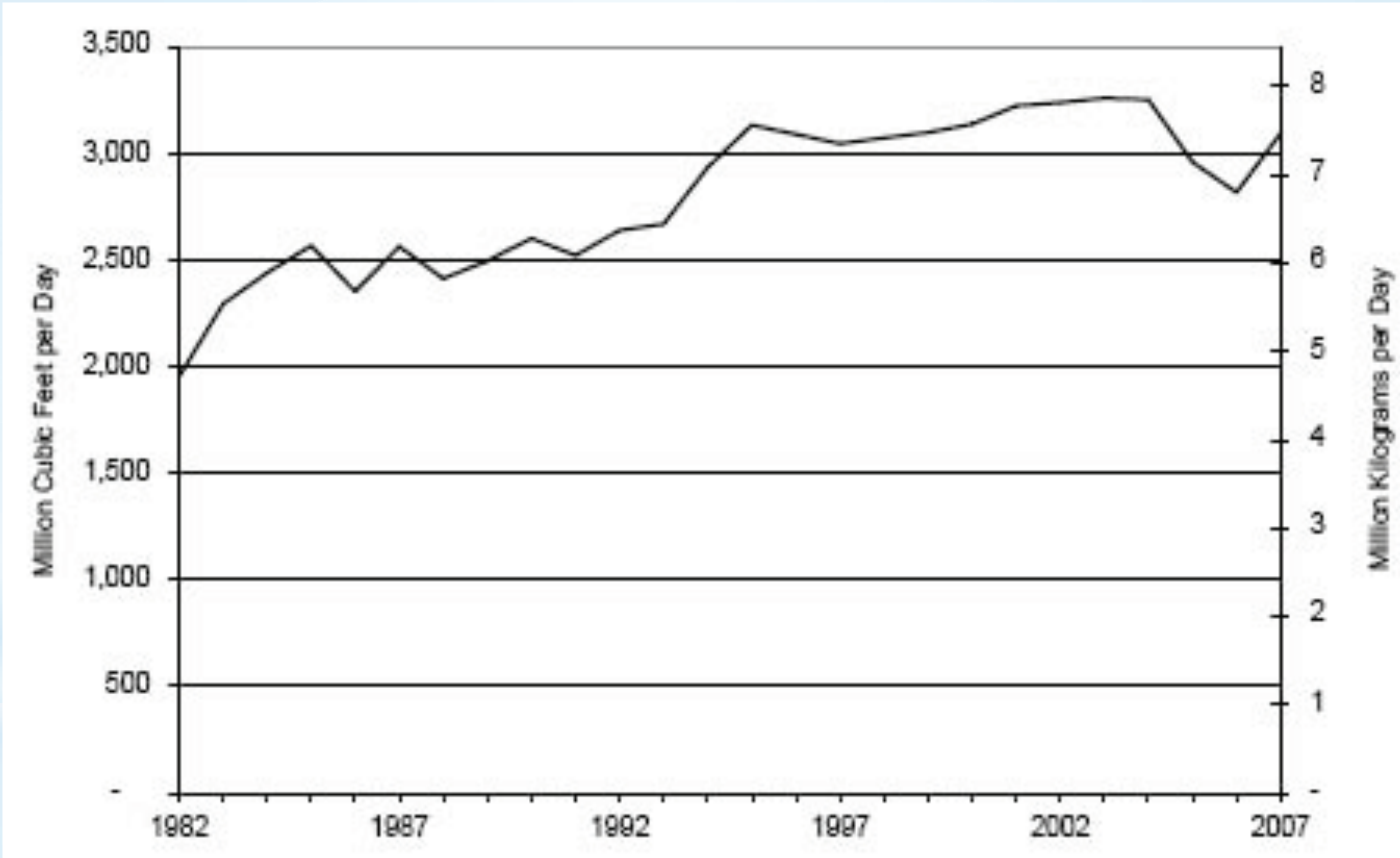
[a] "On-purpose" are those units where hydrogen is the main product, as opposed to "byproduct" units where hydrogen is produced as a result of processes dedicated to producing other products.

[b] From membrane, cryogenic and pressure swing adsorption (PSA) units at refineries and other process plants.

Sources: The EIA-820 Refinery Survey, The Census Bureau MA28C and MQ325C Industrial Gas Surveys, SRI Consulting, The Innovation Group, Air Products and Chemicals, Bilge Yildiz and Argonne National Laboratory (Report # ANL 05/30, July 2005), and EIA analysis.

Source: EIA, 2008

U.S. Refinery Production Flat – Merchant Purchases Increasing



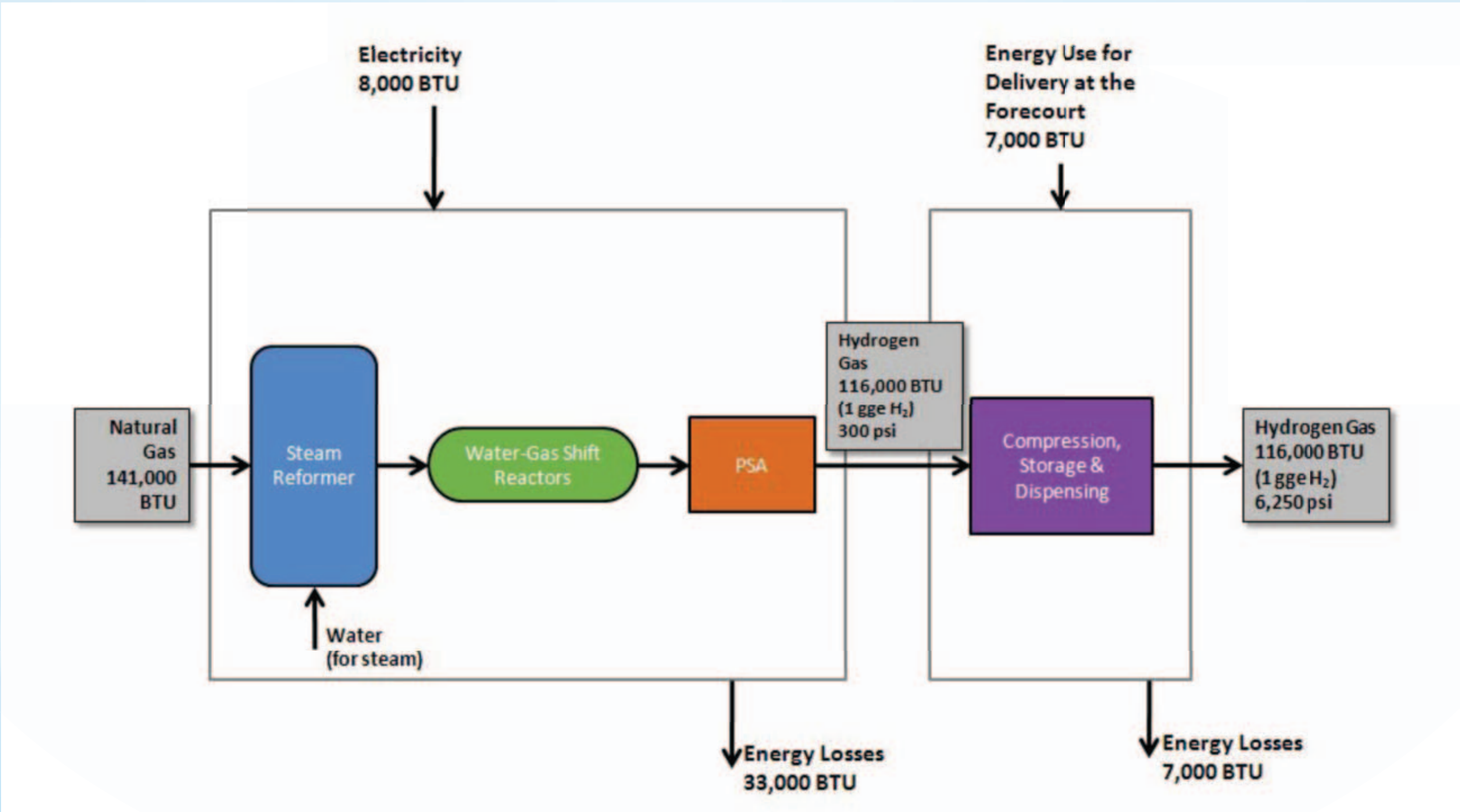
Source: EIA, 2008

Hydrogen Pipelines in L.A.

Source: Air Products and Chemicals, Inc.

Hydrogen Production with SMR

Est. 72% overall efficiency from NG (LHV)



Source: U.S. DOE, 2010 (draft)

Electrolysis - “Water Splitting”

Chemical Reaction
$2\,H_2O \rightarrow 2\,H_2 + O_2$

electric power

H_2

O_2

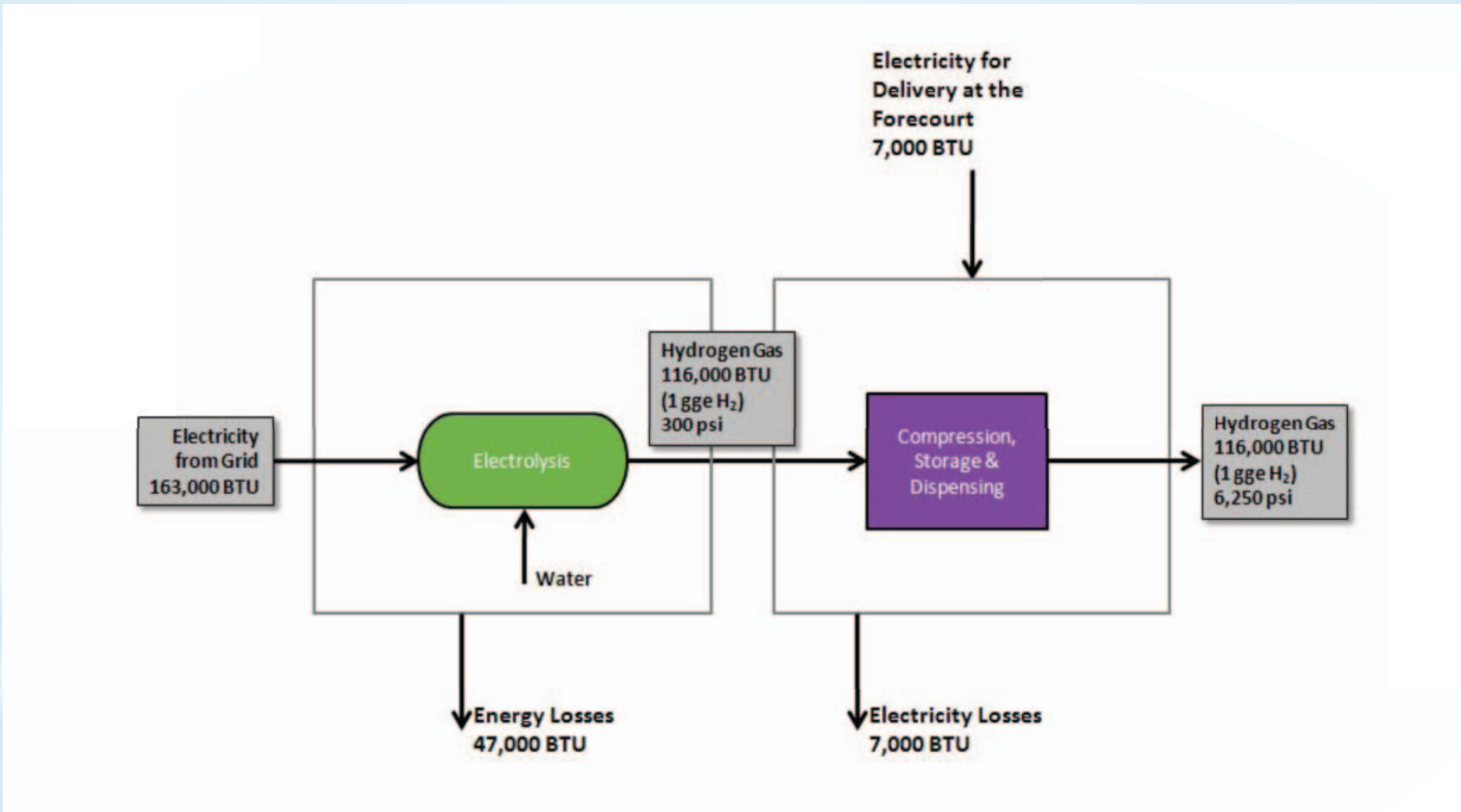
Heat

Teledyne Altus 20 alkaline electrolyzer at the Schatz Solar Hydrogen Project, Trinidad, CA

By providing electricity, water (H_2O) can be dissociated into the diatomic molecules of hydrogen (H_2) and oxygen (O_2).

Source: H2E3 Program

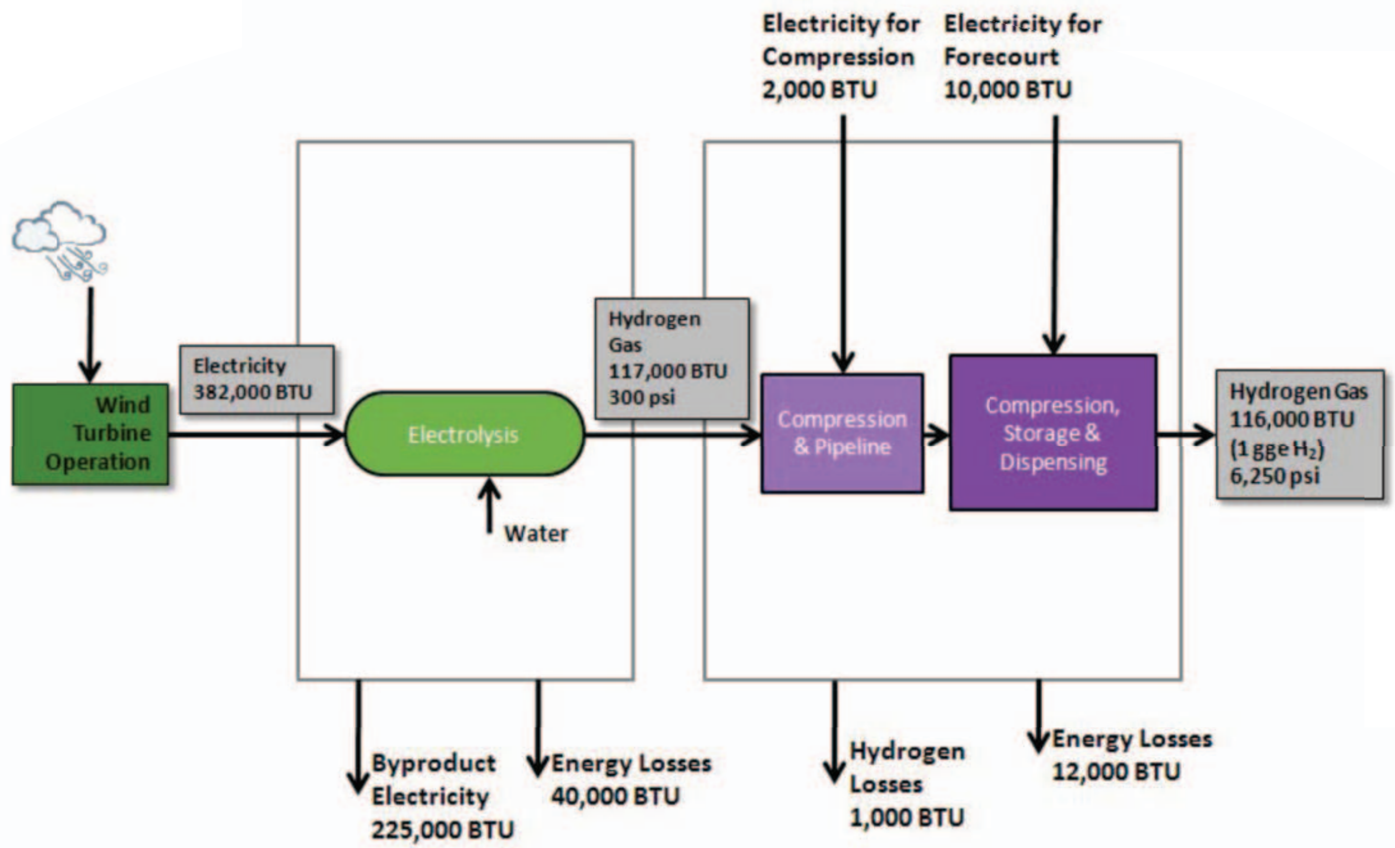
Hydrogen Production with Electrolysis
Est. 68% overall efficiency w/grid power (LHV)



Source: U.S. DOE, 2010 (draft)

Hydrogen from Large-Scale Wind

Est. 69% overall efficiency (LHV)



Source: U.S. DOE, 2010 (draft)

Electrolyzers Can Be Small or Quite Large - These Are 2000 kW!

Source: Norsk Hydro

Hydrogen Production Economics

Technology and Fuel	Capacity MGPD	Overnight Capital Cost: Million Dollars	Overnight Capital Cost: Dollars per MGPD	Capacity Factor (Percent)	Hydrogen Production Cost (Dollars per Kilogram): Capital[a]	Feed-stock	O&M	Total
Central SMR of Natural Gas[b]	379,387	$181	$477	90	$0.18	$1.15	$0.14	**$1.47**
Distributed SMR of Natural Gas[c]	1,500	$1.14	$760	70	$0.40	$1.72	$0.51	**$2.63**
Central Coal Gasification w/ CCS[d]	307,673	$691	$2,246	90	$0.83	$0.56	$0.43	**$1.82**
Central Coal Gasification w/o CCS[d]	283,830	$436	$1,536	90	$0.57	$0.56	$0.09	**$1.21**
Biomass Gasification[e]	155,236	$155	$998	90	$0.37	$0.52	$0.55	**$1.44**
Distributed Electrolysis[f]	1,500	$2.74	$1,827	70	$0.96	$5.06	$0.73	**$6.75**
Central Wind (Electrolysis)[g]	124,474	$500	$4,017	90	$1.48	$1.69	$0.65	**$3.82**
Distributed Wind (Electrolysis)[h]	480	$2.75	$5,729	70	$3.00	$3.51	$0.74	**$7.26**
Central Nuclear Thermochemical[i]	1,200,000	$2,468	$2,057	90	$0.76	$0.20	$0.43	**$1.39**

SMR = Steam Methane Reforming; CCS = Carbon Capture and Sequestration; MGPD = thousand kilograms per day; O&M = Operations and Maintenance.

Note: Table excludes transportation and delivery costs and efficiency losses associated with compression or transportation.

[a]For all cases a 12-percent discount rate is used. Economic life of 20 years assumed for distributed technologies and 40 years for all other technologies. Average United States prices for 2007 are used where practicable.

[b]Assumes industrial natural gas price of $7.4 per million Btu and industrial electric price of 6.4 cents per kilowatthour.

[c]Assumes commercial natural gas price of $11 per million Btu and commercial electric price of 9.5 cents per kilowatthour.

[d]Assumes coal price of $2.5 per million Btu.

[e]Assumes biomass price of $2.2 per million Btu ($37.8 per ton).

[f]Assumes commercial electric price of 9.5 cents per kilowatthour.

[g]Excludes opportunity cost of wind power produced.

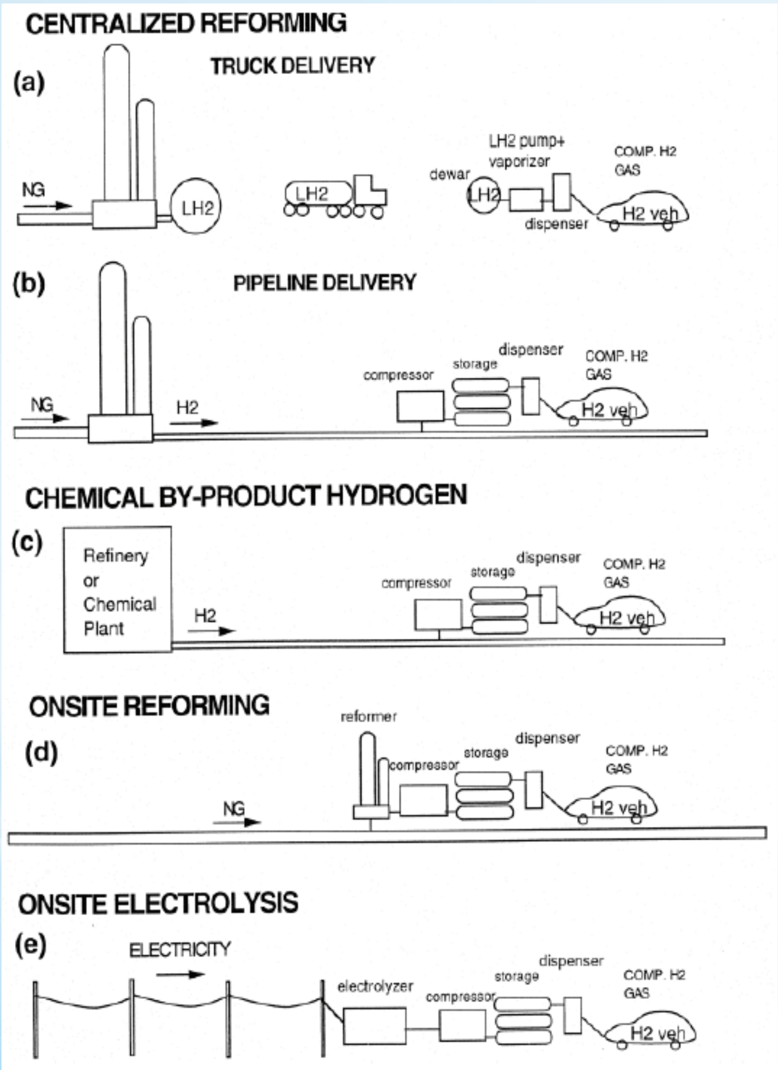
[h]Assumes grid supplies 70 percent of power at 9.5 cents per kilowatthour and remainder at zero cost.

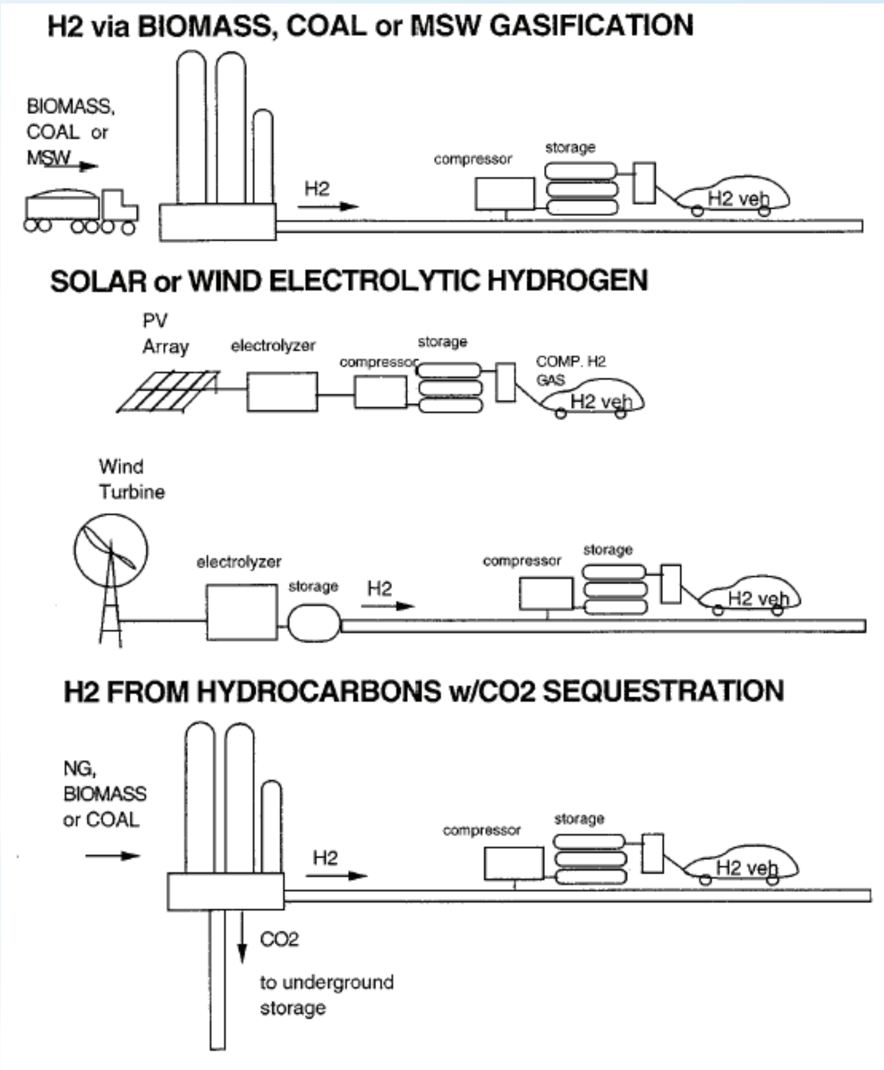
[i]Includes estimated nuclear fuel cost and co-product credit as net feedstock cost, decommissioning costs included in O&M.

Sources: The National Academies, Board on Energy and Environmental Systems, *The Hydrogen Economy: Opportunity, Costs, Barriers, and R&D Needs* (Washington, DC, February 2004), web site www.nap.edu/catalog/10922.html; and U.S. Department of Energy, Hydrogen Program, *DOE H2A Analysis*, web site www.hydrogen.energy.gov/h2a_analysis.html.

Source: EIA, 2008

Hydrogen Production and Distribution





Sources: Annu. Rev. Energy Environ. 1999, 24:227-79

Hydrogen Storage

- Hydrogen is bulky – stores lots of energy by mass but not very much by volume
- Optimal hydrogen storage system would have high energy density (by wgt. and vol.), low cost, quick refueling, and good safety
- Major candidates are:
  - Compressed gas (2,400-10,000 psi)
  - Cryogenic liquid
  - Material based solutions such as metal hydrides, high surface area adsorbents, and chemical hydrides
- No perfect solution yet – trade-offs among systems

Hydrogen Storage

"Tube Trailer" with 30 cylinders and 105 kg capacity (2,400 psi)

Hydrogen Storage

Cryogenic liquid storage with 13,000 gallon/3,500 kg capacity

Hydrogen Storage

Next generation compressed gas with 600 kg of storage at 3,600 psi

Source: Baldwin, 2009

Hydrogen Storage

ASME certified ground storage

Source: Cohen and Snow, 2008

Hydrogen Storage

DOT certified conformable storage using composite materials (now up to 10,000 psi/700 bar)

Renewable Hydrogen - Example 1
Utsira Norway

Installed in 2004 on windy Norwegian island

Supplies 10 households with constant power

Both hydrogen fuel cells and gen-sets have been used

Demonstrates use of renewable hydrogen for “power autonomy” on islands

Platts Award for Renewable Project of the Year (2004)

Renewable Hydrogen – Example 2

Small-scale solar hydrogen for vehicles

Source: Honda (in U.S. DOE, 2010 - draft)

Located in Torrance, CA

Household scale

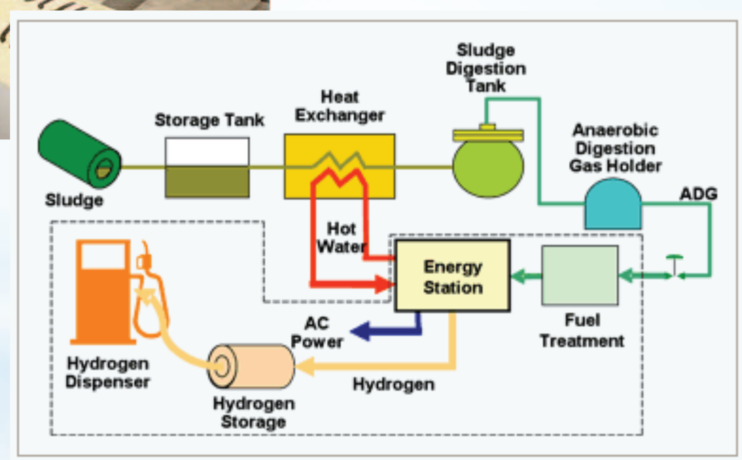
6 kW of solar PV

0.5 kg of H_2 per 8 hour period daylight

New type of electrolyzer eliminates need for H_2 compressor, raising efficiency by ~25%!

Renewable Hydrogen - Example 3

Orange County Sanitation District



Energy source is biogas from WWT

250 kW of fuel cell power

Enough H_2 to fill 40 cars per day

Project cost of $8-9 million

Scalable to 2 MW and 400 car fills per day!

Sources: Orange County Register, 2010 and Air Products and Chemicals, Inc.

Renewable Hydrogen – Example 3

Co-product hydrogen from MCFC power

FuelCell Energy

Co-Production Capacity of DFC-H2® Power Plants

DFC300®

DFC1500®

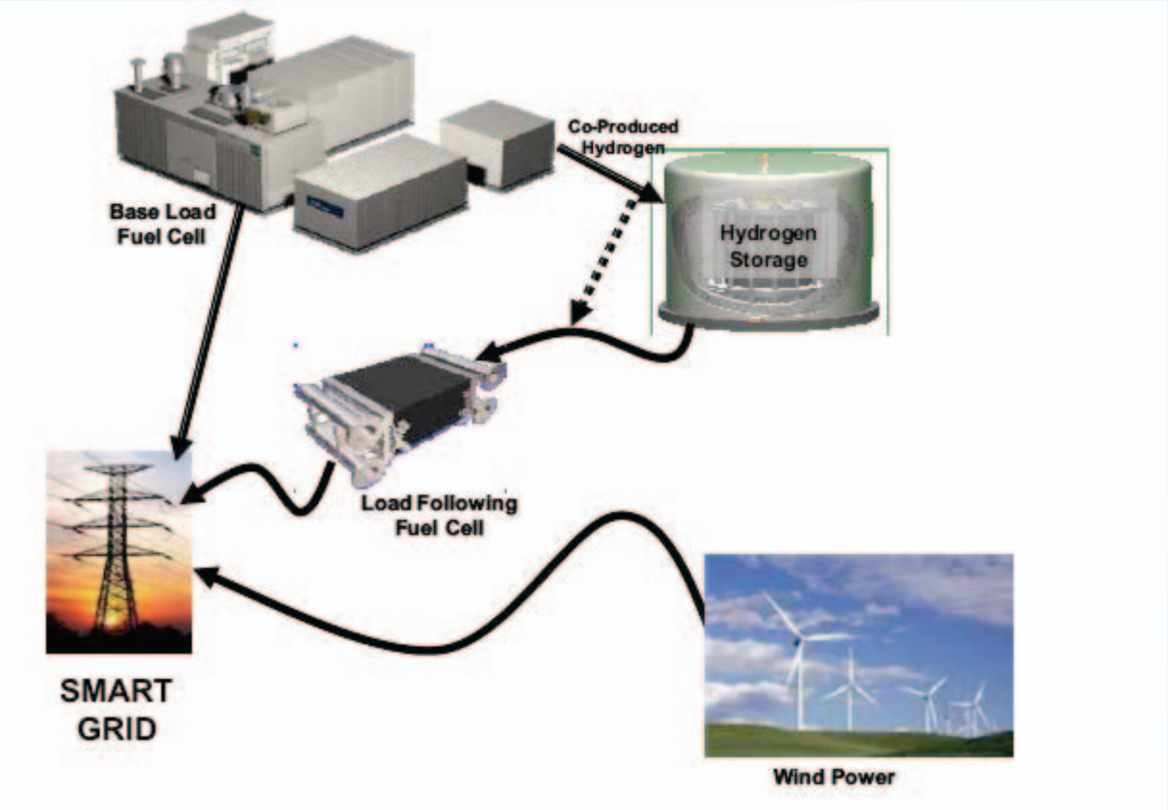
DFC3000®

	DFC300®	DFC1500®	DFC3000®
<u>Co-product</u>			
Power, kW	250	1,000	2,000
Hydrogen, kg/day	125	500	1,000
Heat, mmBtu/hr	0.5	2.0	4.0
<u>Peaker Capacity</u>			
Peak Power (8 hrs/day), kw	500	2,000	4,000
<u>Refueling Capacity</u>			
Fuel Cell Cars, 0.5 kg/day	300	1,200	2,400

Source: Patel et al., 2010

Renewable Hydrogen – Example 3

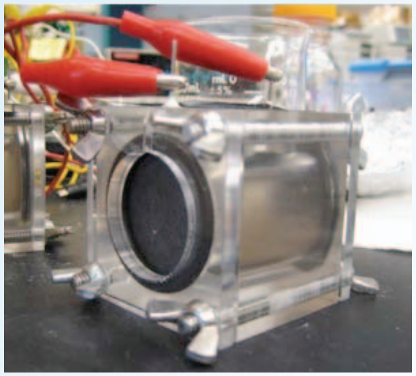
Co-product hydrogen from MCFC power



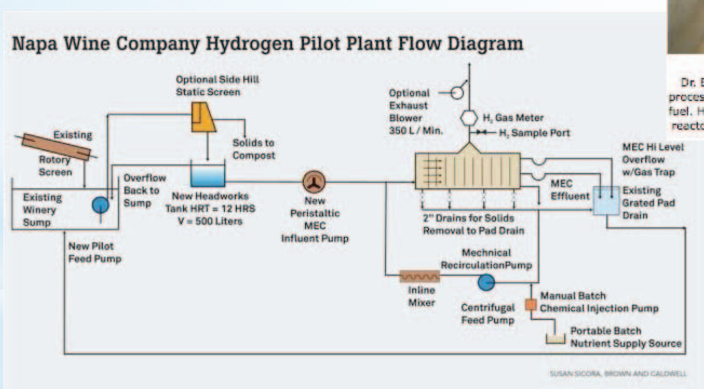
Source: Patel et al., 2010

Renewable Hydrogen - Example 4

Microbial Fuel Cell in Napa, CA Winery



Dr. Bruce Logan has spent more than 13 years developing a process that converts biodegradable liquid wastes into hydrogen fuel. Here he is pictured with a microbial electrolysis cell unit, or reactor, being used in a field study at the Napa Wine Company.



Bacteria turns unused sugar and vinegar from winemaking process into electricity

Then the electricity supplemented by grid power is used to split water in “microbial electrolysis”

Estimated 10x more energy available than needed to process it

Produces methane as well as hydrogen

Sources: Penn State Univ. and www.winebusiness.com

Conclusions

- Hydrogen Market is Well Developed in Industry but Not Yet at Commercial and Consumer Levels
- H_2 and FCs Offer Potential for Deep Cuts in Carbon and Very Low Air Pollutant Emissions
- Commercial Applications Proliferating
  - Electricity production with fuel cells
  - Backup/premium power
  - Transportation
- Remaining Challenges
  - High costs of stationary systems
  - Challenges with economically dispensing high-purity H_2
  - Codes and standards gaps and issues
  - Safety for various applications still being proven but general good record so far
- Markets are Expanding and New Developments are Rapid!

Thanks For Your Attention!

- Tim Lipman, PhD telipman@berkeley.edu
- Clean Energy States Alliance: www.cleanenergystates.org

CleanEnergy States Alliance

- TSRC: tsrc.berkeley.edu

tsrc Transportation Sustainability RESEARCH CENTER

- Pacific RAC: www.pacificcleanenergy.org
- H2E3: hydrogencurriculum.org
- U.S. DOE Hydrogen Program: www.hydrogen.energy.gov

Appendix: Hydrogen Applications

- Stationary Power
  - Fuel cells (predominant) and gen-sets (possible)
  - Combined heat and power market is developing well
- Transportation Applications
  - Heavy duty (buses, delivery vehicles)
  - Light-duty (all major OEMs)
  - Forklifts (now commercial)
- Backup Power
  - Telecommunications
  - Redundancy for premium power markets
  - In conjunction with stationary fuel cell CHP
- Educational Teaching Tools
  - Electrolyzer/fuel cell kits
  - FC test stations for advanced classes

Hydrogen Applications – Fuel Cells

Recent Commercial Status (Source: U.S. DOE, 2010)

- More than 50 types and sizes of commercial fuel cells are currently being sold
- Value of shipments reached $498 million in 2009 (globally)
- 40% growth from 2008
- Approximately 15,000 commercial units were shipped in 2009 including 9,000 stationary units
- Additional approximate 9,000 small units sold for educational purposes

Stationary Fuel Cells w/CHP
200 kW PAFC Unit from UTC

Source: UTC Fuel Cells

Demonstrated:

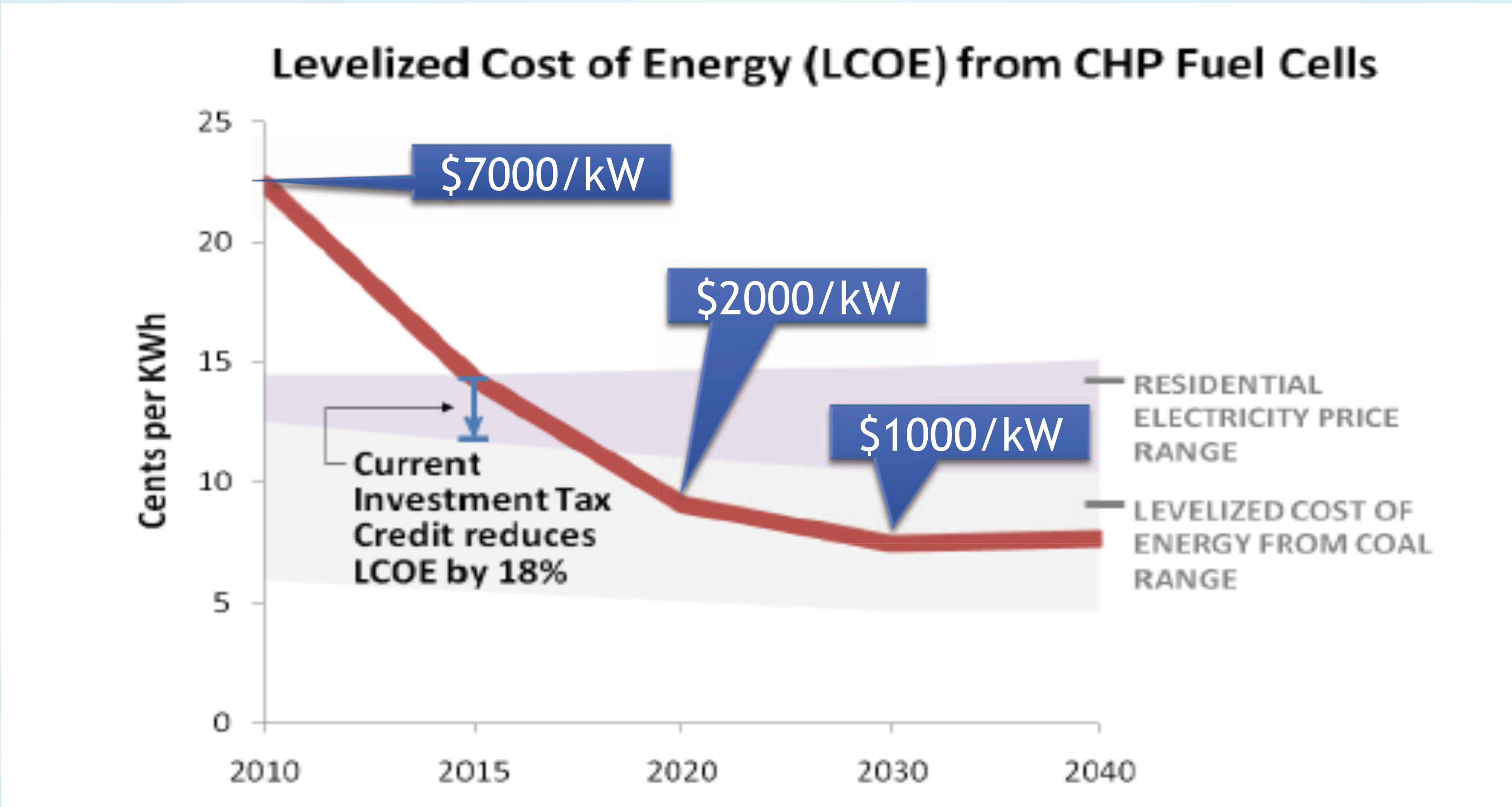
Overall efficiency of ~90% (claimed)

Very low emissions

90,000+ hours of operation (likely with stack replacements)

99% Availability

Stationary Fuel Cells w/CHP

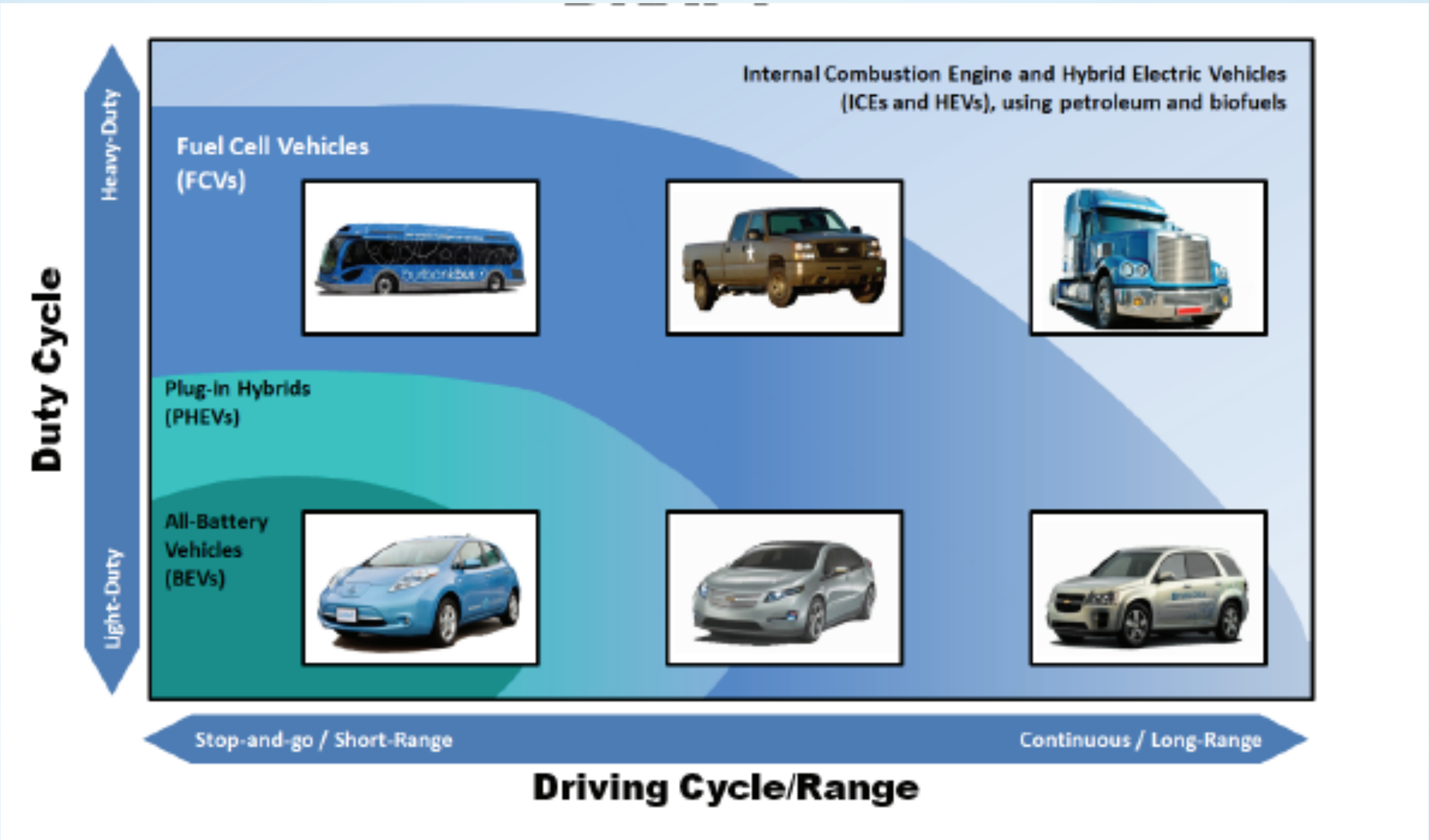


Source: U.S. DOE, 2010 (draft)

Backup Power for Telecomm etc.

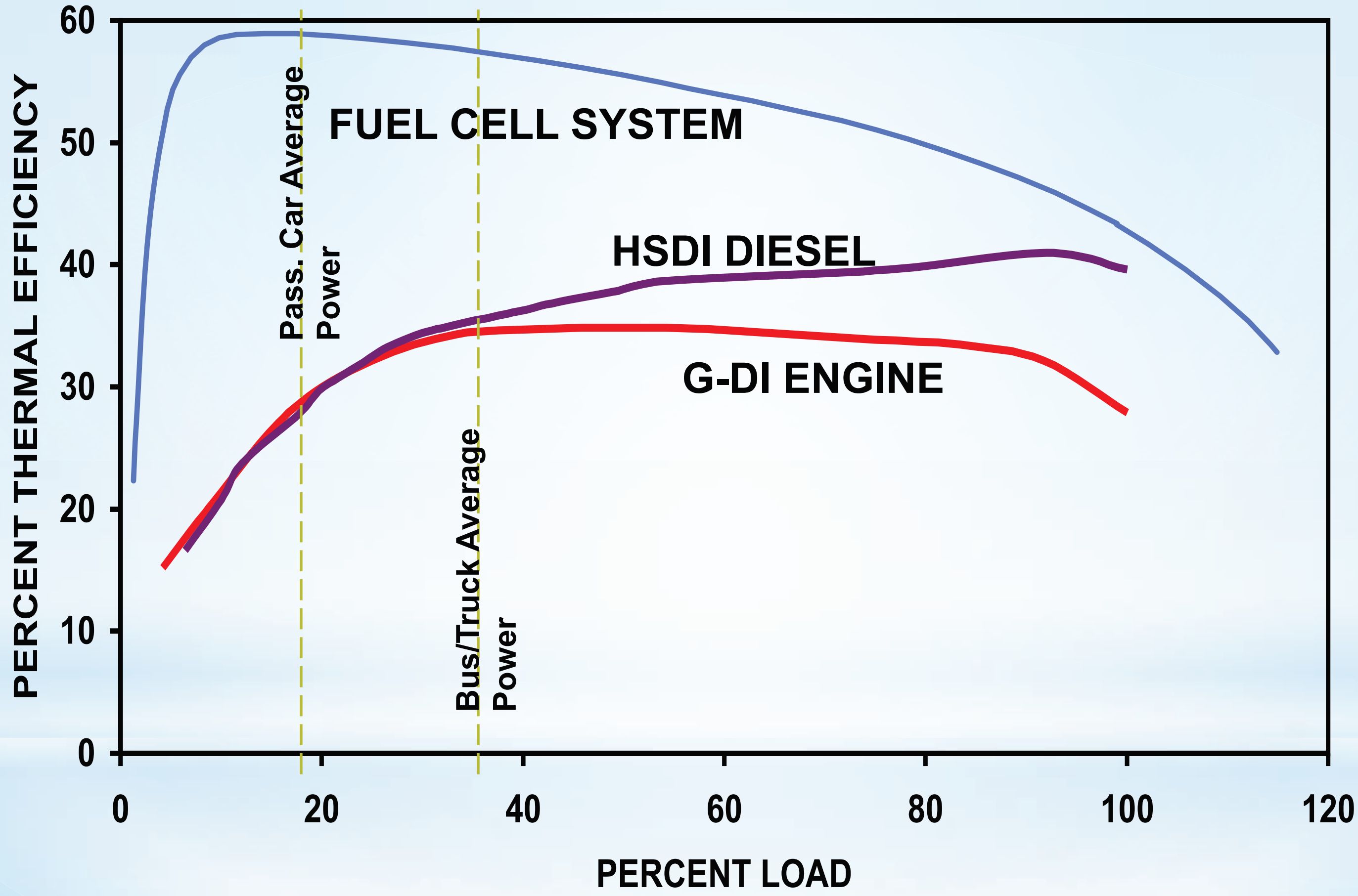
Source: Altergy Systems

Transportation Applications



Source: U.S. DOE, 2010 (draft)

Transportation Applications



Source: Ricardo

Transportation Applications

Backup Power for Telecomm etc.

Source: Altergy Systems