Fuel Cells

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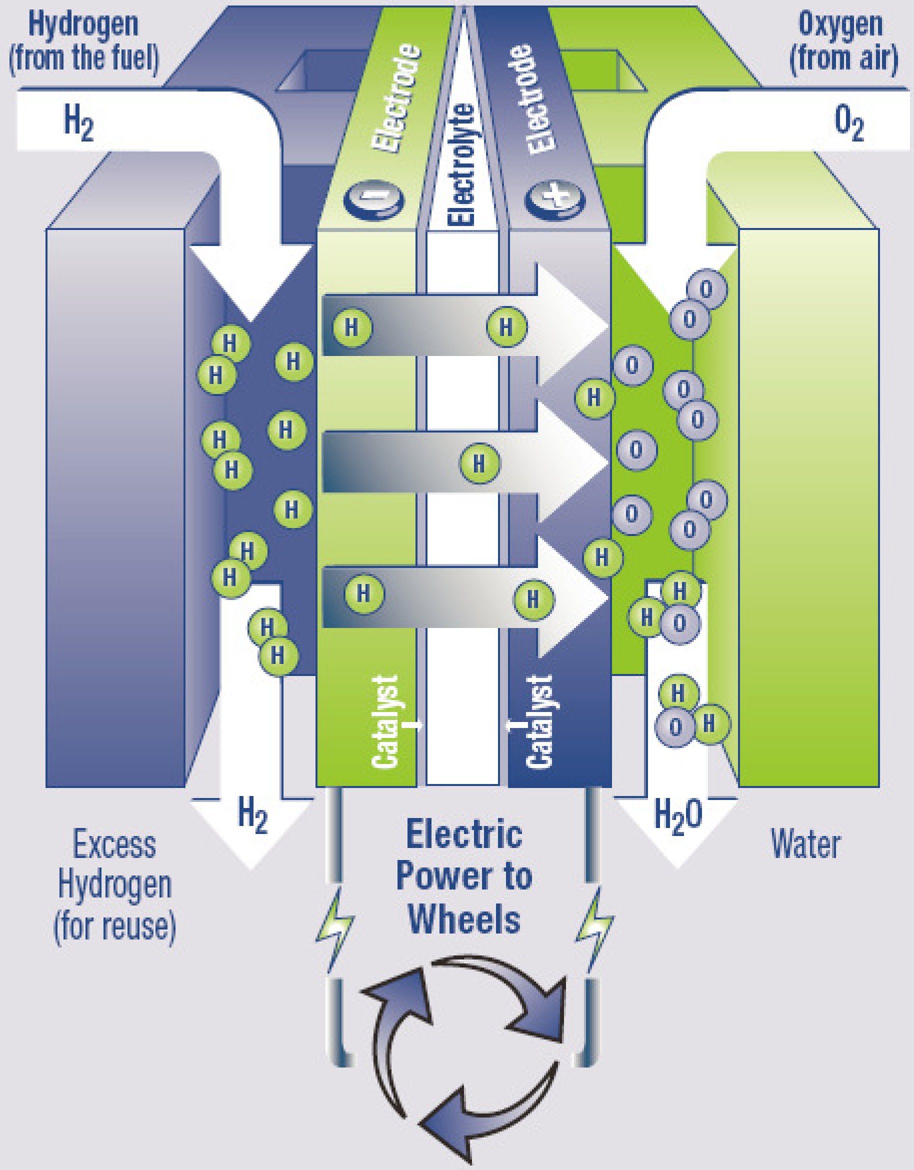
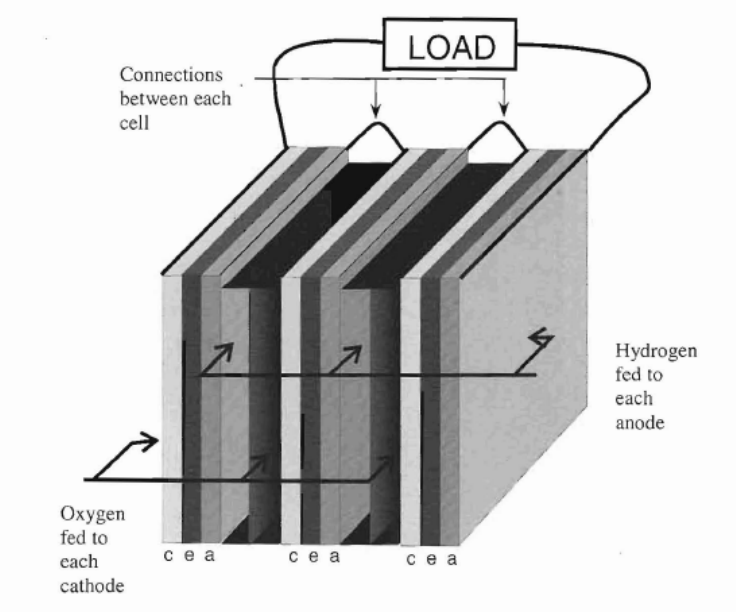
1. Fuel cell basics
2. Fuel cell stacks – bipolar plates
3. Types of fuel cells
4. Proton Exchange Membrane fuel cells
5. Current status

Individual Fuel Cell



Cell voltage: connecting cells in series

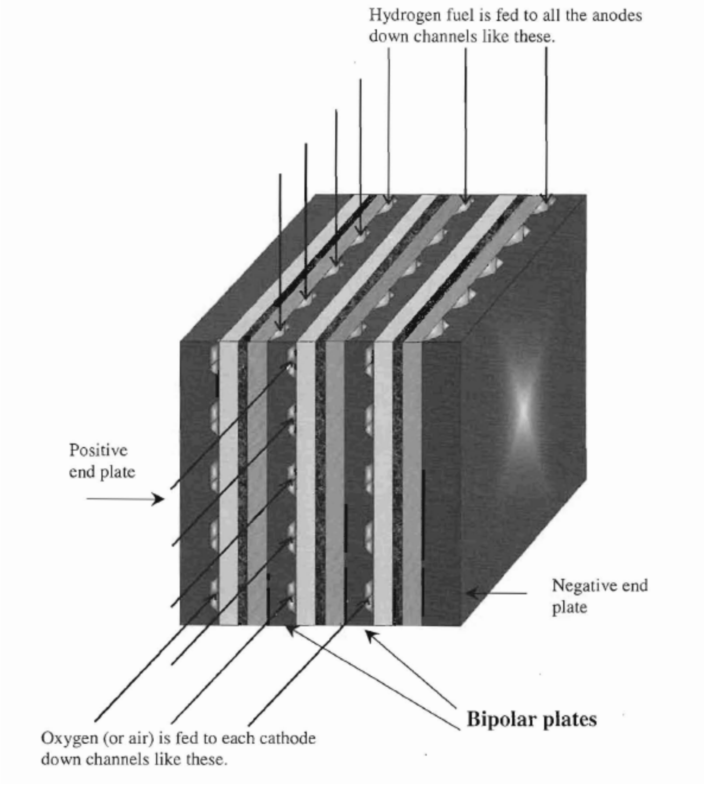
Voltage of one fuel cell = 0.7 V
For useful voltage → collection of fuel cells needed → ‘stack’

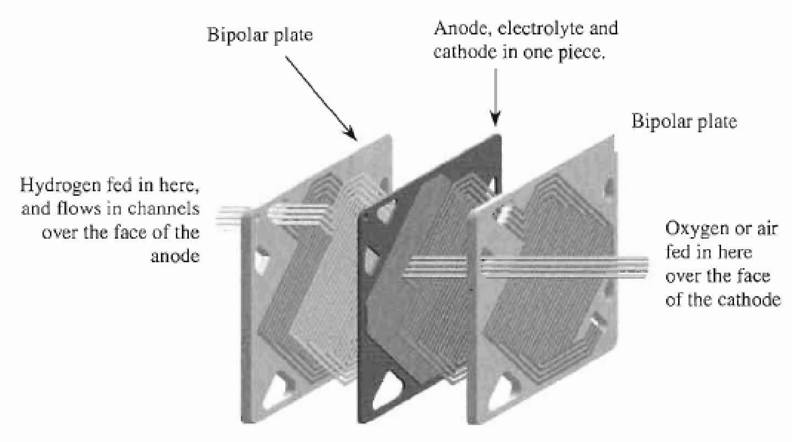


-current collection issues → voltage drop

BIPOLAR plate

- Better method for cell interconnection
- makes connection all over one cathode and the anode of the next cell and also Serves as a means of feeding O2 to cathode and fuel to the anode





- complex design; expensive to manufacture
- made from graphite

Practical issues:

1. Slower reaction rate → low current & power
2. Availability of H_2 as a fuel

Types of Fuel Cells

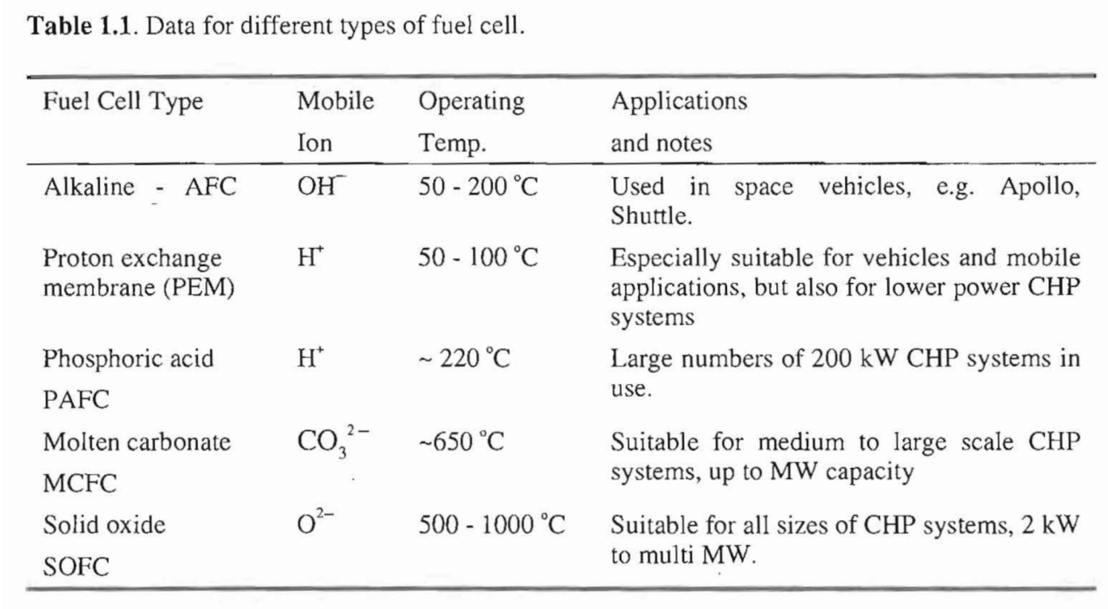
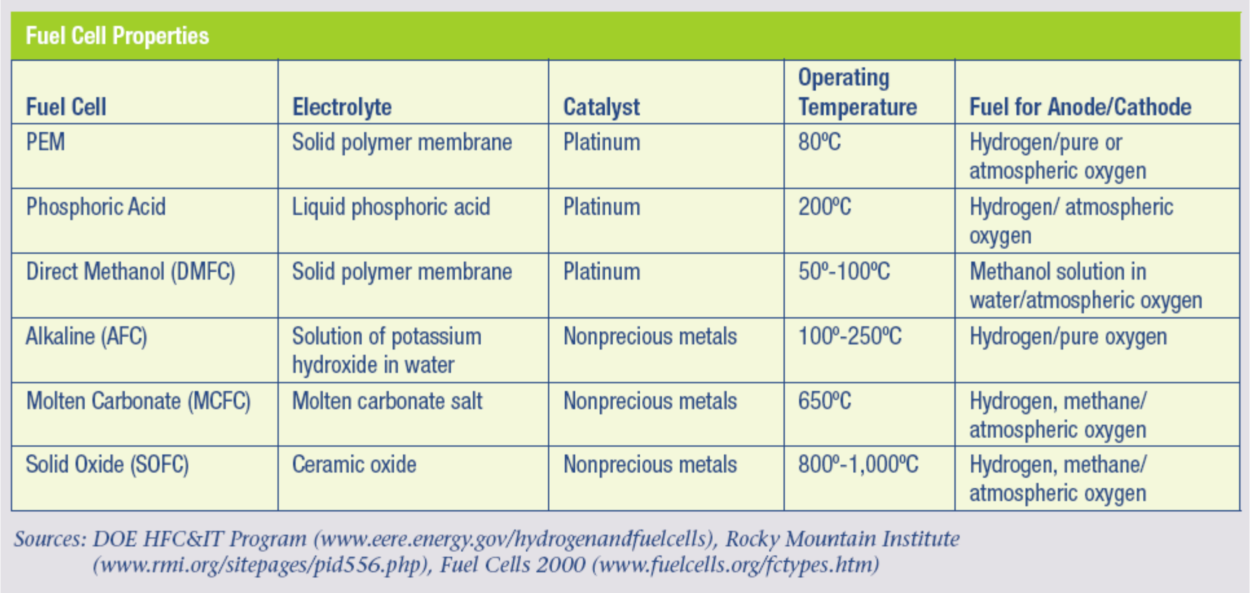


Table 1.1. Data for different types of fuel cell.

Fuel Cell Type	Mobile Ion	Operating Temp.	Applications and notes
Alkaline - AFC	OH^-	50 - 200 °C	Used in space vehicles, e.g. Apollo, Shuttle.
Proton exchange membrane (PEM)	H^+	50 - 100 °C	Especially suitable for vehicles and mobile applications, but also for lower power CHP systems
Phosphoric acid PAFC	H^+	~ 220 °C	Large numbers of 200 kW CHP systems in use.
Molten carbonate MCFC	CO_3^{2-}	~650 °C	Suitable for medium to large scale CHP systems, up to MW capacity
Solid oxide SOFC	O^{2-}	500 - 1000 °C	Suitable for all sizes of CHP systems, 2 kW to multi MW.



Fuel Cell Properties

Fuel Cell	Electrolyte	Catalyst	Operating Temperature	Fuel for Anode/Cathode
PEM	Solid polymer membrane	Platinum	80ºC	Hydrogen/pure or atmospheric oxygen
Phosphoric Acid	Liquid phosphoric acid	Platinum	200ºC	Hydrogen/ atmospheric oxygen
Direct Methanol (DMFC)	Solid polymer membrane	Platinum	50º-100ºC	Methanol solution in water/atmospheric oxygen
Alkaline (AFC)	Solution of potassium hydroxide in water	Nonprecious metals	100º-250ºC	Hydrogen/pure oxygen
Molten Carbonate (MCFC)	Molten carbonate salt	Nonprecious metals	650ºC	Hydrogen, methane/ atmospheric oxygen
Solid Oxide (SOFC)	Ceramic oxide	Nonprecious metals	800º-1,000ºC	Hydrogen, methane/ atmospheric oxygen

Sources: DOE HFC&IT Program (www.eere.energy.gov/hydrogenandfuelcells), Rocky Mountain Institute (www.rmi.org/sitepages/pid556.php), Fuel Cells 2000 (www.fuelcells.org/fctypes.htm)

Proton Exchange Membrane(PEM) Fuel Cells

ion conduction polymer electrolyte (mobile ion = H^+ ion or proton)

Anode-electrolyte-cathode ‘all-in-one’ assembly
→ “membrance electrode assemblies”

Low temperature operation → can start quickly

Applications:
-cars, buses, combined heat and power systems

How the polymer electrolyte works

Sulfonated fluoropolymers …. Nafion (Dupont)

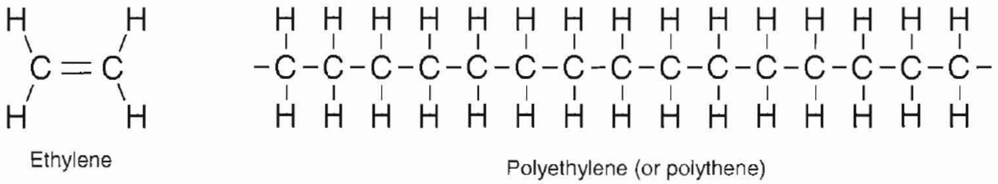


Figure 4.2 Structure of polyethylene

Strong C-F bonds resists chemical attacks

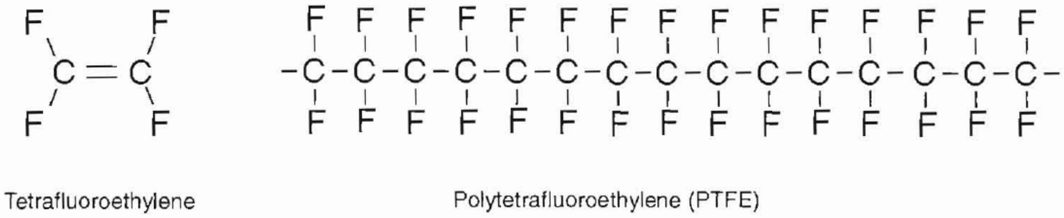


Figure 4.3 Structure of PTFE

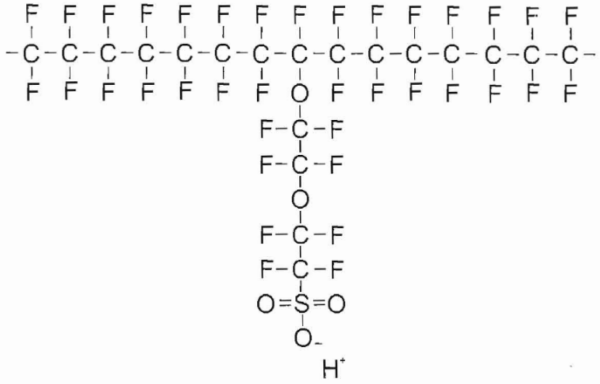


Figure 4.4 Example structure of a sulphonated fluoroethylene, (also called 'perfluorosulphonic acid PFTE copolymer')

Polymer sulphonated with HSO3 to add an SO3- ion

Polymer – hydrophobic
SO3- → hydrophilic

This leads to interesting hydrophilic/hydrophobic “micro-phase separated morphology”

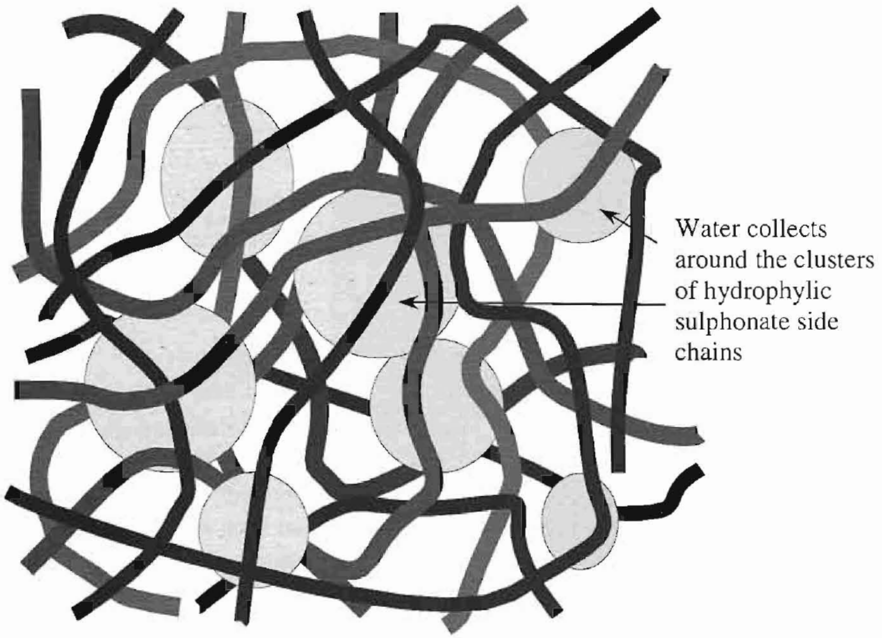


Figure 4.5 showing the structure of Nafion type membrane materials. Long chain molecules containing hydrated regions around the sulphonated side chains.

→dilute acidic regions with a tough and strong hydrophobic structure

Electrodes and electrode structure

Pt catalyst → cathode and anode

Few years ago, 28 mg per cm3 was used…
Today, 0.2 mg/cm2 is used (use of nanoparticles, etc)

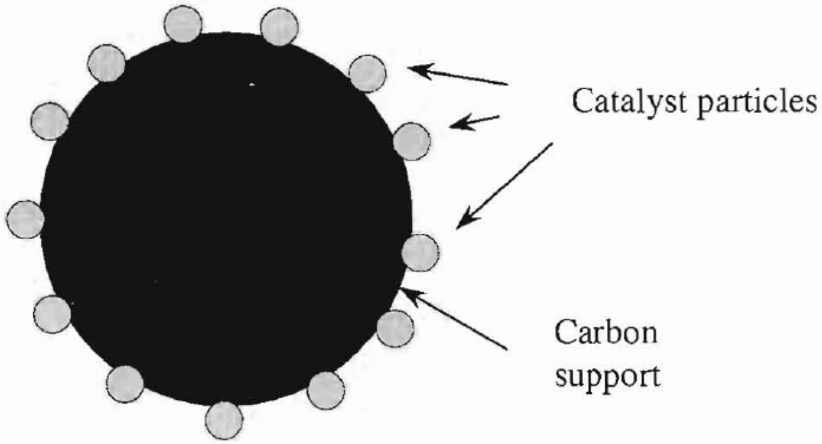
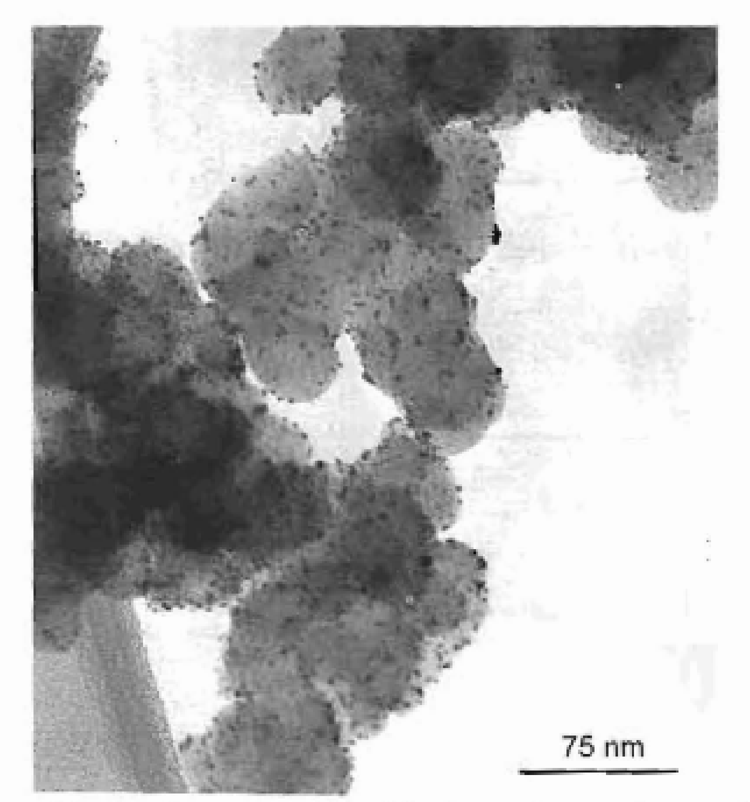


Figure 4.6 The structure, idealised, of a carbon supported platinum catalyst.

TEM image of fuel cell catalyst



Fuelling fuel cells

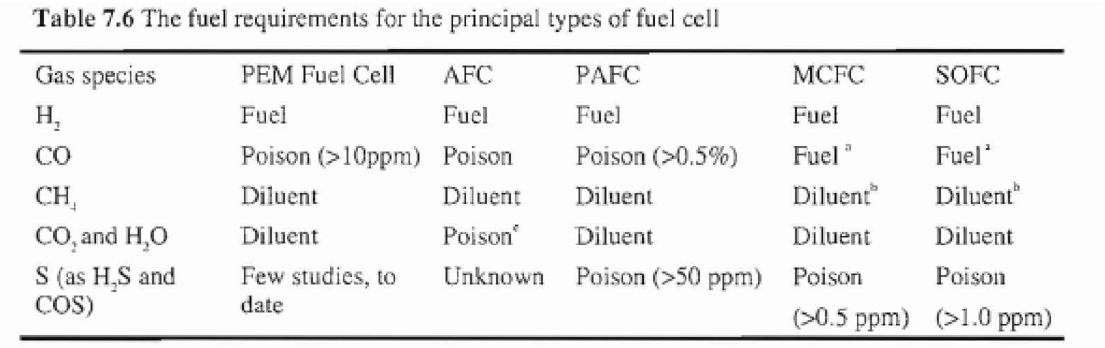
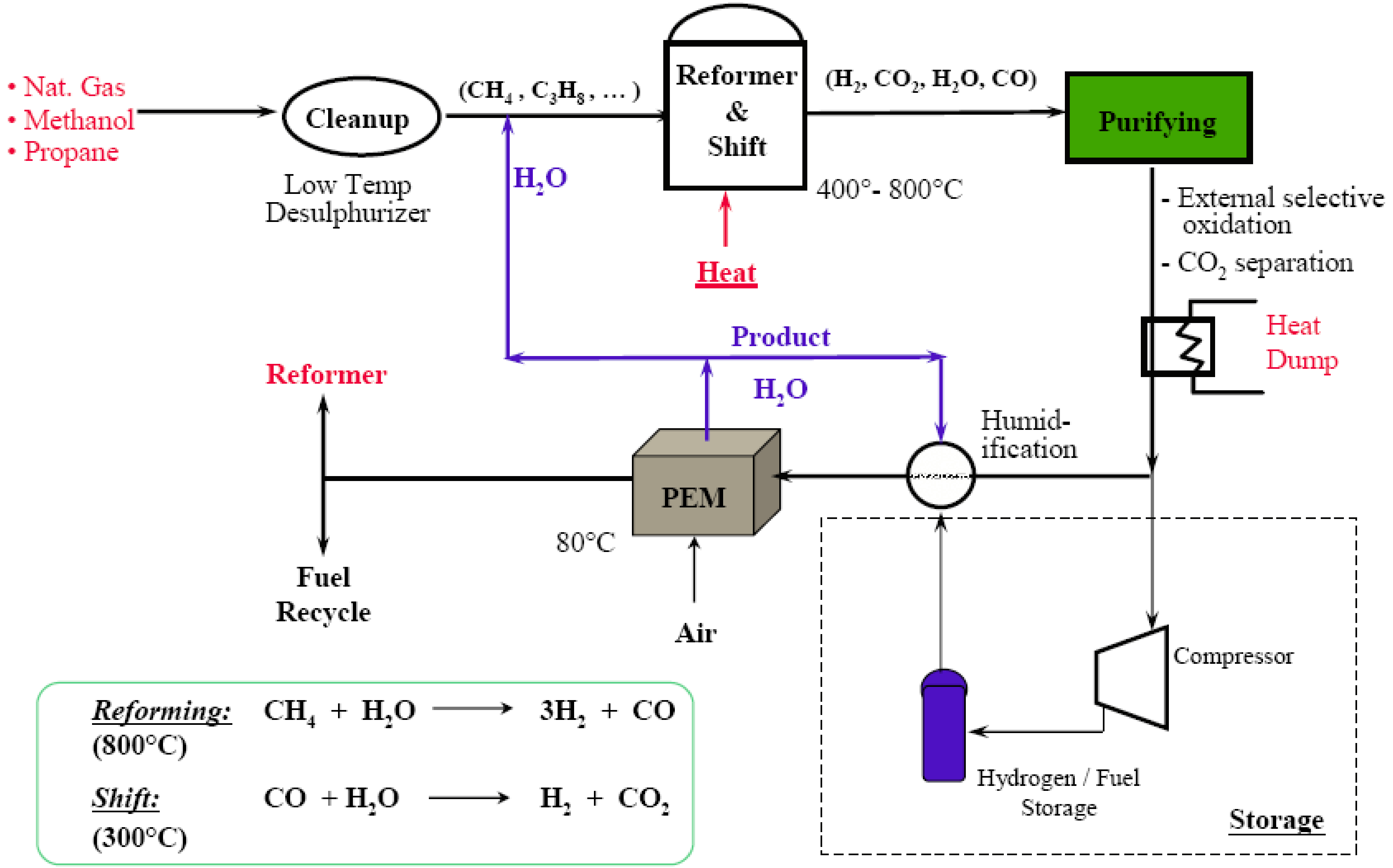


Table 7.6 The fuel requirements for the principal types of fuel cell

Gas species	PEM Fuel Cell	AFC	PAFC	MCFC	SOFC
H_2	Fuel	Fuel	Fuel	Fuel	Fuel
CO	Poison (>10ppm)	Poison	Poison (>0.5%)	Fuel[a]	Fuel[a]
CH_4	Diluent	Diluent	Diluent	Diluent[b]	Diluent[b]
CO_2 and H_2O	Diluent	Poison[c]	Diluent	Diluent	Diluent
S (as H_2S and COS)	Few studies, to date	Unknown	Poison (>50 ppm)	Poison (>0.5 ppm)	Poison (>1.0 ppm)

H_2 produced from
- Fossil fuels
  - Petroleum
  - Coal
- Bio-fuels

Fuel Processing System for PEMs



- Nat. Gas
- Methanol
- Propane

Cleanup

Low Temp Desulphurizer

(CH_4 , C_3H_8 , ...)

H_2O

Reformer & Shift

400°- 800°C

Heat

(H_2, CO_2, H_2O, CO)

Purifying

- External selective oxidation
- CO_2 separation

Heat Dump

Product

H_2O

Humid-ification

Reformer

PEM

80°C

Fuel Recycle

Air

Compressor

Hydrogen / Fuel Storage

Storage

Reforming: **(800°C)** $CH_4 + H_2O \longrightarrow 3H_2 + CO$

Shift: **(300°C)** $CO + H_2O \longrightarrow H_2 + CO_2$

Hydrogen storage

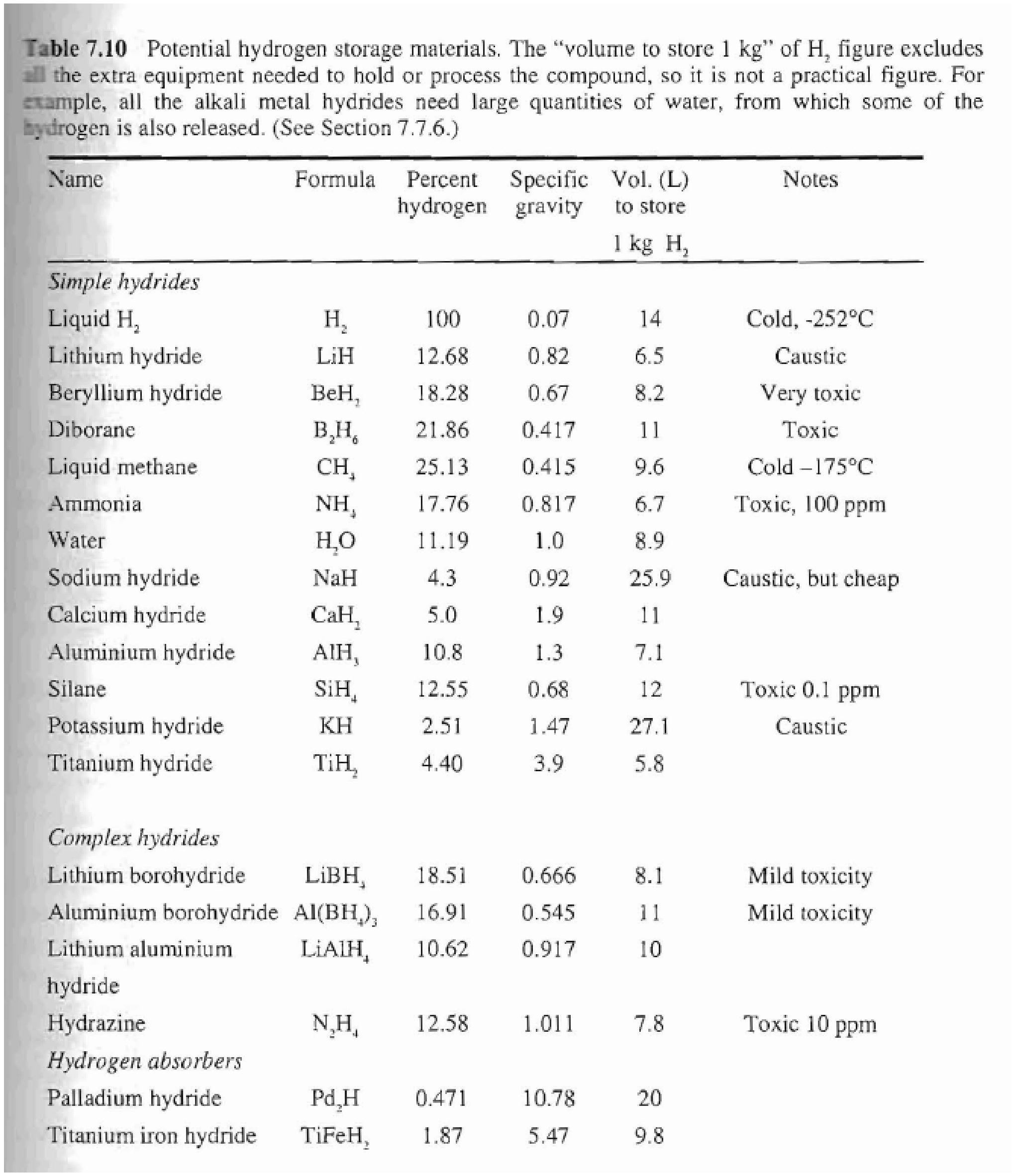


Table 7.10 Potential hydrogen storage materials. The "volume to store 1 kg" of H_2 figure excludes all the extra equipment needed to hold or process the compound, so it is not a practical figure. For example, all the alkali metal hydrides need large quantities of water, from which some of the hydrogen is also released. (See Section 7.7.6.)

Name	Formula	Percent hydrogen	Specific gravity	Vol. (L) to store 1 kg H_2	Notes
Simple hydrides					
Liquid H_2	H_2	100	0.07	14	Cold, -252°C
Lithium hydride	LiH	12.68	0.82	6.5	Caustic
Beryllium hydride	BeH_2	18.28	0.67	8.2	Very toxic
Diborane	B_2H_6	21.86	0.417	11	Toxic
Liquid methane	CH_4	25.13	0.415	9.6	Cold –175°C
Ammonia	NH_4	17.76	0.817	6.7	Toxic, 100 ppm
Water	H_2O	11.19	1.0	8.9	
Sodium hydride	NaH	4.3	0.92	25.9	Caustic, but cheap
Calcium hydride	CaH_2	5.0	1.9	11	
Aluminium hydride	AlH_3	10.8	1.3	7.1	
Silane	SiH_4	12.55	0.68	12	Toxic 0.1 ppm
Potassium hydride	KH	2.51	1.47	27.1	Caustic
Titanium hydride	TiH_2	4.40	3.9	5.8	
Complex hydrides					
Lithium borohydride	$LiBH_4$	18.51	0.666	8.1	Mild toxicity
Aluminium borohydride	$Al(BH_4)_3$	16.91	0.545	11	Mild toxicity
Lithium aluminium hydride	$LiAlH_4$	10.62	0.917	10	
Hydrazine	N_2H_4	12.58	1.011	7.8	Toxic 10 ppm
Hydrogen absorbers					
Palladium hydride	Pd_2H	0.471	10.78	20	
Titanium iron hydride	$TiFeH_2$	1.87	5.47	9.8	

-compressed gas cylinders
-cryogenic liquids
-reversible metal hydride
-metal hydride reactions with water

Safety issues – Hindenburg disaster

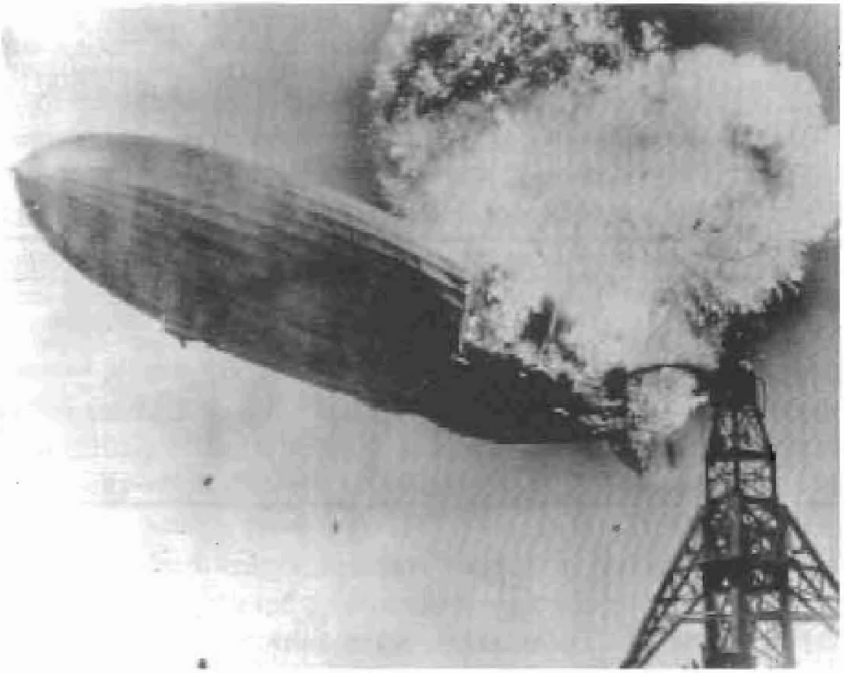


Figure 7.13 Icon of a myth. The "Hindenburg disaster" of 6th May 1937 put an end to the airship as a means of transport, and it has also been a major "public relations" problem for hydrogen, since this was the lifting gas used. The accident led to the widely held myth that hydrogen is a particularly dangerous substance. Although the accident was tragic for those involved, the number of casualties was 37, quite low for an aircraft crash. About 2/3 of those on board survived. Many of those who died were burnt by the diesel fuel for the propulsion system, and in any case the fire did not start with the hydrogen, but in the skin of the airship, which was made of a highly flammable compound. (Brain and VanVorst, 1999).

BIPOLAR plate

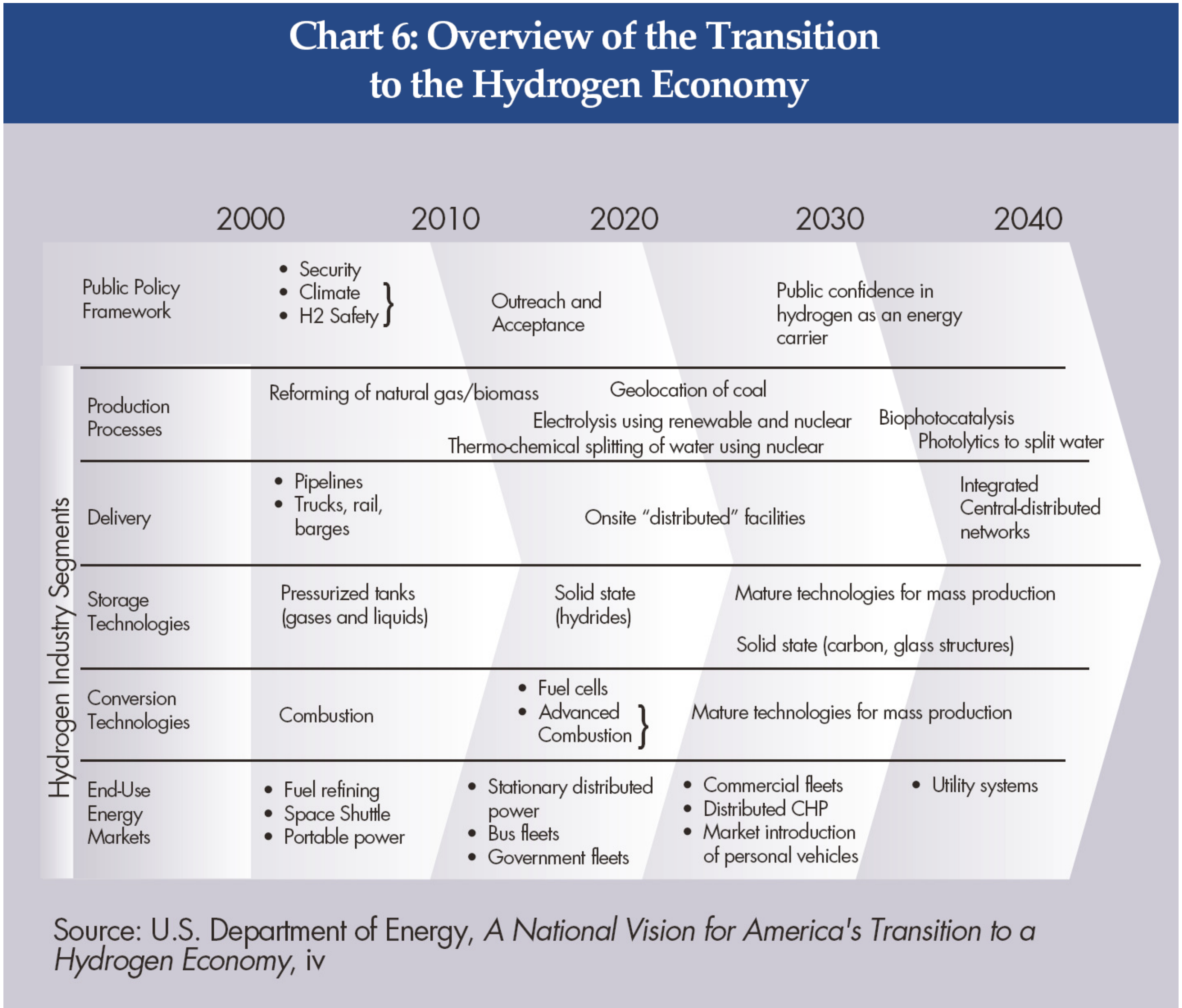


Chart 6: Overview of the Transition to the Hydrogen Economy

2000 2010 2020 2030 2040

Hydrogen Industry Segments

Public Policy Framework	Security Climate H2 Safety	Outreach and Acceptance	Public confidence in hydrogen as an energy carrier	
Production Processes	Reforming of natural gas/biomass	Geolocation of coal Electrolysis using renewable and nuclear Thermo-chemical splitting of water using nuclear		Biophotocatalysis Photolytics to split water
Delivery	Pipelines Trucks, rail, barges	Onsite "distributed" facilities		Integrated Central-distributed networks
Storage Technologies	Pressurized tanks (gases and liquids)	Solid state (hydrides)	Mature technologies for mass production Solid state (carbon, glass structures)	
Conversion Technologies	Combustion	Fuel cells Advanced Combustion	Mature technologies for mass production	
End-Use Energy Markets	Fuel refining Space Shuttle Portable power	Stationary distributed power Bus fleets Government fleets	Commercial fleets Distributed CHP Market introduction of personal vehicles	Utility systems

Source: U.S. Department of Energy, *A National Vision for America's Transition to a Hydrogen Economy*, iv

Chart 14: Deployment Barriers Faced by Fuel Cell Vehicle Technologies

	Types of Barriers				
Technology Areas	**Fundamental**	**Developmental**	**Maturity**	**Experience**	**Infrastructure**
Hydrogen PEM stack			■	■	
Ancillary devices		■	■	■	
Fuel processors (methanol, gasoline)	■	■	■	■	
Fuel storage (hydrogen)	■	■	■	■	■
Fuel supply (hydrogen, methanol)				■	■
Electric drive components			■	■	

Types of Barriers: ***Fundamental*** barriers mean that basic laboratory research work is still needed. ***Developmental*** barriers require additional engineering R&D to develop practical designs. ***Maturity*** barriers remain if suitable designs exist, but the likelihood of further improvement renders mass-production commitments premature. ***Experience*** barriers exist if costs are still higher than the long-run potential because of a lack of production learning. ***Infrastructural*** barriers limit deployment because of a lack of appropriate fuel or service facilities.

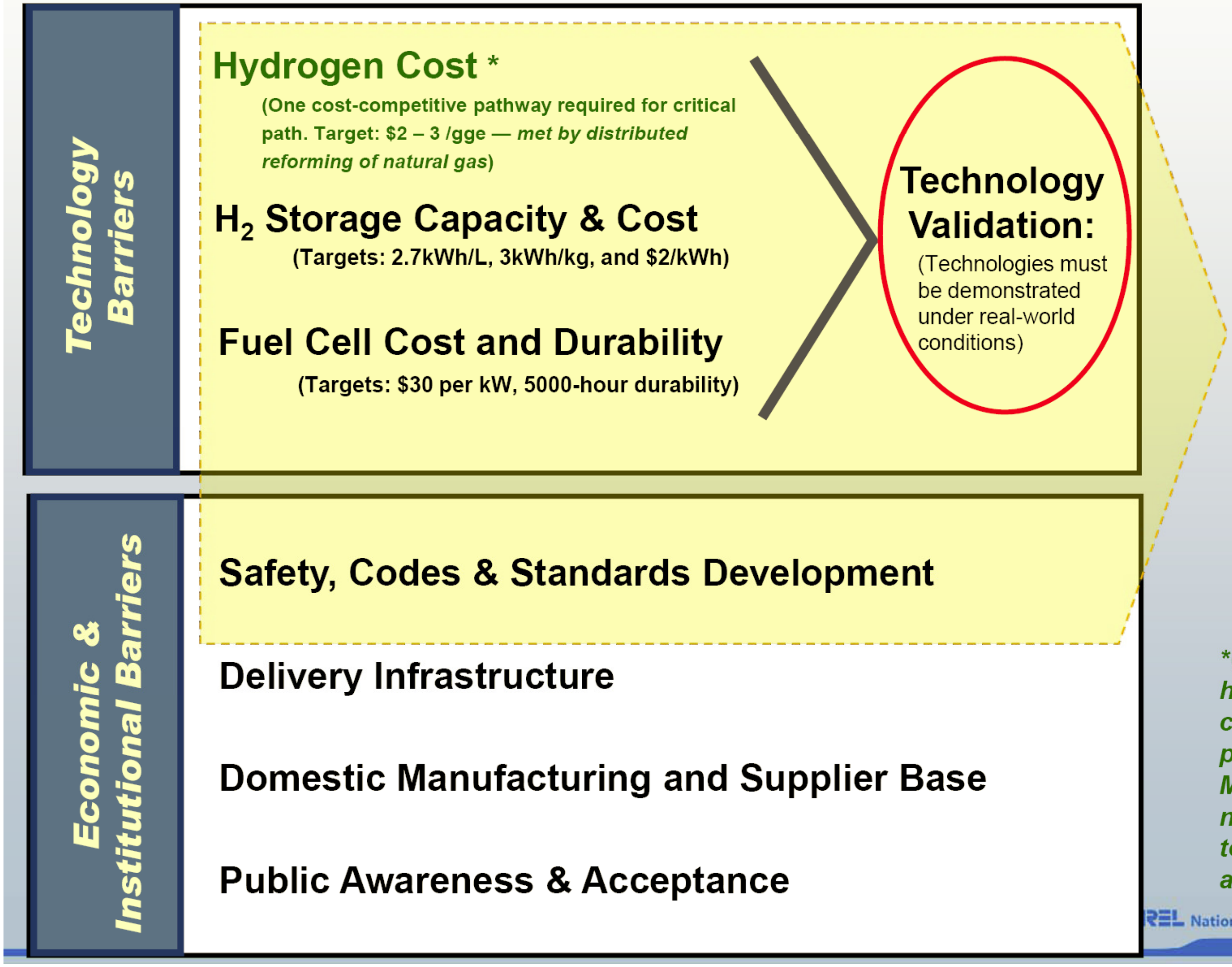
Source: John M. Decicco, *Fuel Cell Vehicles: Technology, Market, and Policy Issues,* SAE Research Report, 2001, x

BIPOLAR plate

DOE's Hydrogen Fuel Cell Activities: Developing Technology and Validating it through Real-World Evaluation

Alternative Fuels & Vehicles Conference
Las Vegas, NV
May 12, 2008

Vehicular Hydrogen Challenges and Barriers



Technology Barriers

Hydrogen Cost *

(One cost-competitive pathway required for critical path. Target: $2 – 3 /gge — *met by distributed reforming of natural gas*)

H_2 Storage Capacity & Cost

(Targets: 2.7kWh/L, 3kWh/kg, and $2/kWh)

Fuel Cell Cost and Durability

(Targets: $30 per kW, 5000-hour durability)

Technology Validation:

(Technologies must be demonstrated under real-world conditions)

Economic & Institutional Barriers

Safety, Codes & Standards Development

Delivery Infrastructure

Domestic Manufacturing and Supplier Base

Public Awareness & Acceptance

Critical Path Barriers for Fuel Cell Vehicle Technology Readiness in 2015

****Critical Path for hydrogen cost is one cost-competitive production pathway. Multiple pathways are needed for longer-term energy security and sustainability.***

Fuel Cell Vehicle Learning Demonstration Seeks to Validate Real-World Progress

- Objectives
  - Validate H_2 FC Vehicles and Infrastructure in Parallel
  - Identify Current Status and Evolution of the Technology
    - Assess Progress Toward Technology Readiness
    - Provide Feedback to H_2 Research and Development

Key Targets

Performance Measure	2009	2015
Fuel Cell Stack Durability	2000 hours	5000 hours
Vehicle Range	250+ miles	300+ miles
Hydrogen Cost at Station	$3/gge	$2-3/gge


Solar Electrolysis Station, Sacramento, CA

Photo: NREL

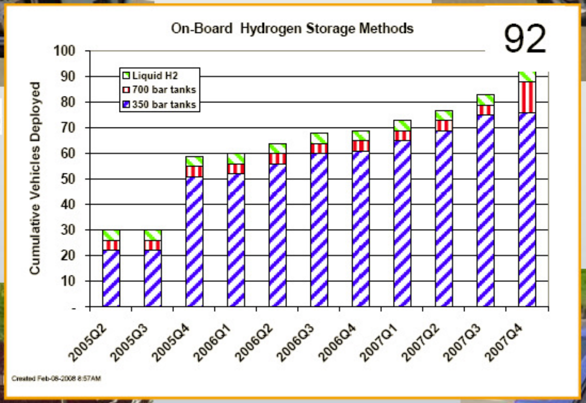
Industry Partners: 4 Automaker/Energy-Supplier Teams; Rollout: 2nd Generation FC Introduction in 2008 Has Begun

CHRYSLER

bp

Ford

bp

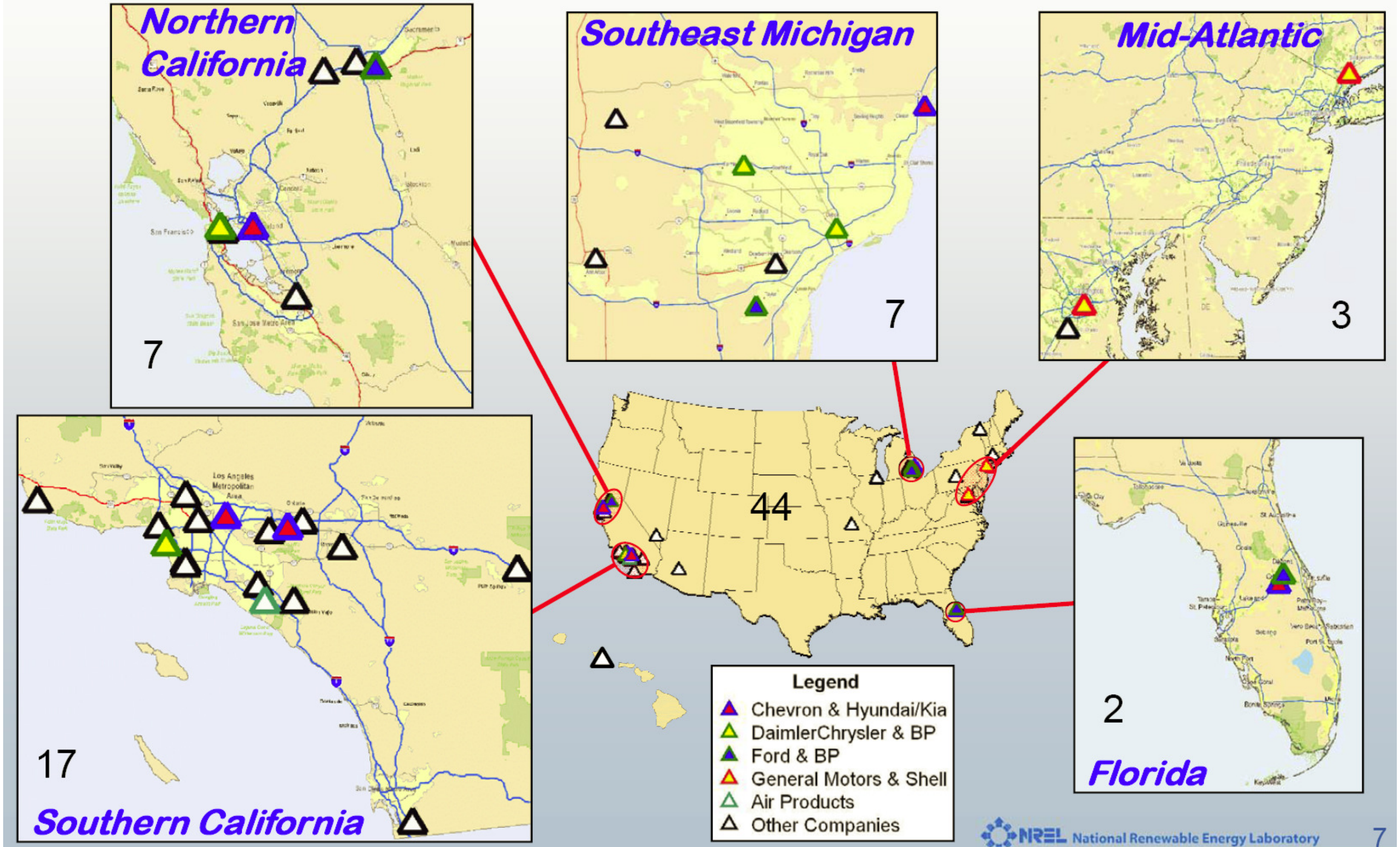


GM

Chevron HYUNDAI KIA UTC Power

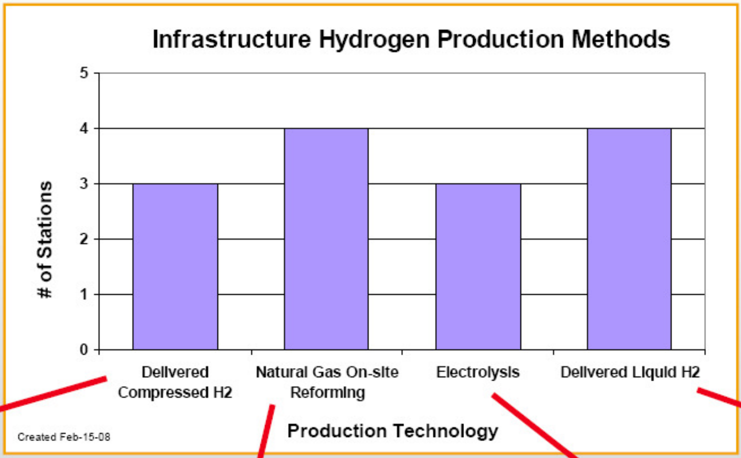
>1.1 Million Miles and
50,000 Vehicle Hours

Refueling Stations Test Performance in Various Climates; Learning Demo Comprises ~1/3 of all US Stations



Majority of Project’s Fixed Infrastructure to Refuel Vehicles Has Been Installed – Examples of 4 Types

Mobile Refueler
Sacramento, CA



Delivered Liquid, 700 bar
Irvine, CA

Steam Methane Reforming
Oakland, CA

Water Electrolysis
Rosemead, CA

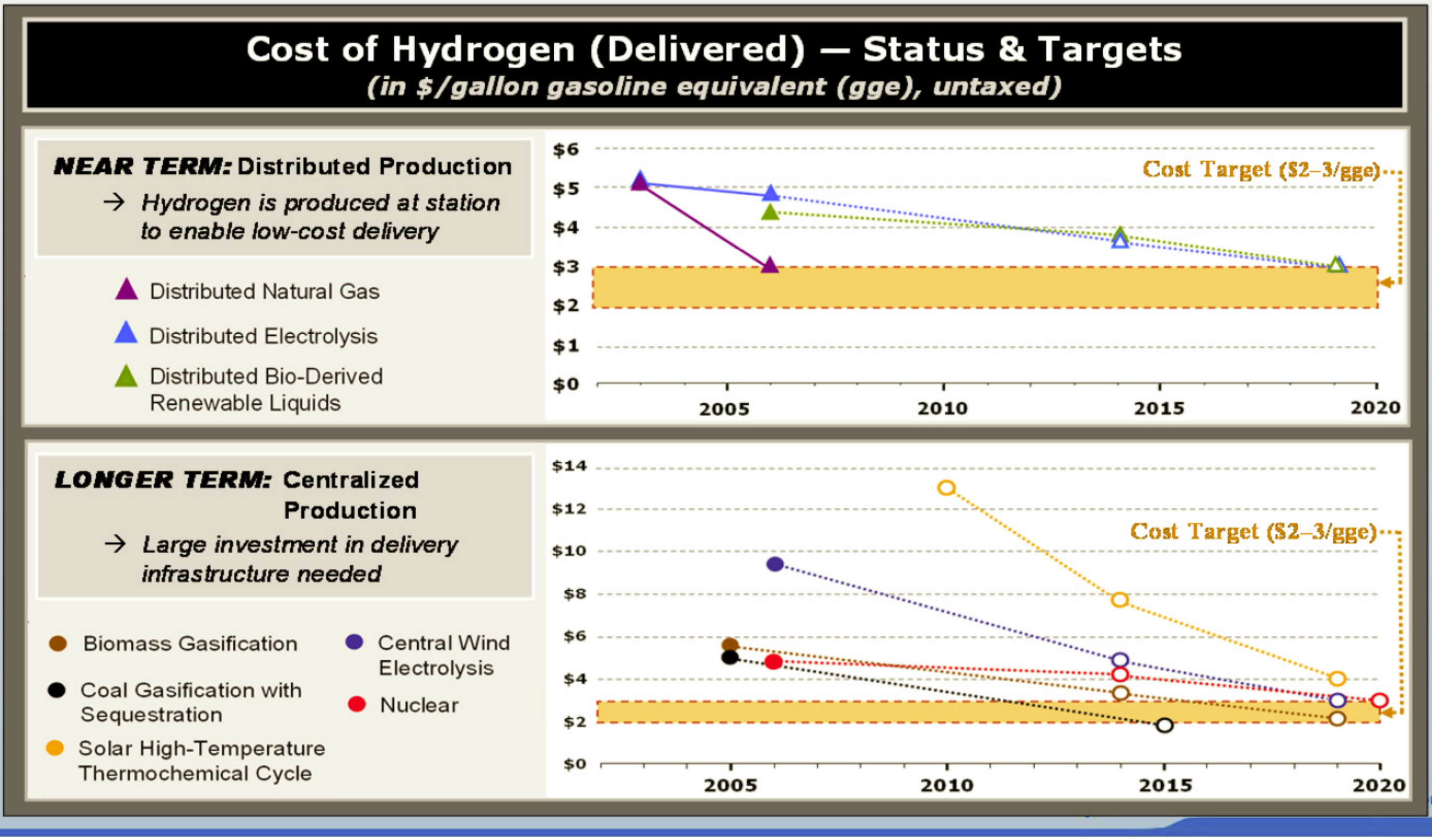
Total of >40,000 kg H2 produced or dispensed

Recent station additions include:
SMUD (BP) and White Plains, NY (Shell).
15 stations now deployed

Hydrogen Production Progress

***GOAL:* Diverse cost-competitive domestic pathways to hydrogen production**

***PROGRESS:* Significant cost reductions have been achieved**



Cost of Hydrogen (Delivered) — Status & Targets

(in $/gallon gasoline equivalent (gge), untaxed)

***NEAR TERM:* Distributed Production**

→ *Hydrogen is produced at station to enable low-cost delivery*

***LONGER TERM:* Centralized Production**

→ *Large investment in delivery infrastructure needed*

Examples of Renewable Pathways for Electricity and Vehicular Fuel Demonstrated

Four Renewable Fuel/Power Demonstration Projects

Hydrogen for Vehicles from On-Site Solar and Water Electrolysis *(ongoing)*

DTE: Southfield, Michigan

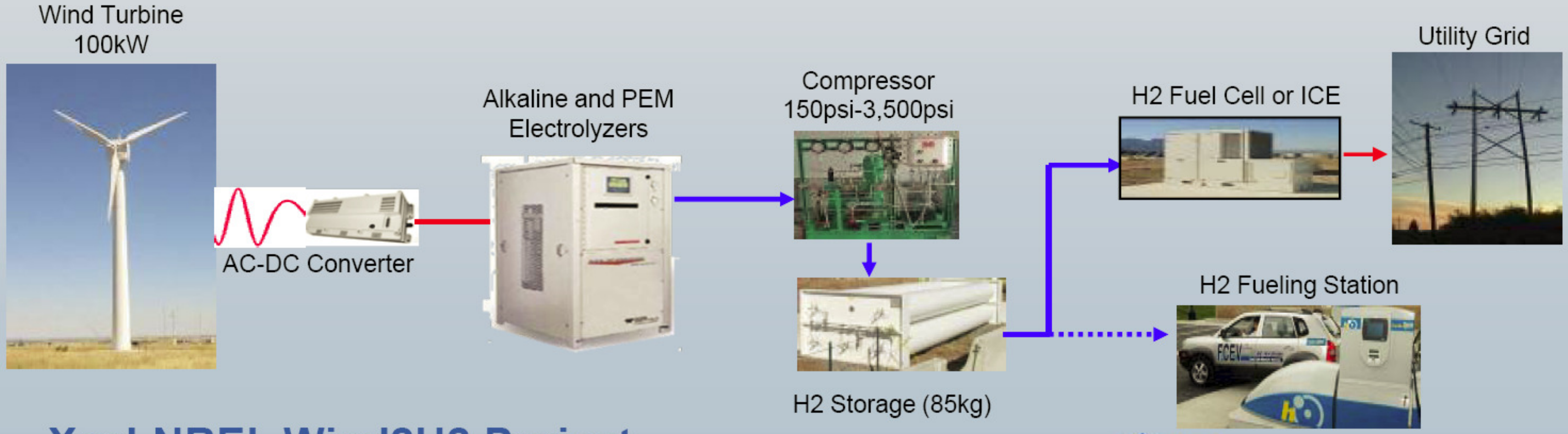
SMUD: Sacramento, CA

Xcel/NREL Wind/Hydrogen Project *(ongoing, shown below)*

Integrates electrolyzers and wind turbines to understand the benefits and impacts of adding hydrogen production facilities to the electric power grid (NREL wind site at Golden, Colorado)

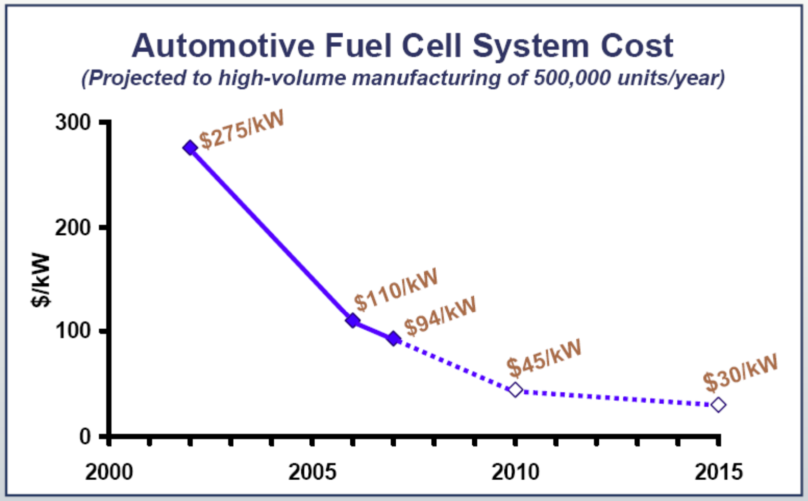
Hawaii *(planned)*

Hydrogen production using curtailed wind and geothermal energy to generate electricity and to fuel hydrogen buses at national parks

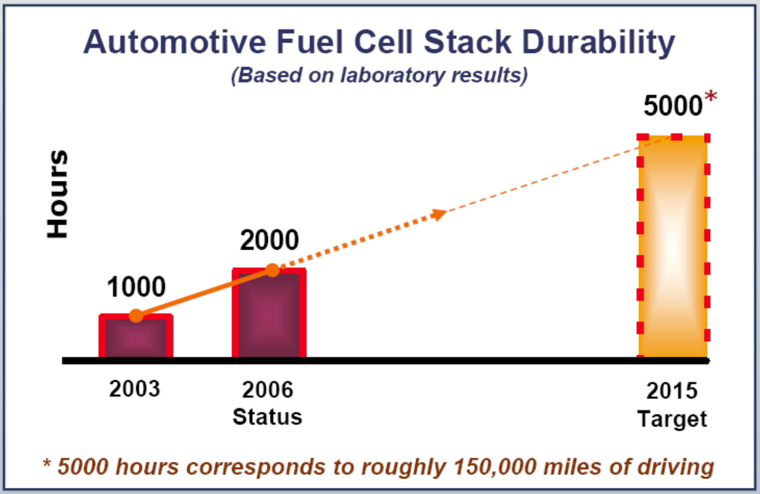


Xcel-NREL Wind2H2 Project

Automotive Fuel Cells Progress:
Projected Cost (at Volume) and Laboratory Durability


Automotive Fuel Cell System Cost

(Projected to high-volume manufacturing of 500,000 units/year)


Automotive Fuel Cell Stack Durability

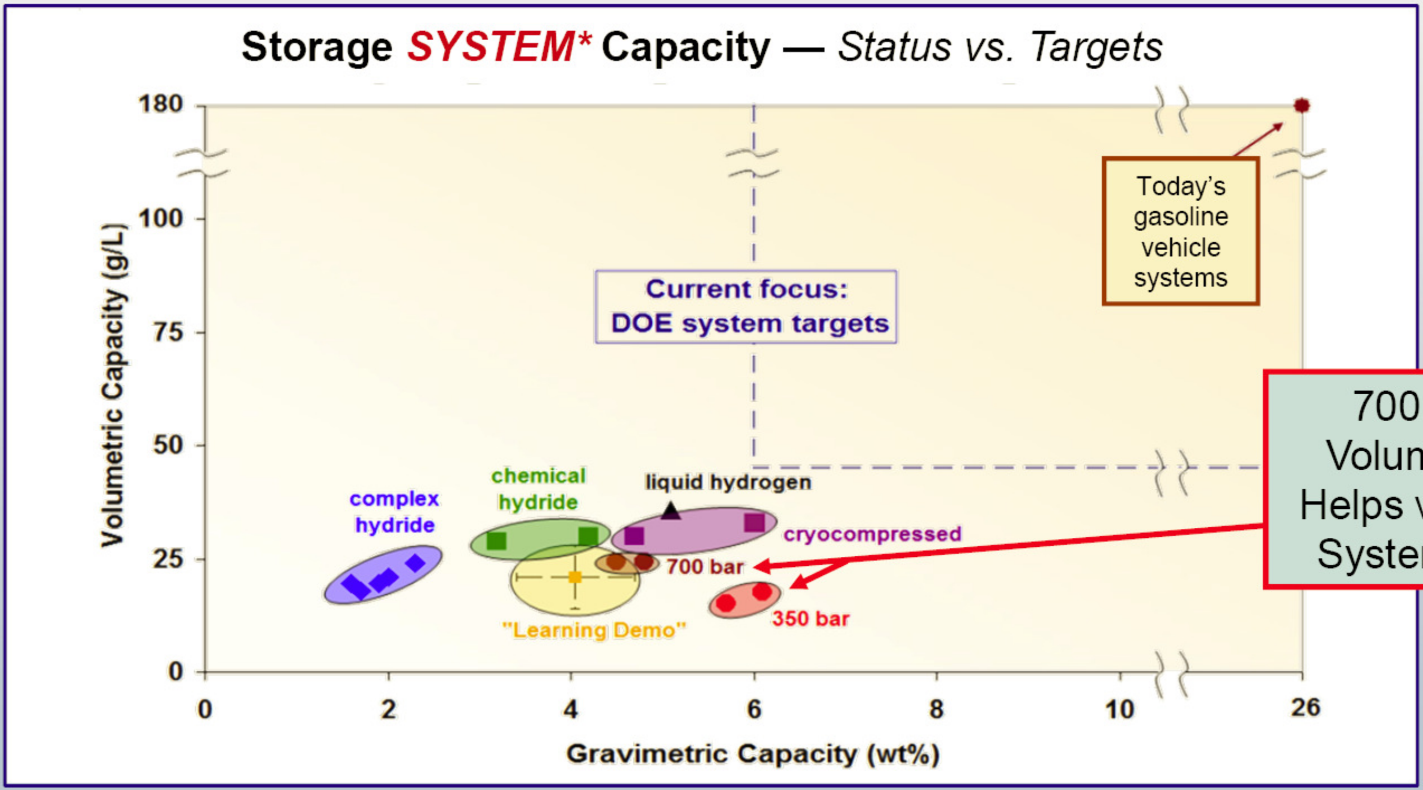
(Based on laboratory results)

** 5000 hours corresponds to roughly 150,000 miles of driving*

Hydrogen Storage Progress: Current Products and Advanced Technology

GOAL: *On board storage with > 300-mile driving range (meeting req. for safety, cost, performance)*

PROGRESS: *The Program has identified materials with > 50% improvement in capacity since 2004*



Storage *SYSTEM Capacity — *Status vs. Targets***

700 bar Improves Volumetric Capacity: Helps with Packaging a System with More H2

** System capacity estimates include materials, tanks, and balance of plant*

Evaluation of Hydrogen and Fuel Cell Buses in Five Fleets

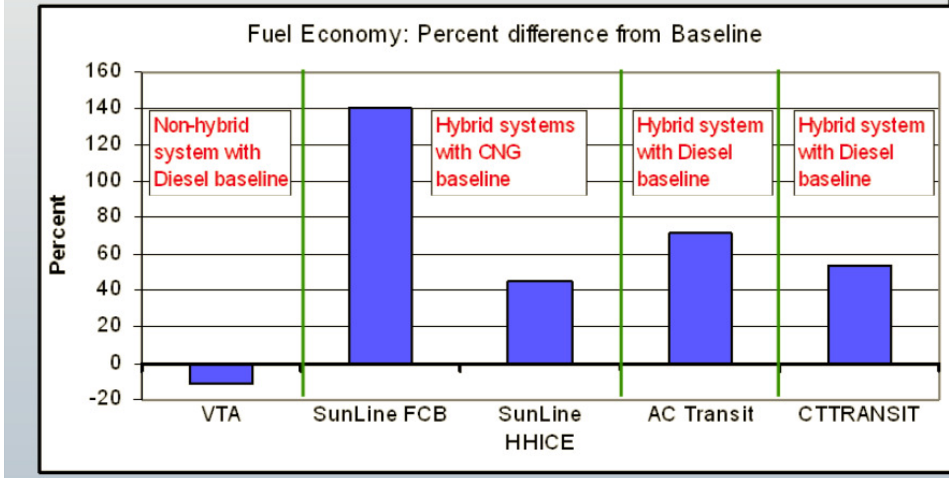
Santa Clara VTA, San Jose, CA

SunLine, Thousand Palms, CA

AC Transit, Oakland, CA

CTTRANSIT, Hartford, CT

Hickam AFB, Honolulu, HI



Fuel economy is highly dependent on duty-cycle and hybridization, but shows improvement approaching 2X