Lectures and Homework

4/13/2016 Lecture 8:

HW:

Homework 1, Due today

Homework 2, Due 4/20/16.

Personal energy audit due 5/9/16 in class

Midterm Exam: 5/9/16 in class

EE180J: Homework#2:
Spring 2016
100 points total (20 pts/problem)

Due April 20.

1. Calculate the efficiency of a system where the useable output power is 10kW and the input power drawn is 2A at 10kV.

2. What is the difference between heat and temperature?

3. Calculate the thermal power transferred through an aluminum bar that is 25 square cm in cross section and 30 cm long when the temperature at the hot end is 100 $^{\circ}$C and the temperature at the cold end is 20 $^{\circ}$C.

4. Consider an automobile powered by PV panels on its roof. Assuming the panels are 20% efficient, compare the power available for such a vehicle on a sunny day in Northern California with the power available with a typical gasoline powered automobile like a Honda Civic at 140 horsepower. You will need to make an estimate of the size of the roof.

5. Using the average cloud free solar insolation in California, what area of a horizontal PV array would be needed to satisfy the residential electricity needs of a city with 80,000 homes if one assumes an average power need per home of 900 kWhr/month? Assume the PV array has an efficiency of 20%.

Midterm Exam

Material from first 8 lectures, quizzes, readings plus Homework #1,2 and energy audit.

MIDTERM EXAM

First and second laws of thermodynamics
Kinetic and potential energy
Heat and temperature
Energy and power
Simple energy/power calculations
Energy efficiencies
Be able to describe how solar devices work
Environmental aspects of renewable energy sources
Biomass as a fuel
Wind energy

EE80J/180J Group Projects

1. Forming teams of 3-4 people. By mid-May

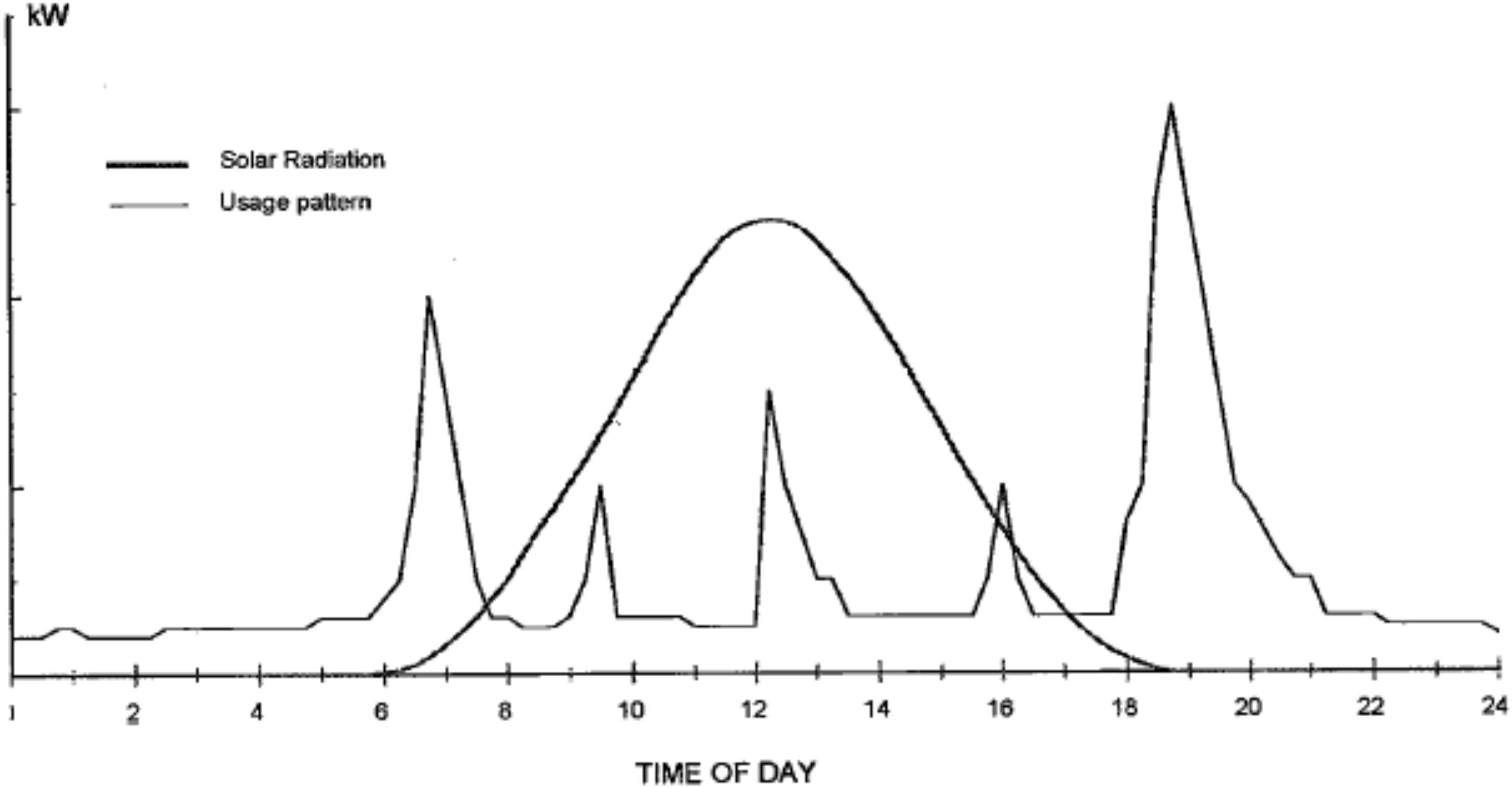
2. Teams will work on alternate solutions to particular problems.

3. You may put in ideas, but we will ultimately choose 1 - 3 projects.

4. Ideas due by April 25.

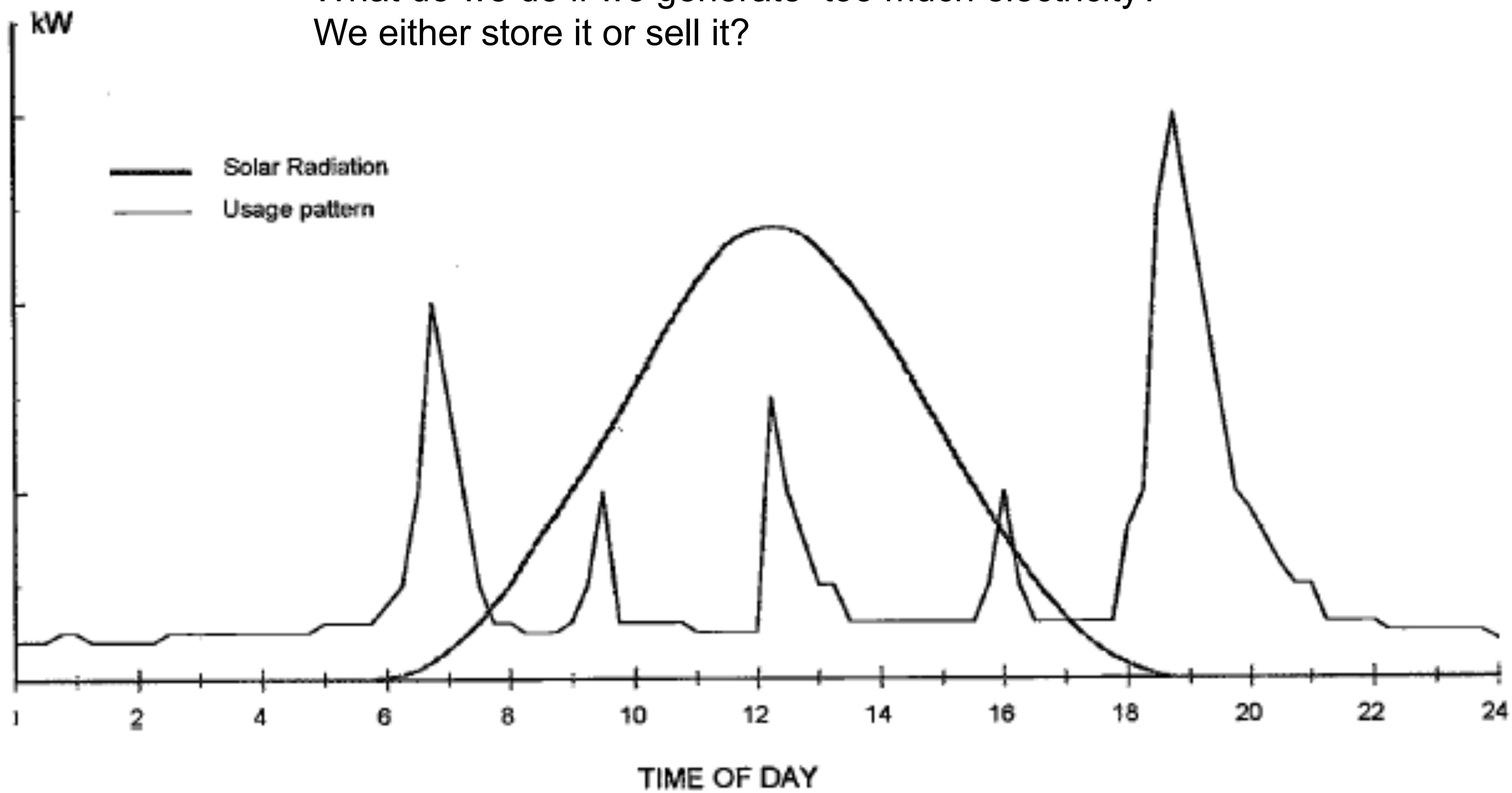
Solar Power input and energy demands
For an average residence

They generally do not match.
What do we do?



Solar Power input and energy demands
For an average residence

They generally do not match.
What do we do if we generate too much electricity?
We either store it or sell it?



Energy Storage Options

What are they?

Homework to read article

SHARE

0

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PERSPECTIVE | CLIMATE CHANGE

Farewell to Fossil Fuels?

Martin I. Hoffert

+ Author Affiliations

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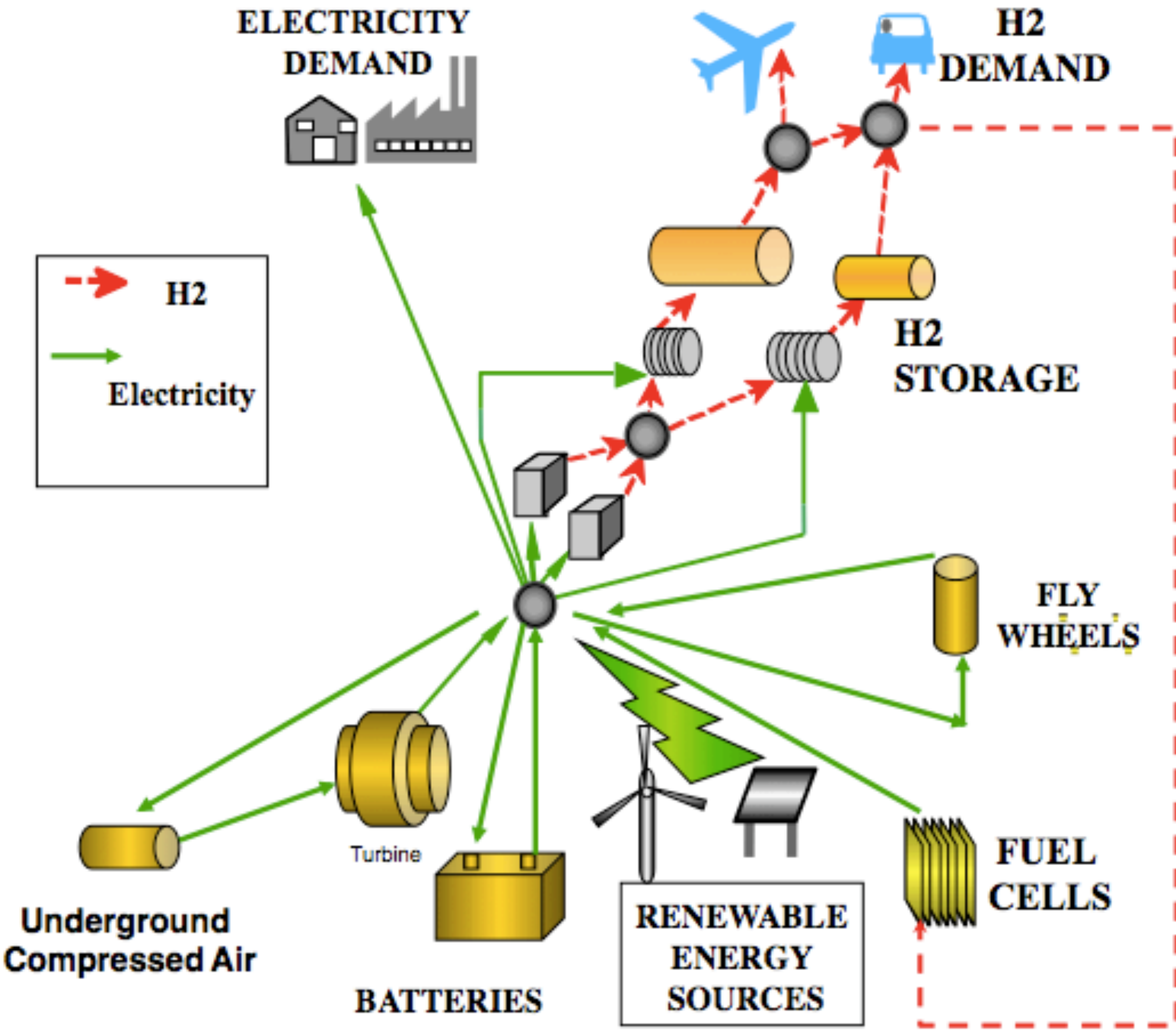
Science 10 Sep 2010:
Vol. 329, Issue 5997, pp. 1292-1294
DOI: 10.1126/science.1195449

Energy Storage Options



Flywheels (high power)

Batteries (convenience)

Compressed Air Turbines (low capital cost)

Fuel Cells (hydrogen)

Marty Hoffert

Advanced Technology Paths to Global Climate Stability: Energy for a Greenhouse Planet

Martin I. Hoffert,[1*] Ken Caldeira,[3] Gregory Benford,[4] David R. Criswell,[5] Christopher Green,[6] Howard Herzog,[7] Atul K. Jain,[8] Haroon S. Kheshgi,[9] Klaus S. Lackner,[10] John S. Lewis,[12] H. Douglas Lightfoot,[13] Wallace Manheimer,[14] John C. Mankins,[15] Michael E. Mauel,[11] L. John Perkins,[3] Michael E. Schlesinger,[8] Tyler Volk,[2] Tom M. L. Wigley[16]

Science 1 November 2002: 981-987. [DOI:10.1126/science.1072357]

Energy Usage in a typical household

Electricity Usage ~15 kWh/day (54 MJ/day) power ~ 625W

Storage:

- Water: 78.6 m^3) at 100 meter (70% conversion efficiency)
- Flywheel: 2138kg, 4m radius, 600rpm (80% conversion efficiency)
- Compressed Air: 3600 liter (0.03 MJ/liter, 50% conversion efficiency)

Hot Water Usage ~25-35MJ

150-200 liter water heated from 15C up to 55C

- Burn 4-5kg of wood in 50% efficient wood stove.

Energy Storage Options

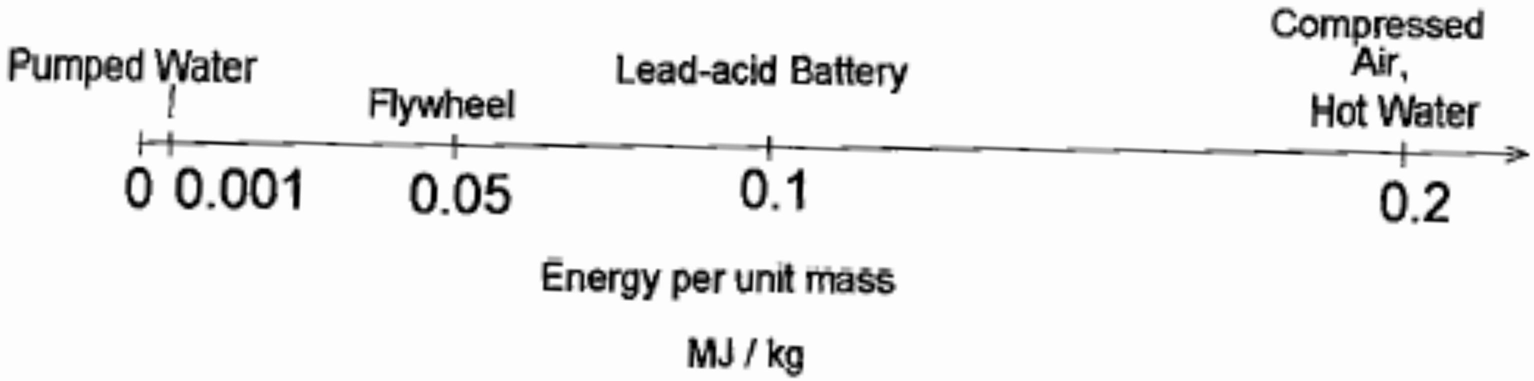


Figure 2 Energy density (by mass) of some storage methods. Compared by volume, the order of merit will be different.

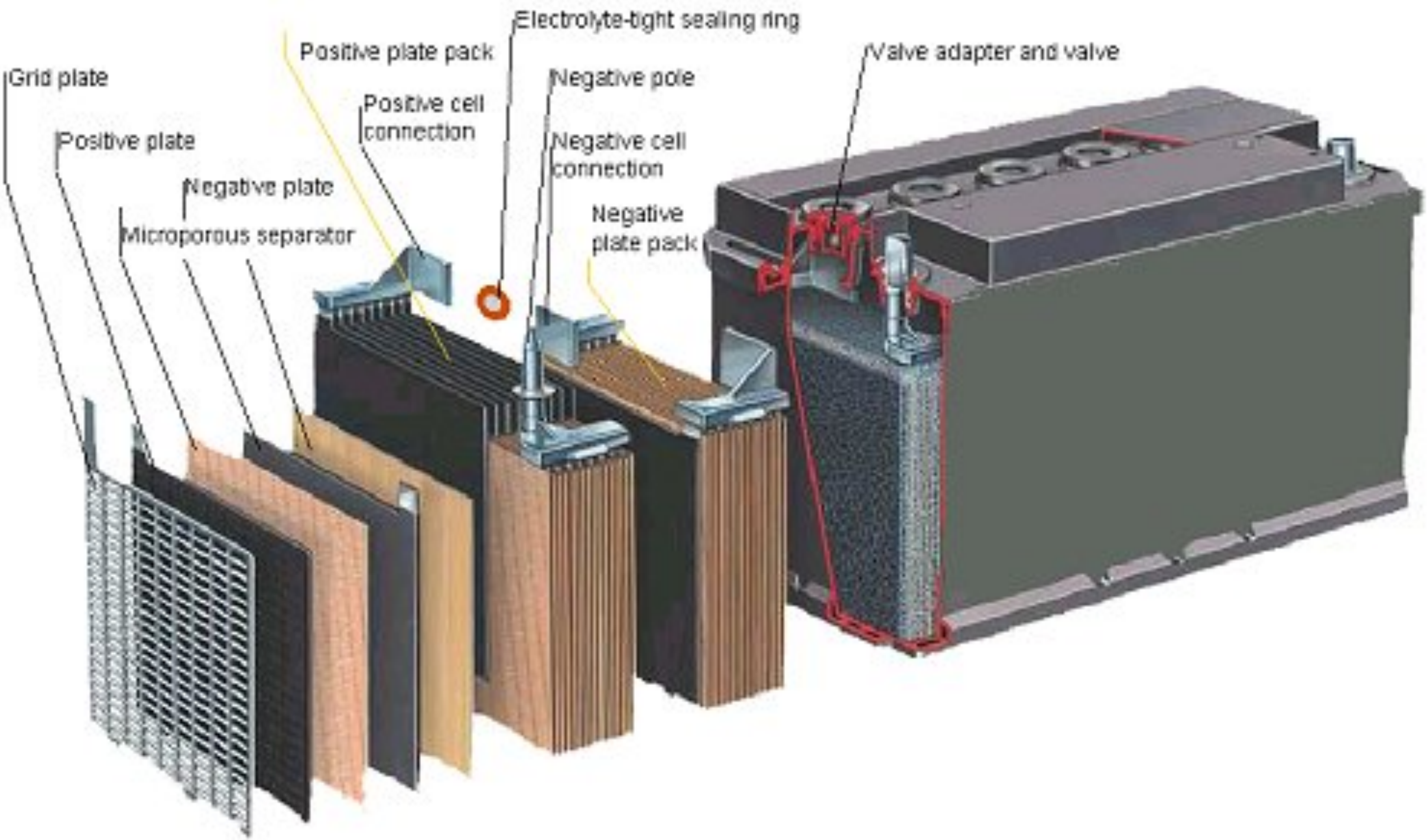
Renewable Energy Centre,
University of Queensland, Australia

Battery Comparison

Technology comparison for Grid-Level applications

Technology	Moving Parts	Room Temperature	Flammable	Toxic Materials	In production	Rare metals
flow[13]	Yes	Yes	No	No	No	Yes
liquid metal	Yes	Yes	No	Yes	No	No
Sodium-Ion	No	No	Yes	No	Yes	No
Lead-Acid[14]	No	No	No	Yes	No	No
Sodium-sulfur batteries	No	No	No	Yes	No	No
Ni-Cd	No	No	No	Yes	No	No
Lithium-ion	No	No	Yes	Yes	No yes	Yes

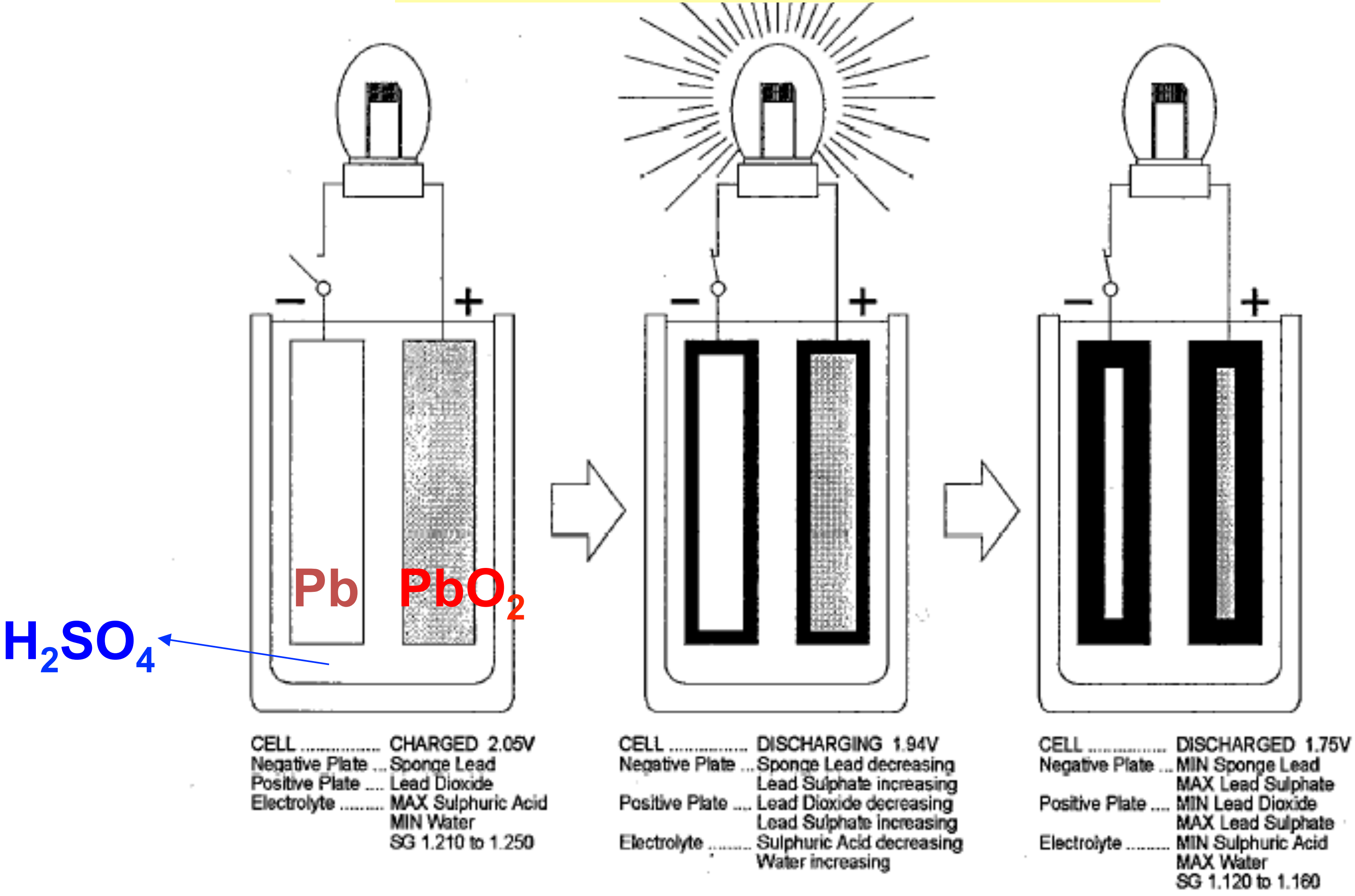
Lead Acid Battery



www.daviddarling.info

Battery Discharging

$$Pb + PbO_2 + 2H_2SO_4 \longrightarrow 2\ PbSO_4 + 2\ H_2O$$



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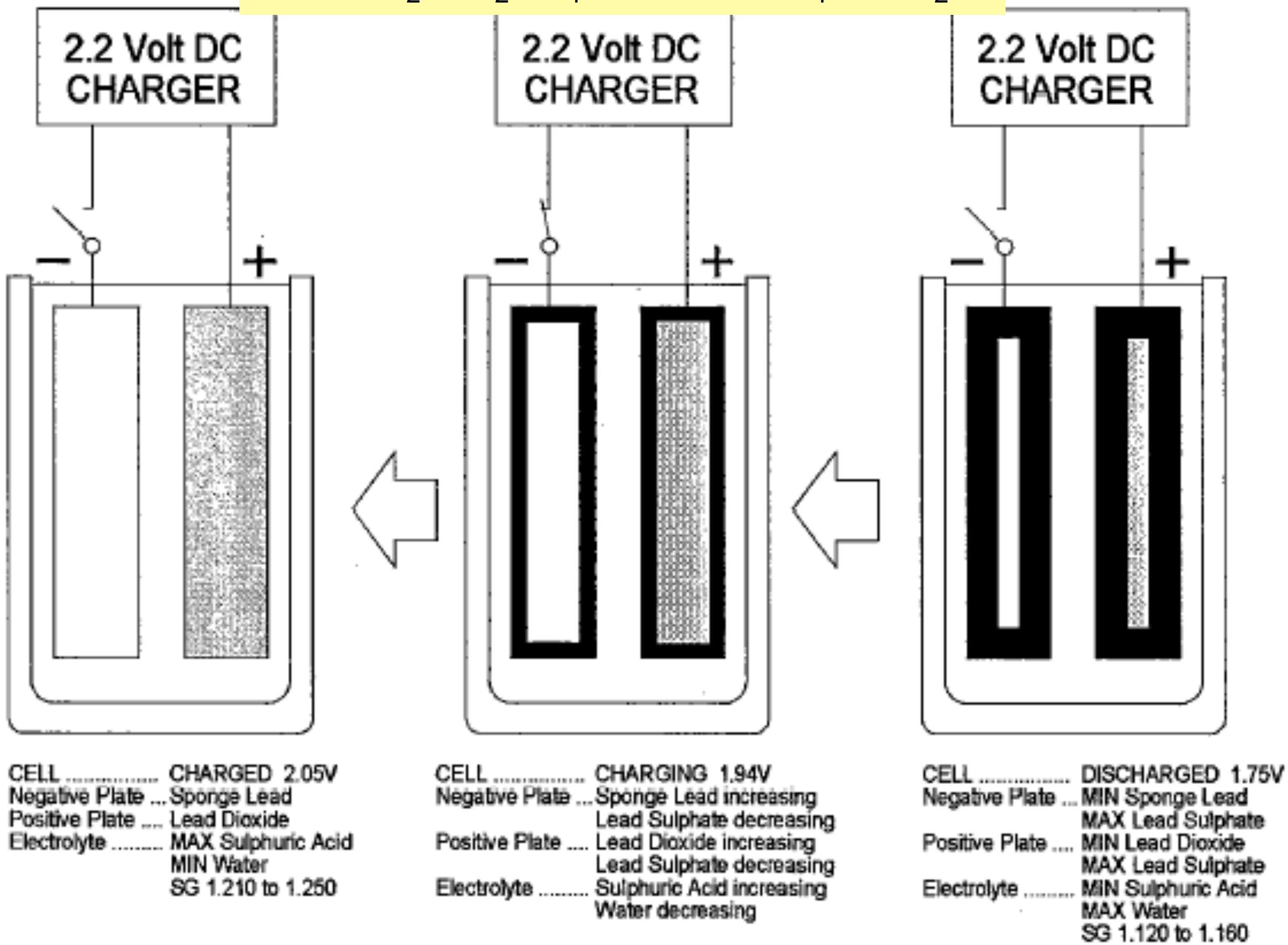


Discharge Characteristics

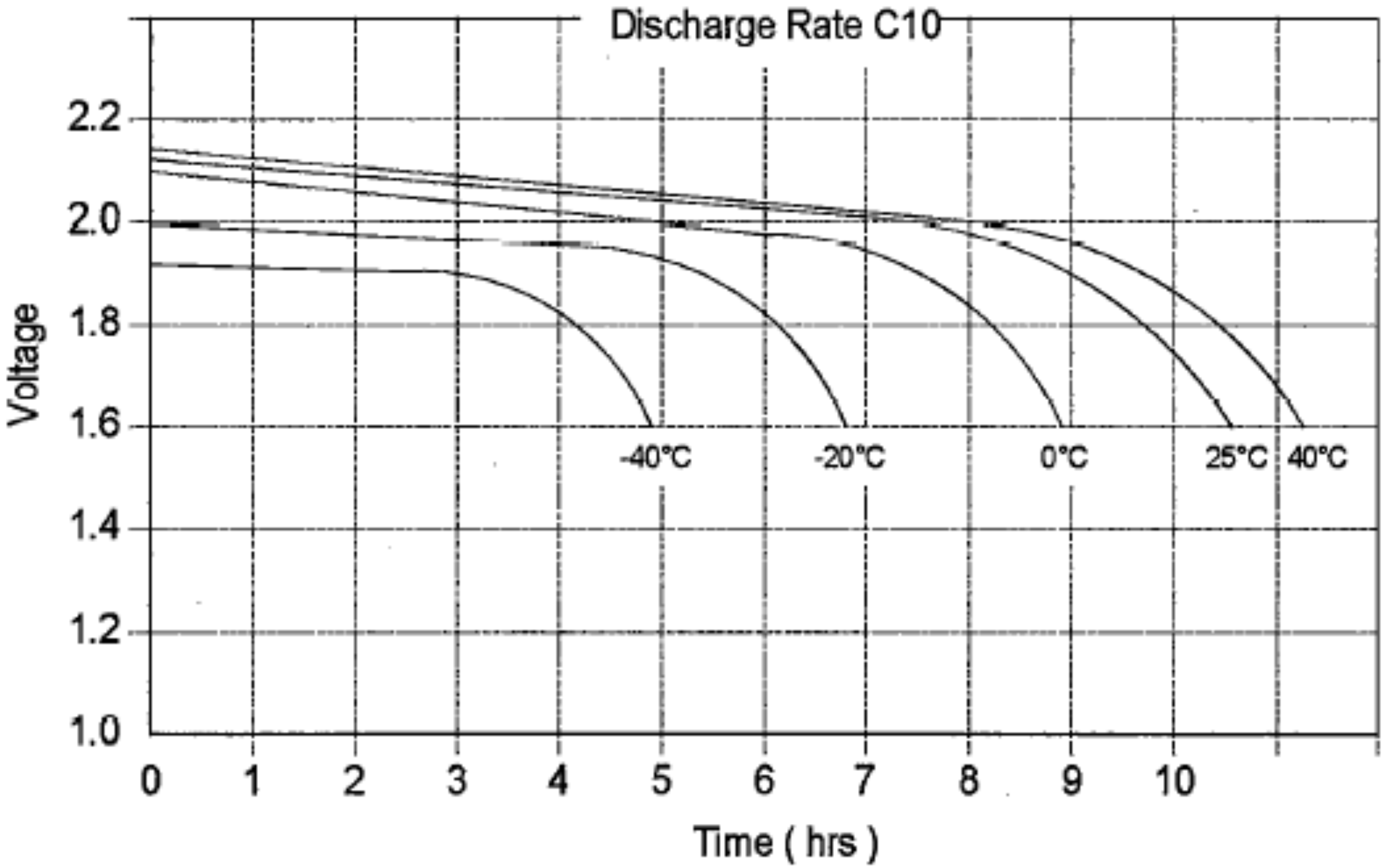
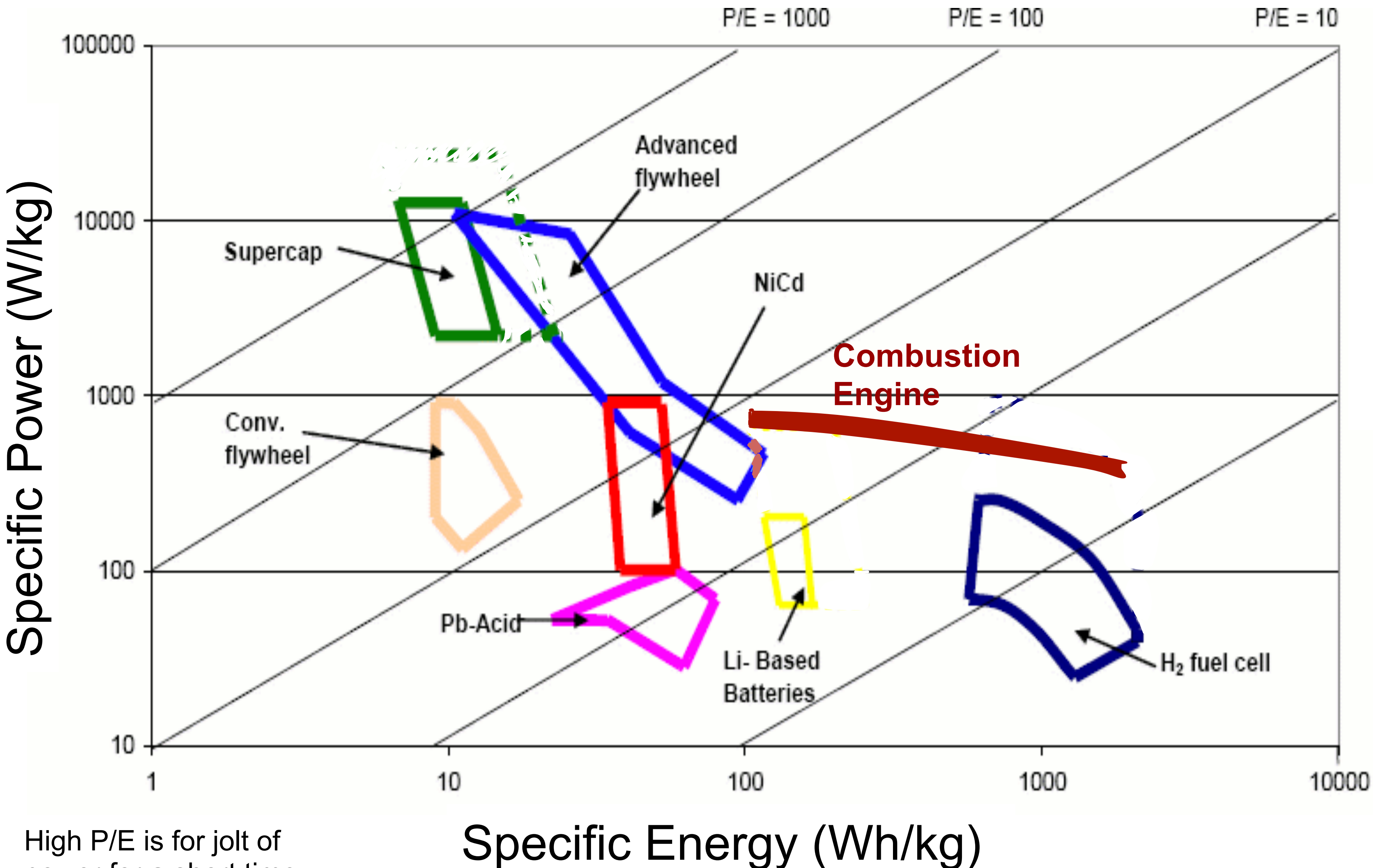


Figure 6 Discharge characteristics of a lead-acid battery. This varies slightly depending on the battery design and its intended application.

Energy Storage Options



High P/E is for jolt of power for a short time

Discharge Characteristics

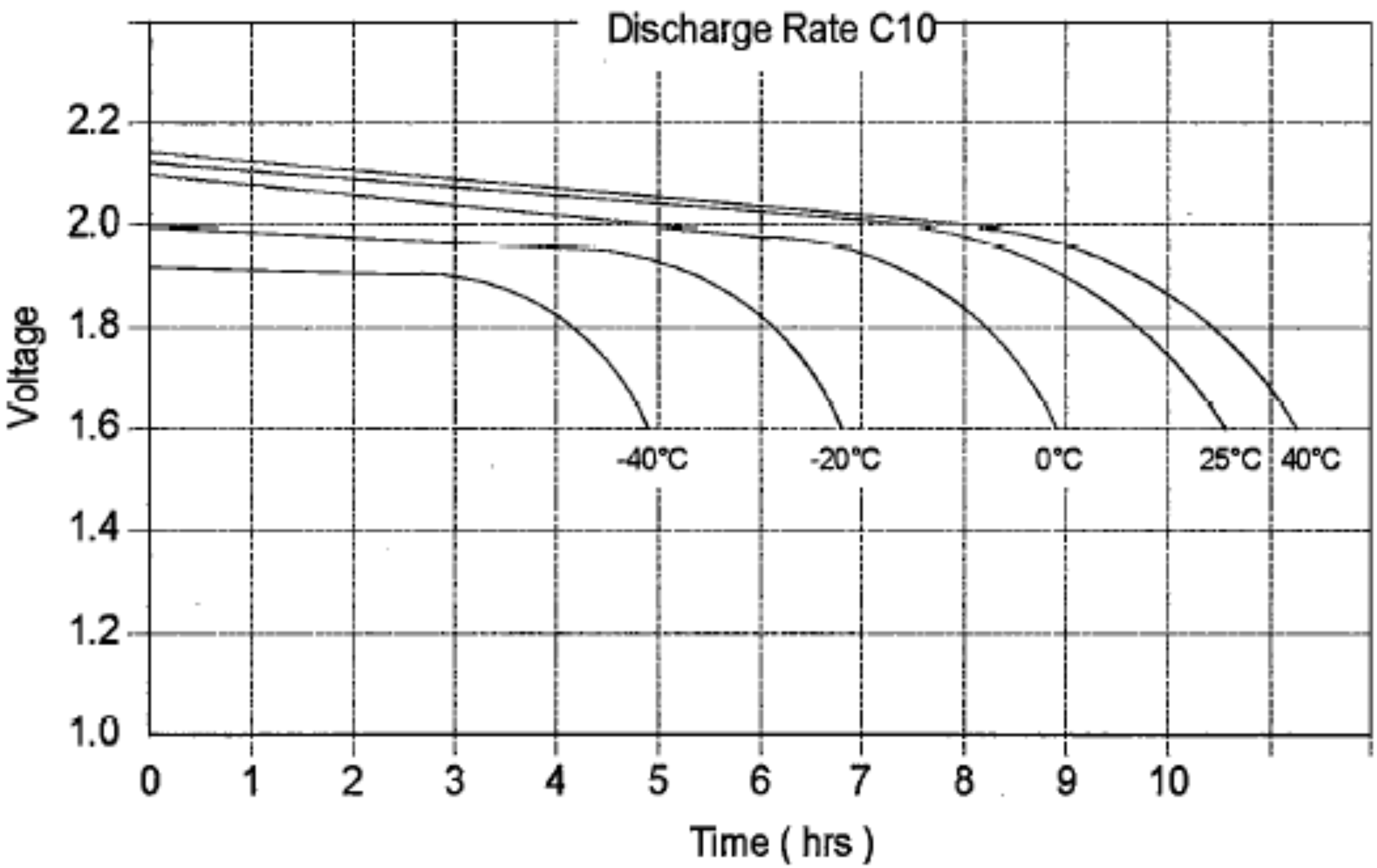


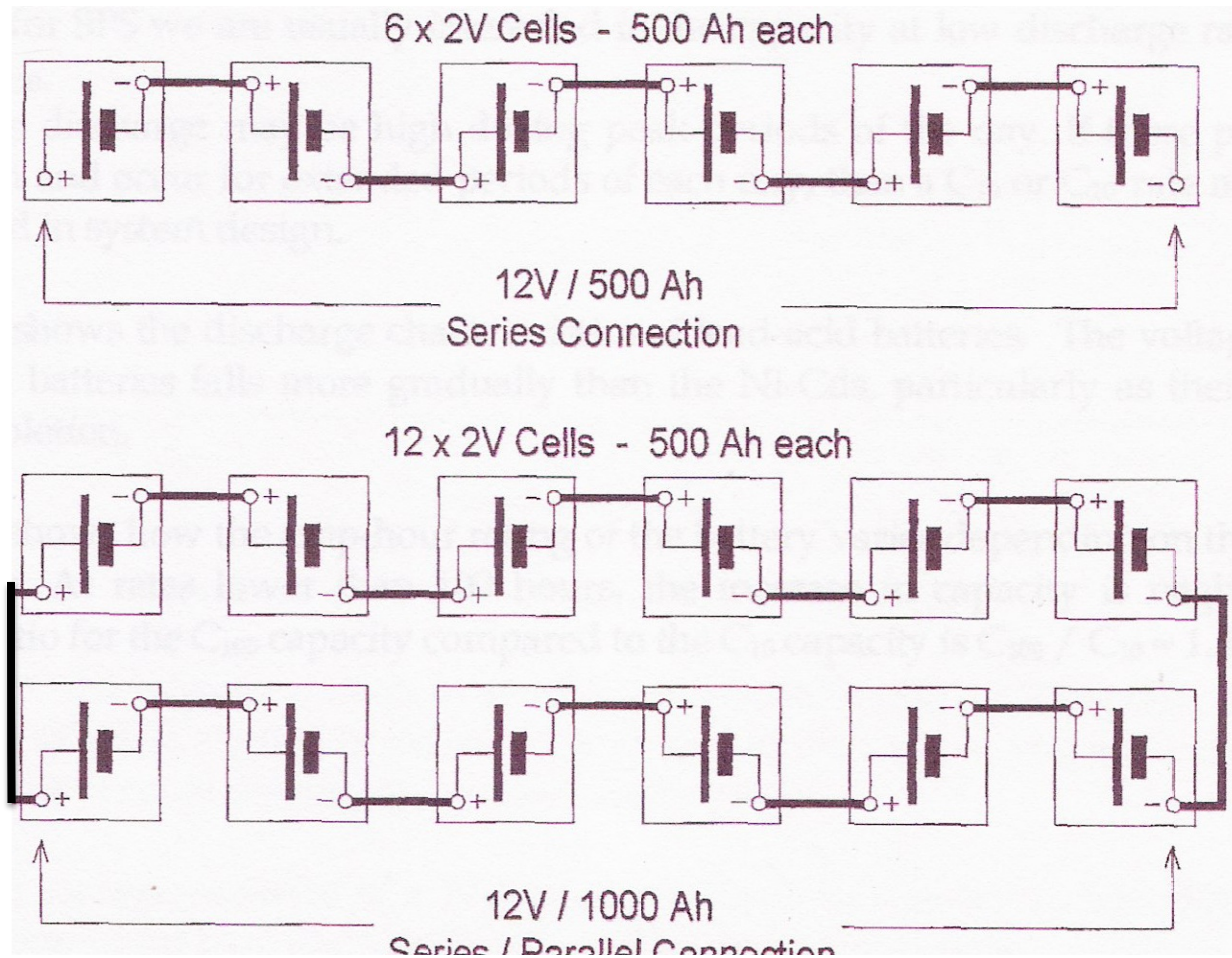
Figure 6 Discharge characteristics of a lead-acid battery. This varies slightly depending on the battery design and its intended application.

Temperature °C	Capacity (ref. 25°C)
25°	100
20°	99
15°	97
10°	96
5°	93
0°	91
-5°	88
-10	85

Table 1 Variation of cell capacity with temperature

Renewable Energy Centre, University of Queensland, Australia

Batteries: series or parallel



Which is more prone to failure?

Renewable Energy Centre, University of Queensland, Australia

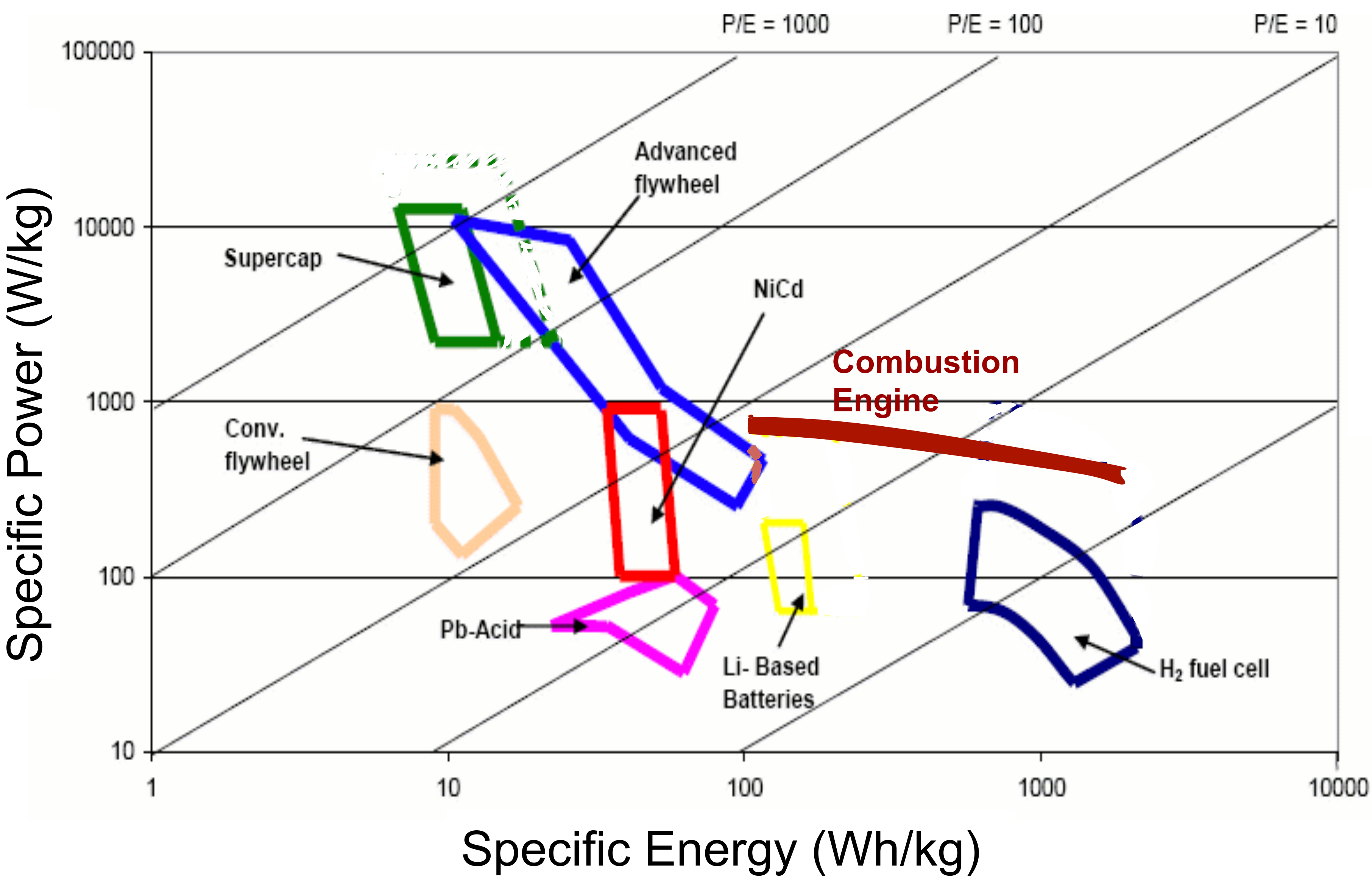
Table 15-1
Selected physical properties of hydrogen, methane, and gasoline[a]

Property	Hydrogen (gas)	Methane (gas)	Gasoline (liquid)
Molecular weight (g/mol)[a]	2.016	16.04	~110
Mass density (kg/m^3)[a,b]	0.09	0.72	720–780
Energy density (MJ/kg)	120[a]	53[c,d]	46[a,c]
Volumetric energy density (MJ/m^3)[a]	11[a]	38[c,d]	35,000[a,c]
Higher heating value (MJ/kg)[a]	142.0	55.5	47.3
Lower heating value (MJ/kg)[a]	120.0	50.0	44.0

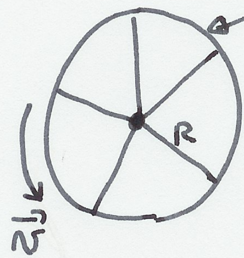
[a] *Ogden [2002, Box 2, page 71].*
[b] *at 1 atm and 0° C.*
[c] *Hayden [2001, page 183].*
[d] *Ramage and Scurlock [1996, Box 4.8, page 152].*

What might be disadvantages of hydrogen?

Energy Storage Options



The Flywheel as a Storage Device



kinetic energy of a rotating flywheel,

$$E_k = \frac{1}{2} M v^2 \quad \text{simplified.}$$

$v = 2\pi R f$ → frequency of rotation (rev/sec)

$$\therefore \; E_k = 2\pi^2 M R^2 f^2$$ ← note: square dependance

either big M, R or f
↳ better here

NOTE: changes a bit of solid wheel

general: $E_k = \frac{1}{2} I \omega^2$, $\omega = 2\pi f$

→ moment of inertia

$$I = \int_V \rho(r) r^2 \, dV$$

Flywheel Storage (cont)

transportation example 1

2 ton car moving at 40mph,
power at axle ~ 9KW = 9×10^3 Joule/sec

$\therefore$ energy used in 1 hour

$$9 \times 10^3 \frac{J}{sec} \times 3.6 \times 10^3 sec \cong 3.2 \times 10^7 \text{ joules}$$

this would be energy needed to be stored in a flywheel to keep the car running for 1 hour.

$$E_K = 2\pi^2 M R^2 f^2$$

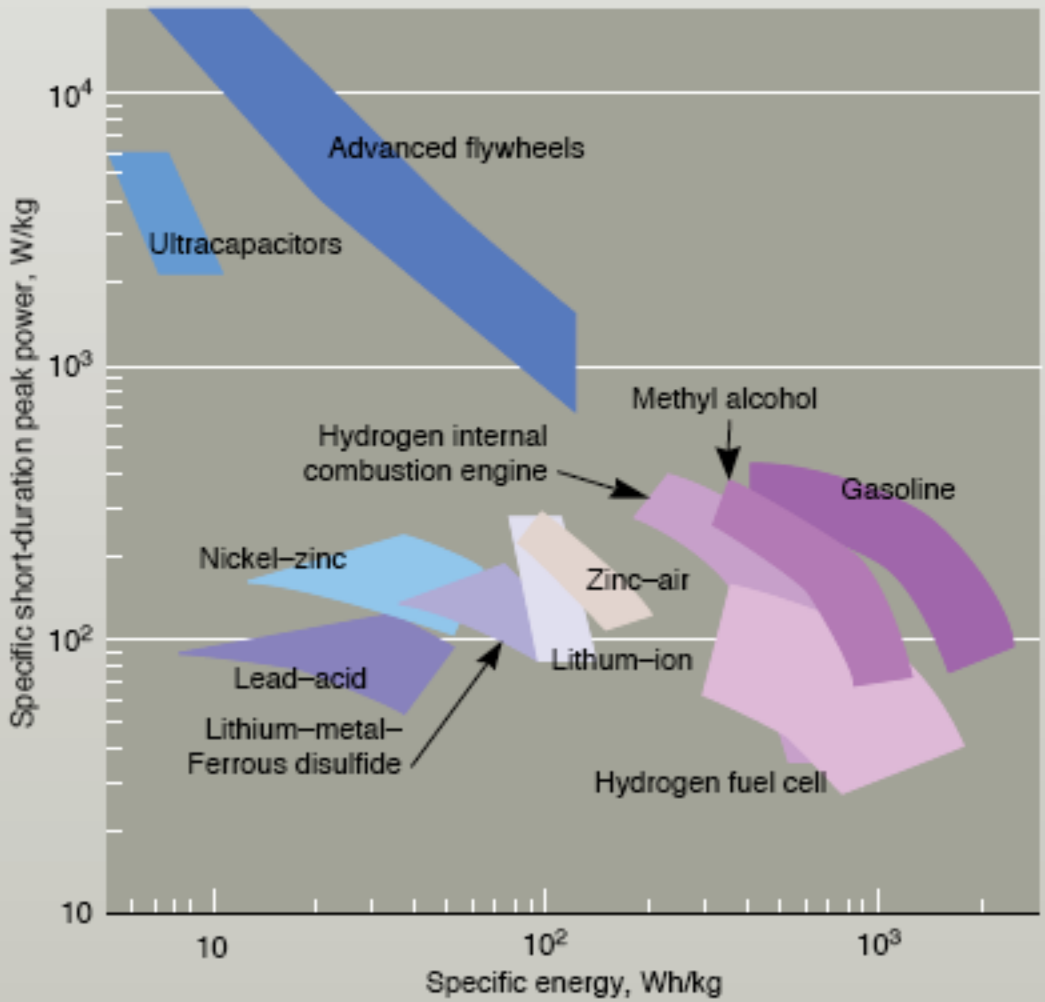
$M = 1 \text{ ton} = 907 \text{ kg}$, $R = 1m$

$$\therefore f^2 = \frac{E_K}{2\pi^2 M R^2} = \frac{3.2 \times 10^7 \text{ Joule}}{2\pi^2 \, 907 kg \, (1) m^2}$$

$$= 1.8 \times 10^3 / sec^2$$

$$\therefore \boxed{f \cong 42 \text{ rev/sec}}$$

NOTE!! material limit – how fast can it spin before breaking?



Various energy storage devices are compared for peak power and specific energy. Batteries and fuels produce roughly the same range of peak power, about one order of magnitude below advanced flywheels.

Sci. Tech. Review. 1996

FLYWHEEL: mechanical to electrical transform

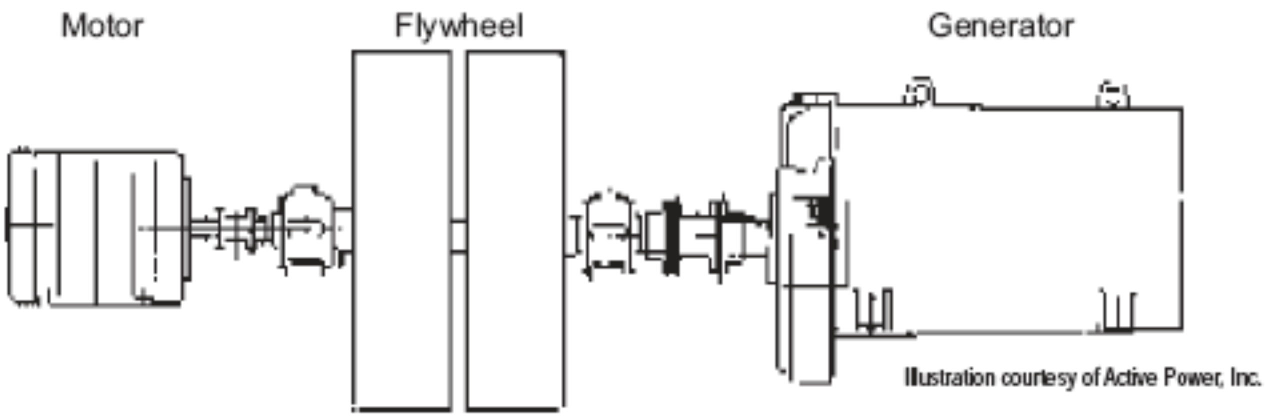


Figure 2. Motor-generator with flywheel.

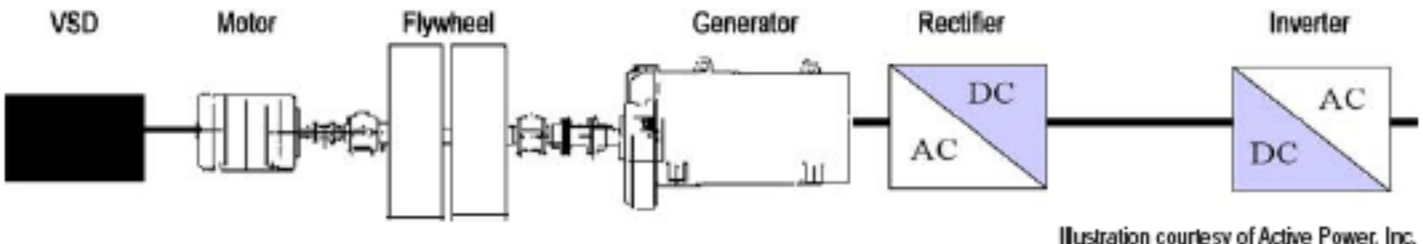


Figure 3. Motor-generator with flywheel and power electronics.

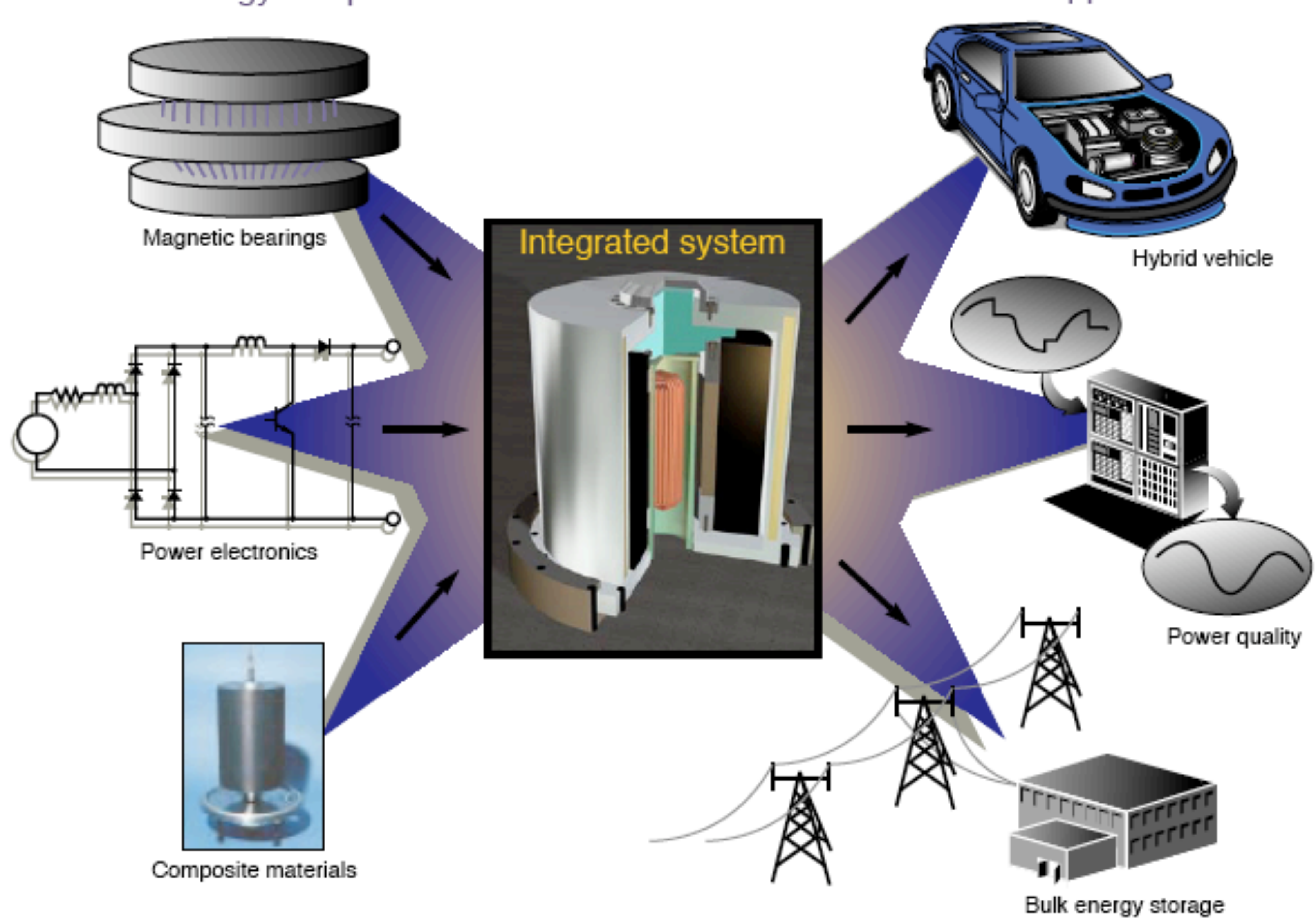
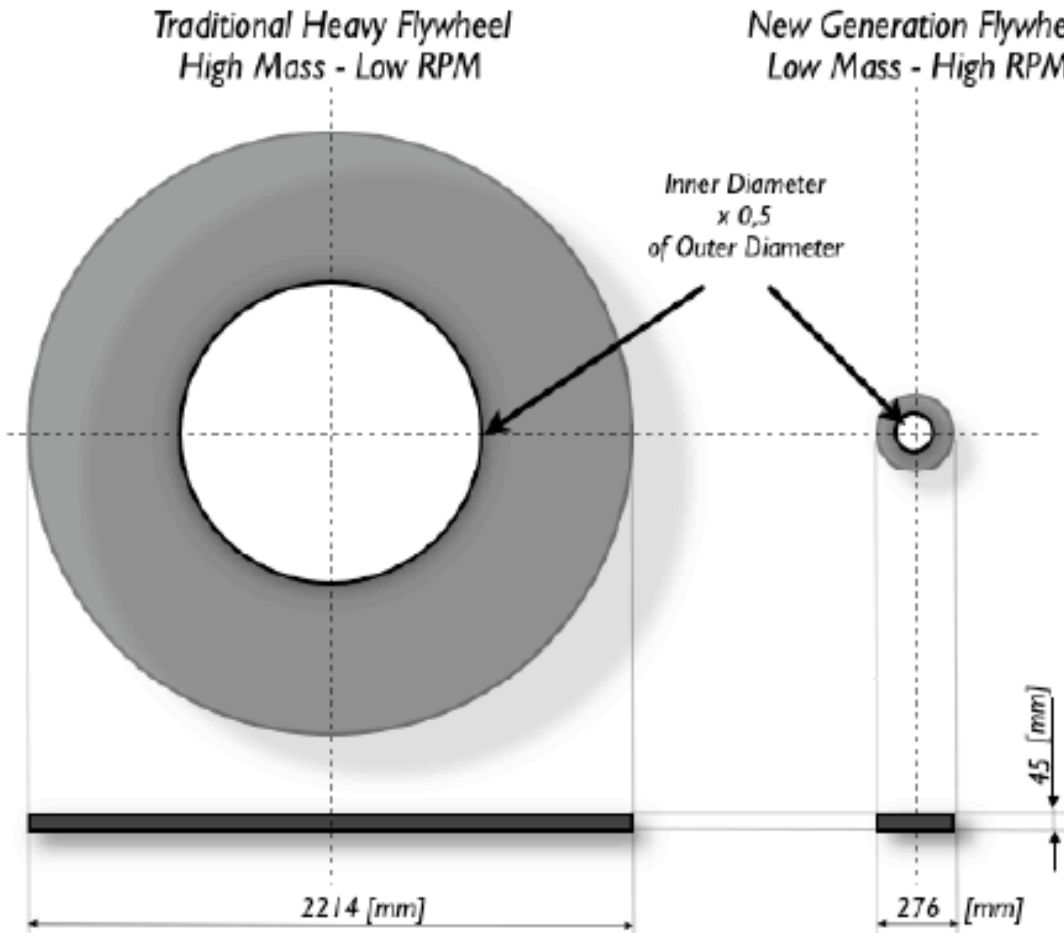


Figure 2. Concept of the flywheel battery system and its applications.

Sci. Tech. Review. 1996



RPM	2000
Mass	214 kg
Outer Diameter	2214 mm

RPM	130 000
Mass	3,33 kg (1,6 % of Heavy FW)
Outer Diameter	276 mm (12,5% of Heavy

Figure 2: Comparison of Flywheels – Constant Energy 1 kWh

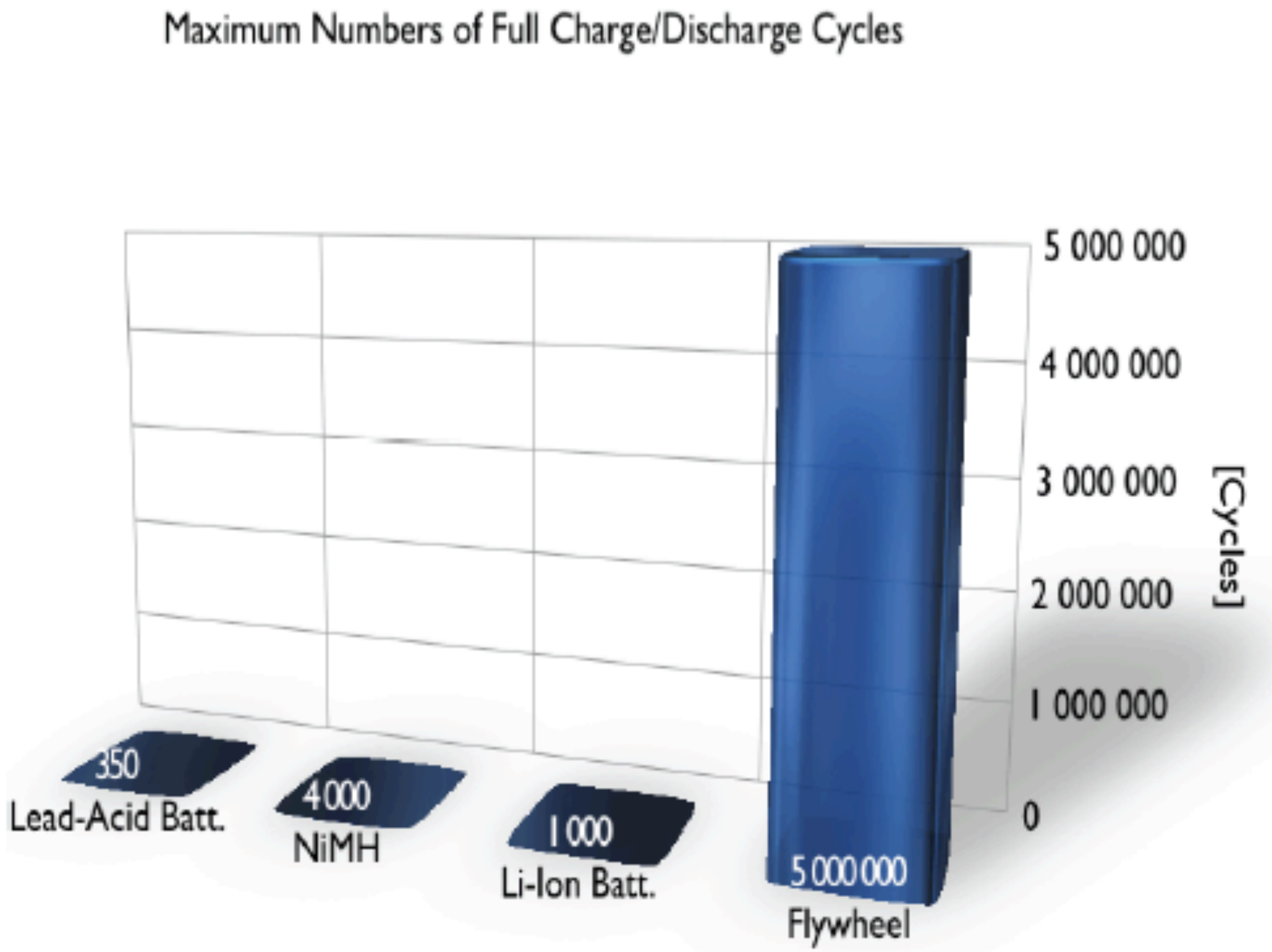


Table 2: ***Expected number of full (charge/discharge cycles [Ref 4]***

4. J. Cibulka, *"Kinetic Energy Recovery System by means of flywheel energy storage"* , Advanced Engineering, 3(2009), ISSN 1846-5900

Engineering, Operations & Technology
Boeing Research & Technology

Boeing Flywheel Energy Storage Technology

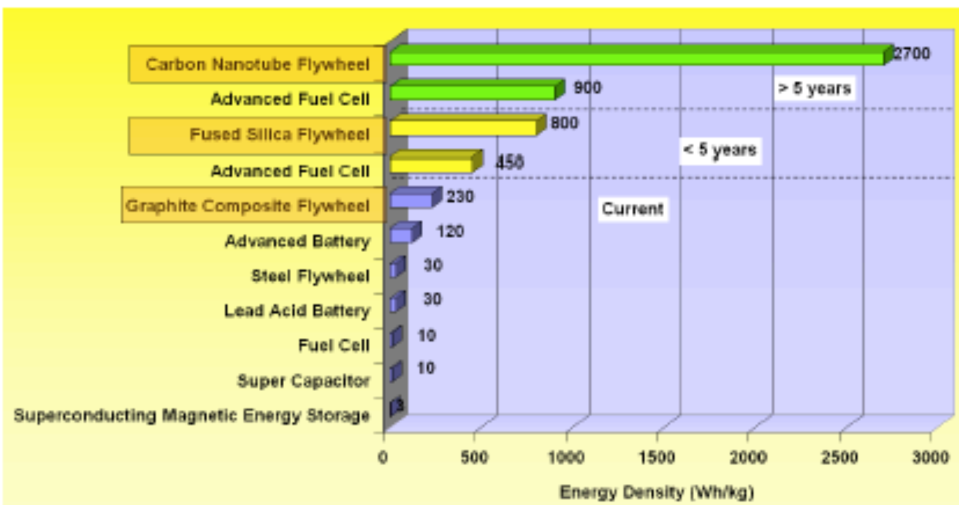
George Roe
Senior Manager
Energy Management
Boeing Research & Technology

This document does not contain technical data as defined in the International Traffic in Arms Regulations (22 CFR 120.10) or the Export Arms Regulations (15 CFR 779.1). Export Control # JHB4137-NT

Flywheels with Superconducting Bearir

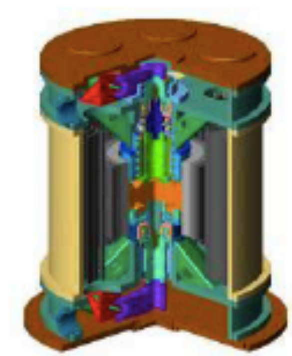
Flywheel Energy Storage

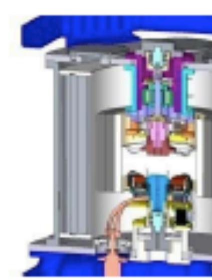
- Non-toxic and low maintenance
- Potential for high power density (W/ kg) and high energy density (W-Hr/ kg)
- Fast charge / discharge times possible
- Cycle life times of >25 years
- Broad operating temperature range



HTS bearings

- Simple passive system
- Very low frictional loss
- Very long lifetime
- Low cost and maintenance
- Lower tolerance for balancing of structures
- High speed capability (> 500,00
- Adjustable stiffness and dampin





Superconducting Bearings Offer Many Design & Operational Benefits Over Conventional Bearing Systems

New Fiber Will Reduce Flywheel Cost

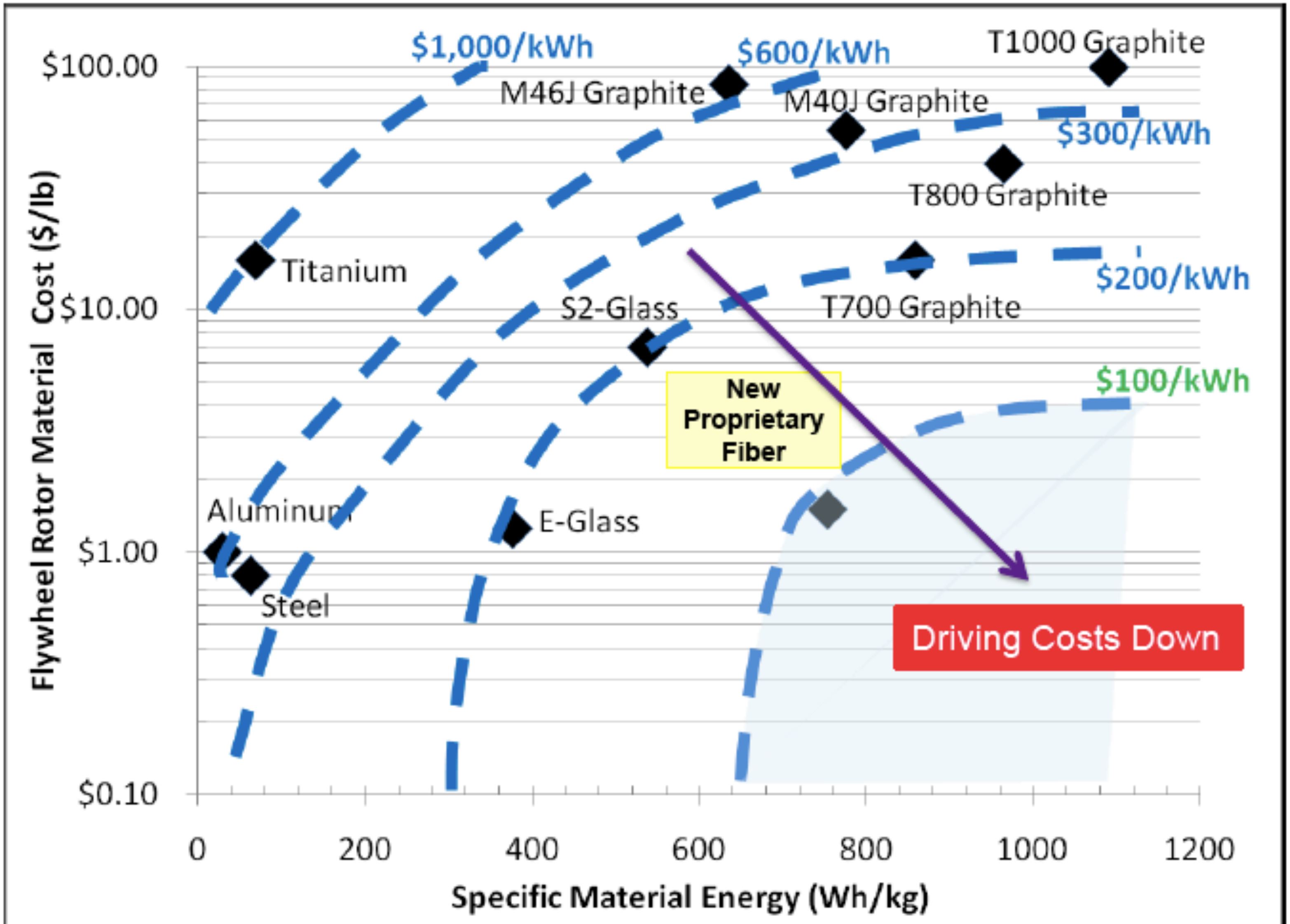


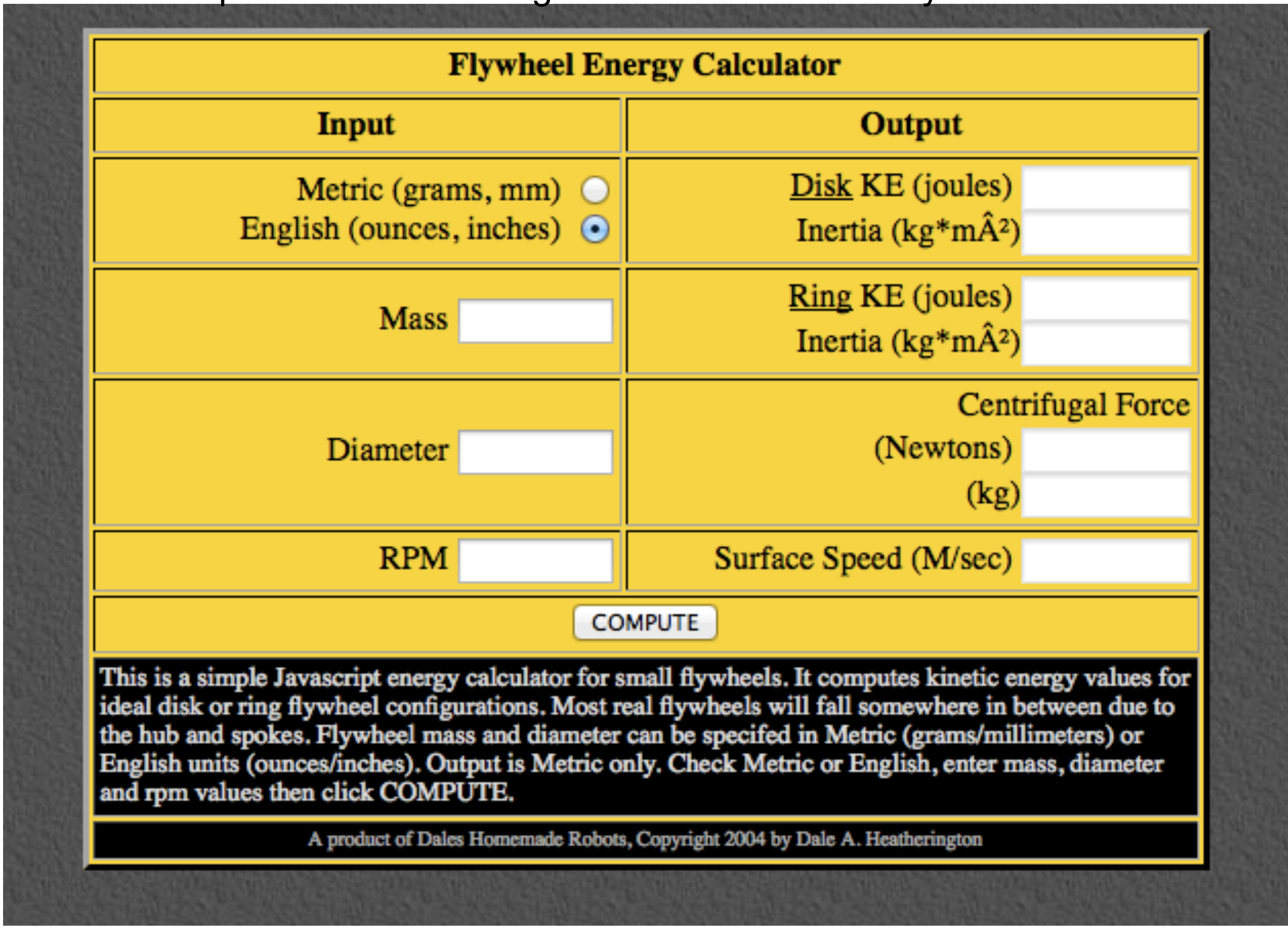
Table of energy storage traits

Flywheel purpose, type	Geometric Shape Factor (k) (unitless - varies with shape)	Mass (kg)	Diameter (cm)	Angular velocity (rpm)	Energy stored (MJ)	Energy stored (kWh)
Small battery	0.5	100	60	20,000	9.8	2.7
Regenerative braking in trains	0.5	3000	50	8,000	33.0	9.1
Electric power backup[7]	0.5	600	50	30,000	92.0	26.0

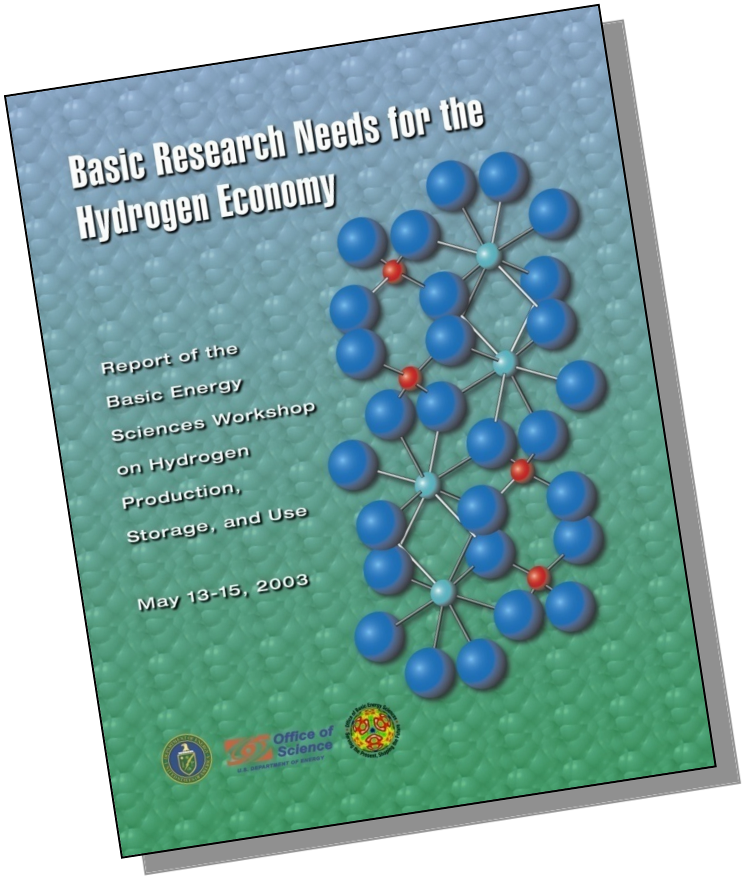
Wikipedia.

Flywheel Energy Output Calculator

http://www.botlanta.org/converters/dale-calc/flywheel.html http://www.botlanta.org/converters/dale-calc/flywheel.html



Basic Research Needs for the Hydrogen Economy



June 24, 2004
DOE Nano Summit
Washington, D.C.

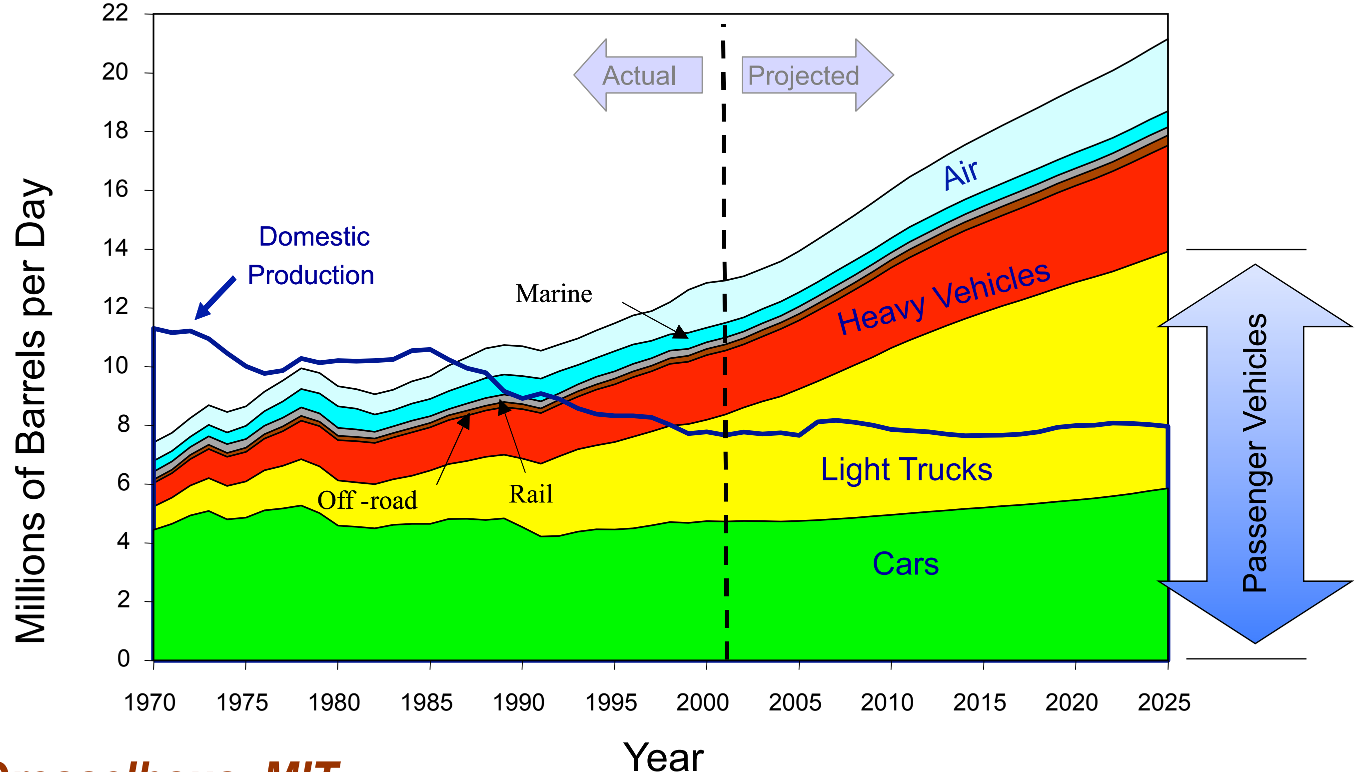
Presented by:
Mildred Dresselhaus
Massachusetts Institute of Technology
millie@mgm.mit.edu
617-253-6864

OFFICE OF SCIENCE
U.S. DEPARTMENT of ENERGY

Drivers for the Hydrogen Economy:

- *Reduce Reliance on Fossil Fuels*
- *Reduce Accumulation of Greenhouse Gases*

Energy Source	% of U.S. Electricity Supply	% of Total U.S. Energy Supply
Oil	3	39
Natural Gas	15	23
Coal	51	22
Nuclear	20	8
Hydroelectric	8	4
Biomass	1	3
Other Renewables	1	1



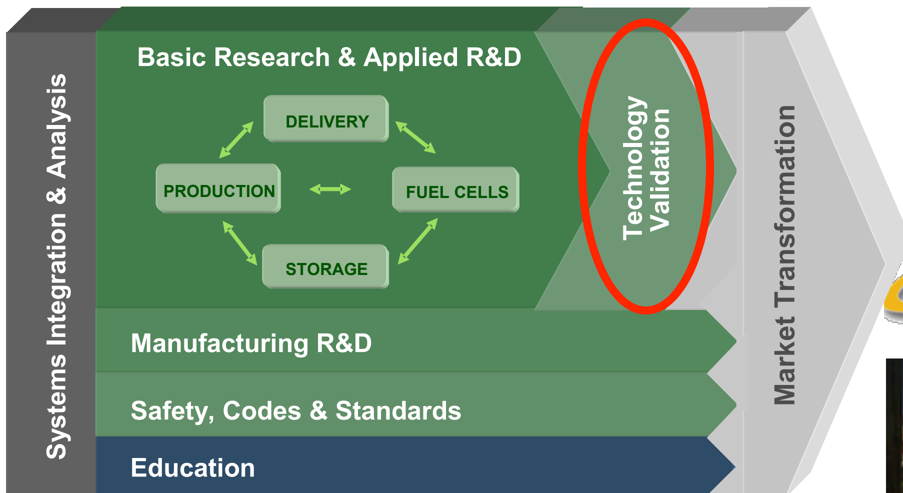
M. S. Dresselhaus, MIT

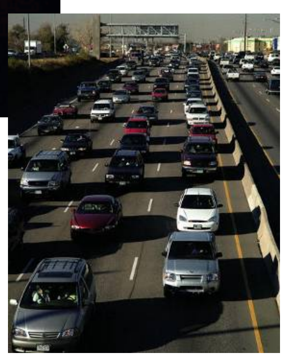
U.S. Department of Energy Hydrogen Program

TODAY

FUTURE

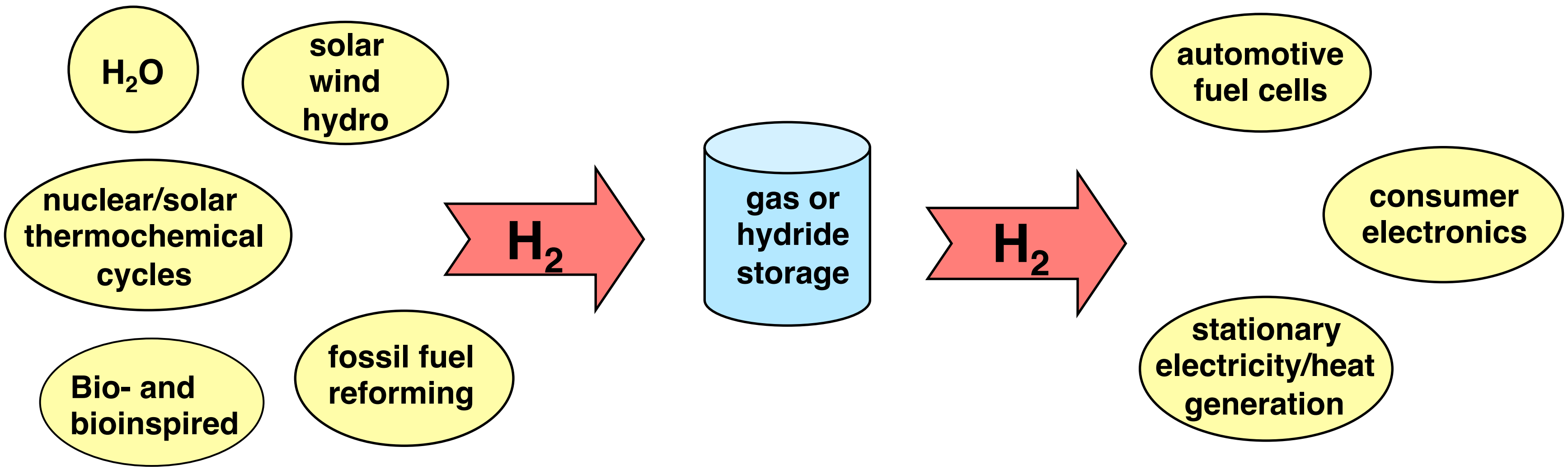
Petroleum-Based Transportation Sector





Keith Wipke
National Renewable Energy Laboratory

The Hydrogen Economy



production

9M tons/yr

↓

150 M tons/yr
(light cars and trucks in 2040)

storage

4.4 MJ/L (Gas, 10,000 psi)
8.4 MJ/L (Liquid H2)

↓

9.70 MJ/L
(2015 FreedomCAR Target)

use in fuel cells

$3000/kW

↓

$30/kW
(Internal Combustion Engine)

M. S. Dresselhaus, MIT

Fundamental Issues

The hydrogen economy is a compelling vision:

- It potentially provides an abundant, clean, secure and flexible energy carrier
- Its elements have been demonstrated in the laboratory or in prototypes

However . . .

- It does not operate as an integrated network
- It is not yet competitive with the fossil fuel economy in cost, performance, or reliability
- The most optimistic estimates put the hydrogen economy decades away

Thus . . .

- An aggressive basic research program is needed, especially in gaining a fundamental understanding of the interaction between hydrogen and materials at the nanoscale

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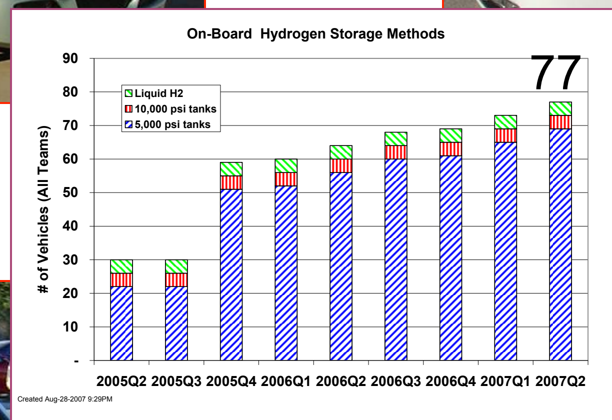
Fuel Cell Vehicle Learning Demonstration Project Underway; 3 Years into 5 Year Demo

- Objectives
  - Validate H_2 FC Vehicles and Infrastructure in Parallel
  - Identify Current Status and Evolution of the Technology

Hydrogen refueling station, Chino, CA   Photo: NREL

Keith Wipke
National Renewable Energy Laboratory

Vehicle Status: All of First Generation Vehicles Deployed, 2nd Generation Initial Introduction in Fall 2007



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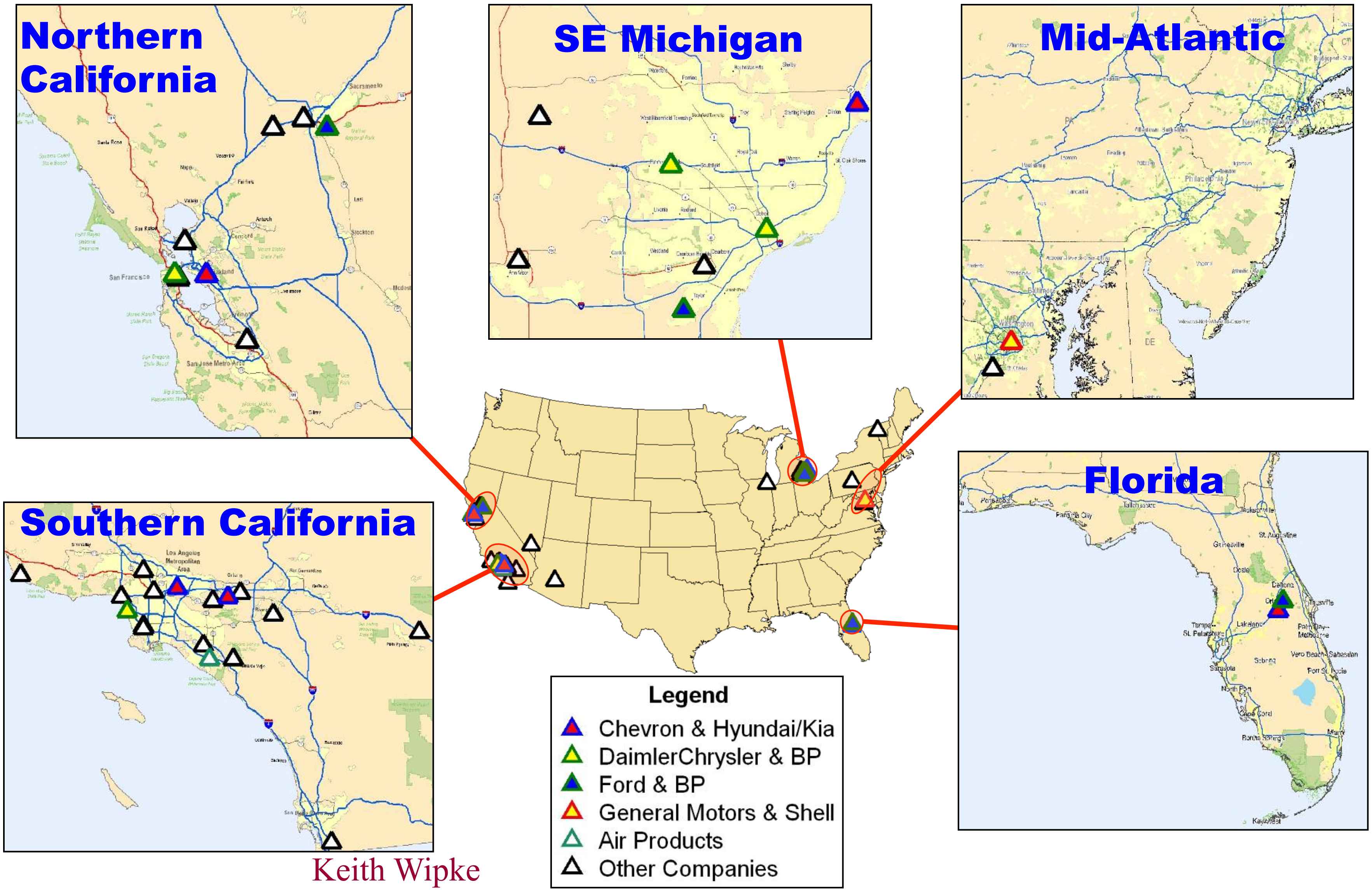
Refueling Stations from All Four Teams Test Vehicle/ Infrastructure Performance in Various Climates



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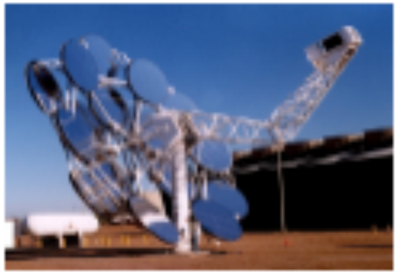
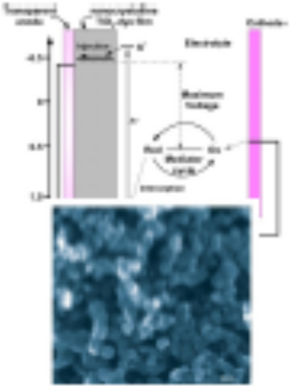
H_2 Production Strategies

Distributed natural gas and electrolysis economics are important for the "transition"

Energy resource diversification is important for the long-term





Source: Steve Chalk, EERE

Hydrogen Production Panel

Panel Chairs: Tom Mallouk (Penn State), Laurie Mets (U of Chicago)

Current status:

- Steam-reforming of oil and natural gas produces 9M tons H_2/yr
- We will need 150M tons/yr for transportation
- Requires CO_2 sequestration.

Alternative sources and technologies:

Coal:

- Cheap, lower H_2 yield/C, more contaminants
- Research and Development needed for process development, gas separations, catalysis, impurity removal.

Solar:

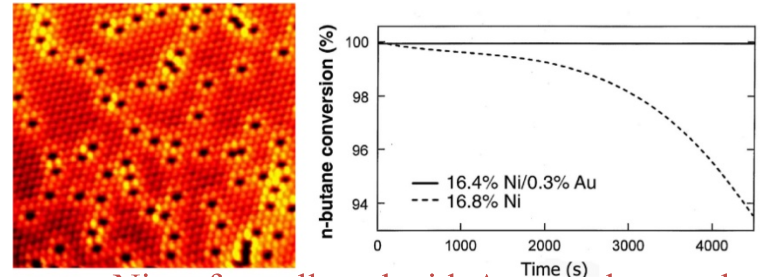
- Widely distributed carbon-neutral; low energy density.
- Photovoltaic/electrolysis current standard – 15% efficient
- Requires 0.3% of land area to serve transportation.

Nuclear: Abundant; carbon-neutral; long development cycle.

Priority Research Areas in Hydrogen Production

Fossil Fuel Reforming Intermediate Term

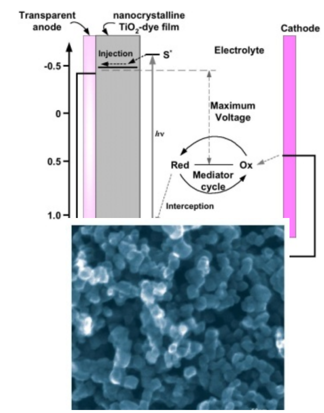
Molecular level understanding of catalytic mechanisms, nanoscale catalyst design, high temperature gas separation



Ni surface-alloyed with Au to reduce carbon poisoning

Solar Photoelectrochemistry/Photocatalysis

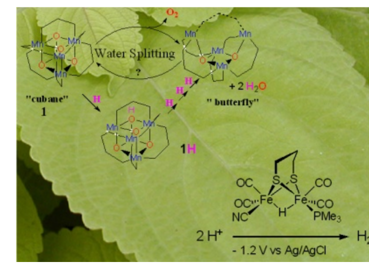
Light harvesting, charge transport, chemical assemblies, bandgap engineering, interfacial chemistry, catalysis and photocatalysis, organic semiconductors, theory and modeling, and stability



Dye-Sensitized Solar Cells

Bio- and Bio-inspired H_2 Production

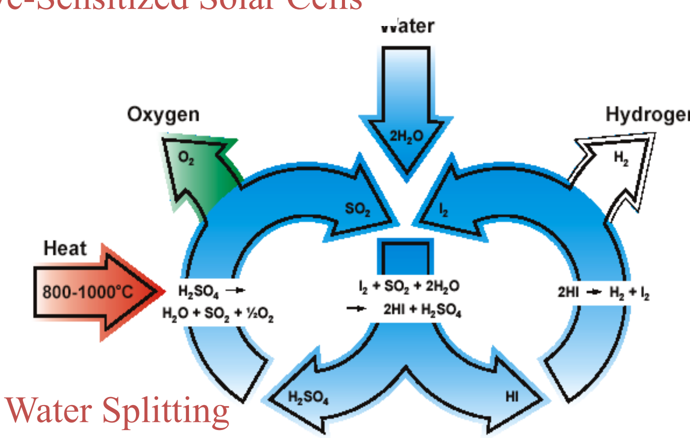
Microbes & component redox enzymes, nanostructured 2D & 3D hydrogen/oxygen catalysis, sensing, and energy transduction, engineer robust biological and biomimetic H_2 production systems



Synthetic Catalysts for H_2 Production

Nuclear and Solar Thermal Hydrogen

Thermodynamic data and modeling for thermochemical cycle (TC), high temperature materials: membranes, TC heat exchanger materials, gas separation, improved catalysts



Thermochemical Water Splitting

Hydrogen Storage Panel

2005

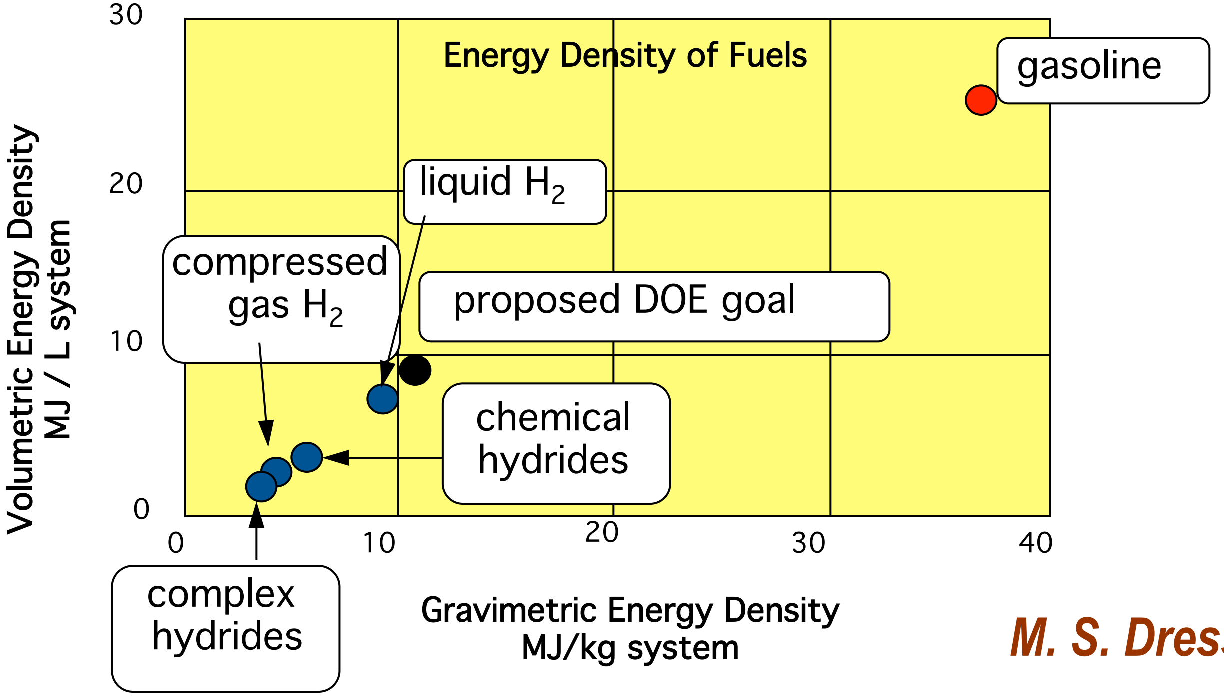
Panel Chairs: Kathy Taylor (GM, Retired) and Puru Jena (Virginia Commonwealth U)

Current Technology for automotive applications

- **Tanks for gaseous or liquid hydrogen storage.**
- **Progress demonstrated in solid state storage materials.**

System Requirements

- **Compact, light-weight, affordable storage.**
- **System requirements set for FreedomCAR: 4.5 wt% hydrogen for 2005, 9 wt% hydrogen for 2015.**
- **No current storage system or material meets all targets.**



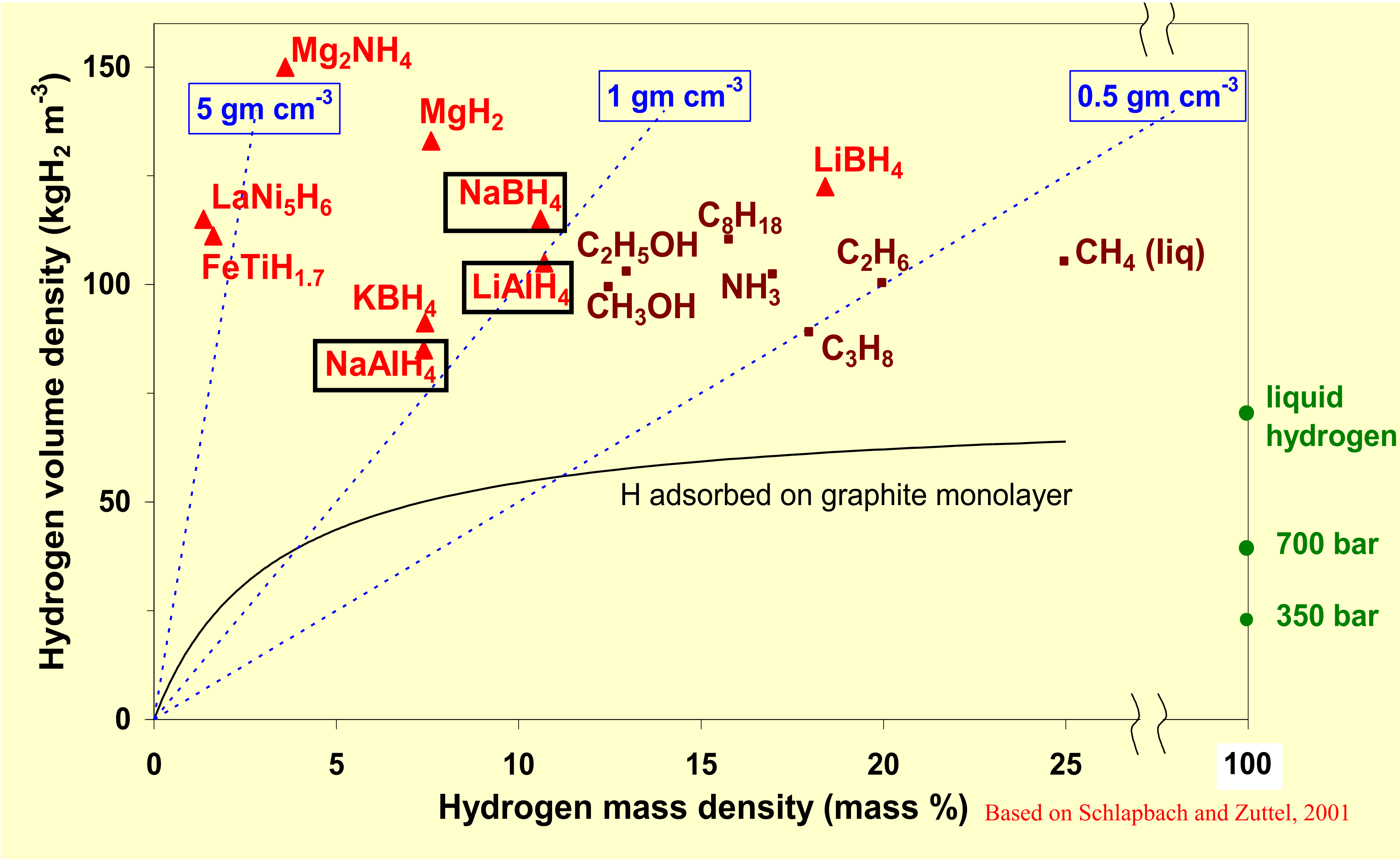
M. S. Dresselhaus, MIT

Ideal Solid State Storage Material

- High gravimetric and volumetric density (9 wt %)
- Fast kinetics
- Favorable thermodynamics
- Reversible and recyclable
- Safe, material integrity
- Cost effective
- Minimal lattice expansion
- Absence of embrittlement

M. S. Dresselhaus, MIT

High Gravimetric H Density Candidates



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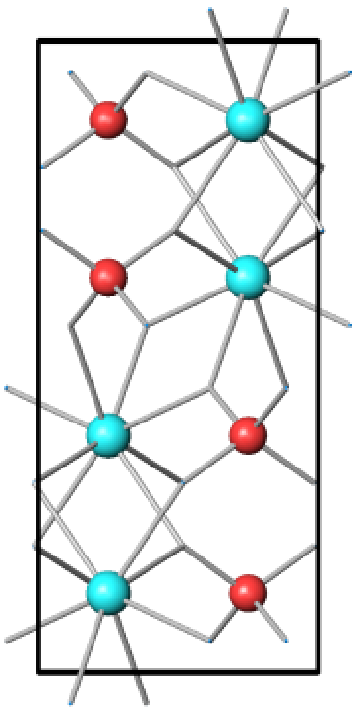
Priority Research Areas in Hydrogen Storage

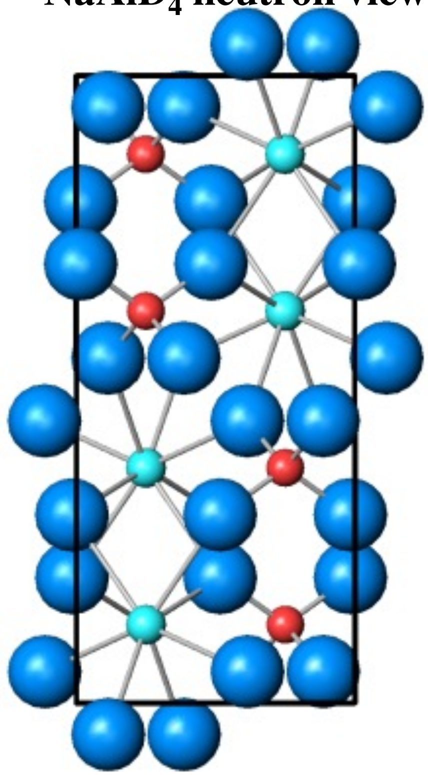
Metal Hydrides and Complex Hydrides

- Metal hydrides such as alanates allow high hydrogen volume density, but temperature of hydrogen release also tends to be high.
- Nanostructured materials may improve absorption volume.
- Incorporated catalysts and nanostructures may improve release.

$NaAlH_4$ X-ray view

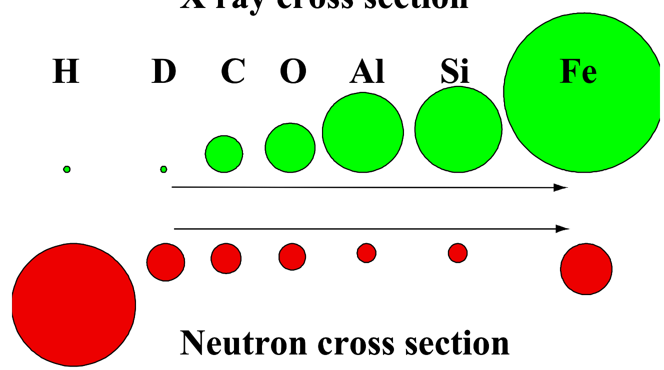


$NaAlD_4$ neutron view



Using Neutrons to "See" Hydrogen

X ray cross section



Neutron cross section

The large neutron cross sections of hydrogen and deuterium make neutrons an ideal probe for in situ studies of hydrogen-based chemical reactions, surface interactions, catalytic reactions and of hydrogen in penetrating through membranes.

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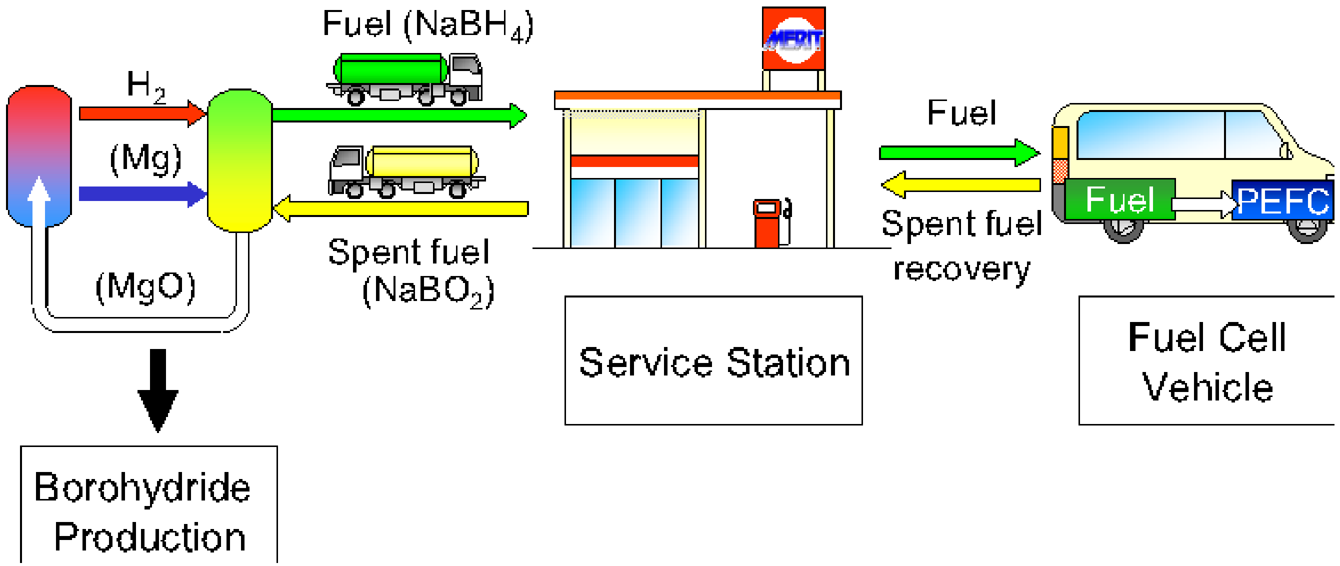
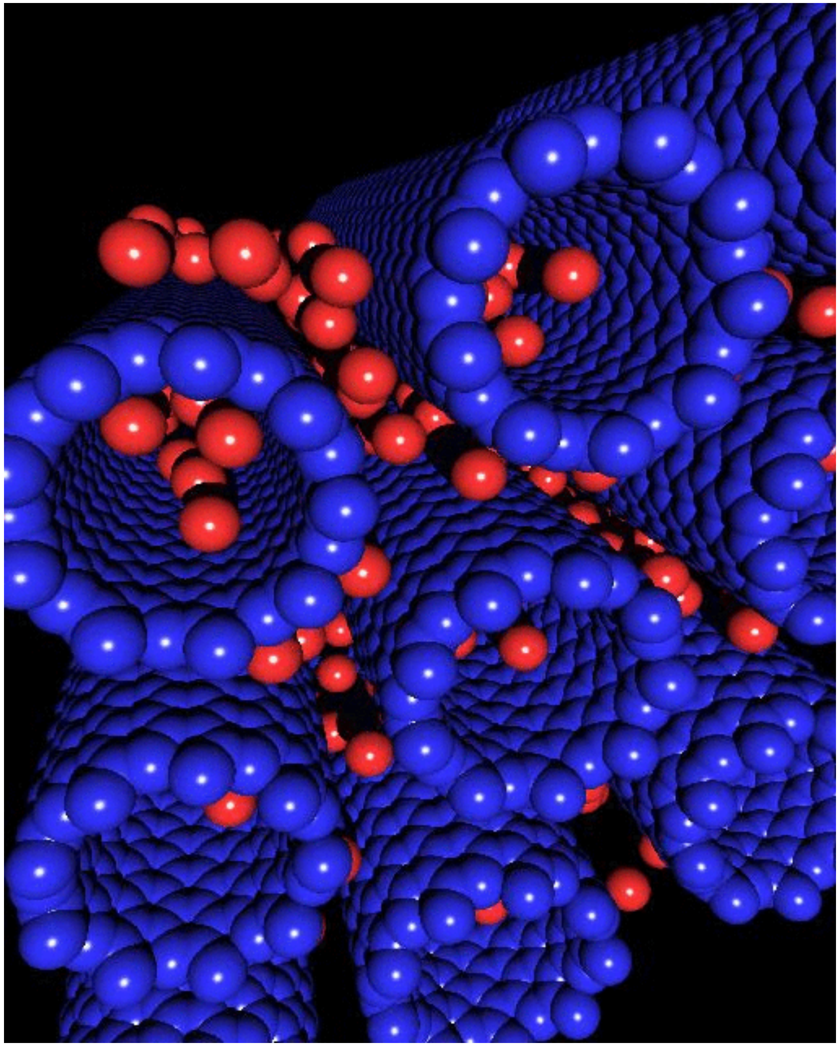
Using $NaBH_4$ for Automotive Hydrogen Storage

$$NaBH_4 + 2\,H_2O \rightarrow 4\,H_2 + NaBO_2$$



- Hydrogen weight % in $NaBH_4$ is 10.7%
- As a fuel (30% $NaBH_4$, 3 wt% NaOH, 67% H_2O) has a hydrogen content of 6.6 wt%.
- However, $NaBH_4$ as a fuel requires regeneration at a processing plant.
- This is one approach under consideration for a hydrogen fuel cell vehicle.

Carbon Nanotubes for Hydrogen Storage



• The very small size and very high surface area of carbon nanotubes make them interesting for hydrogen storage.
• Challenge is to increase the H:C stoichiometry and to strengthen the H—C bonding at 300 K.

A computational representation of hydrogen adsorption in an optimized array of (10,10) nanotubes at 298 K and 200 Bar. The red spheres represent hydrogen molecules and the blue spheres represent carbon atoms in the nanotubes, showing 3 kinds of binding sites. (K. Johnson et al)

Priority Research Areas in Hydrogen Storage

Metal Hydrides and Complex Hydrides

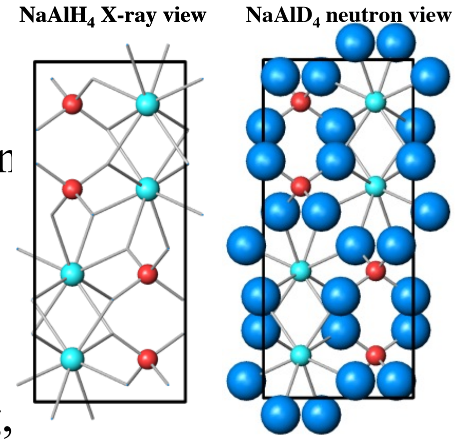
Degradation, thermophysical properties, effects of surfaces, processing, dopants, and catalysts in improving kinetics, nanostructured composites

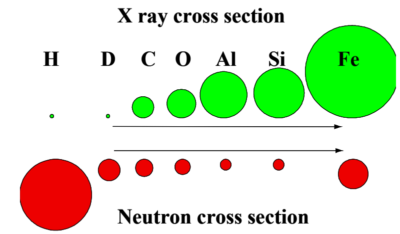
Nanoscale/Novel Materials

Finite size, shape, and curvature effects on electronic states, thermodynamics, and bonding, heterogeneous compositions and structures, catalyzed dissociation and interior storage phase

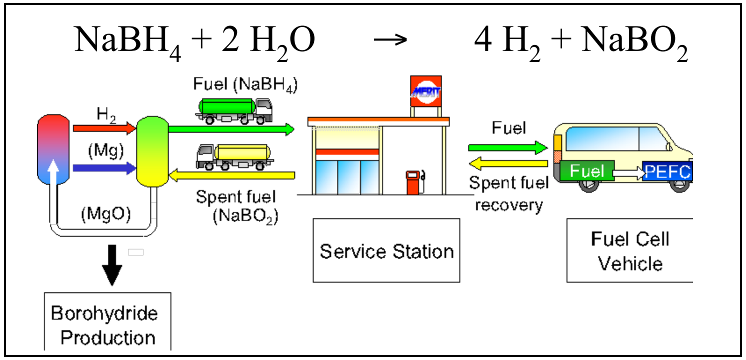
Theory and Modeling

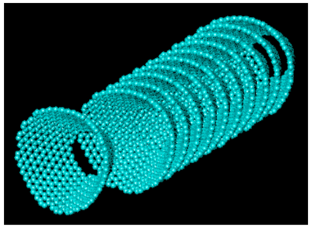
Model systems for benchmarking against calculations at all length scales, integrating disparate time & length scales, first principles methods applicable to condensed phases



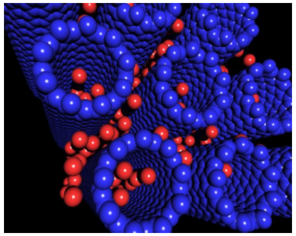


Neutron Imaging of Hydrogen





Cup-Stacked Carbon Nanofiber



H Adsorption in Nanotube Array

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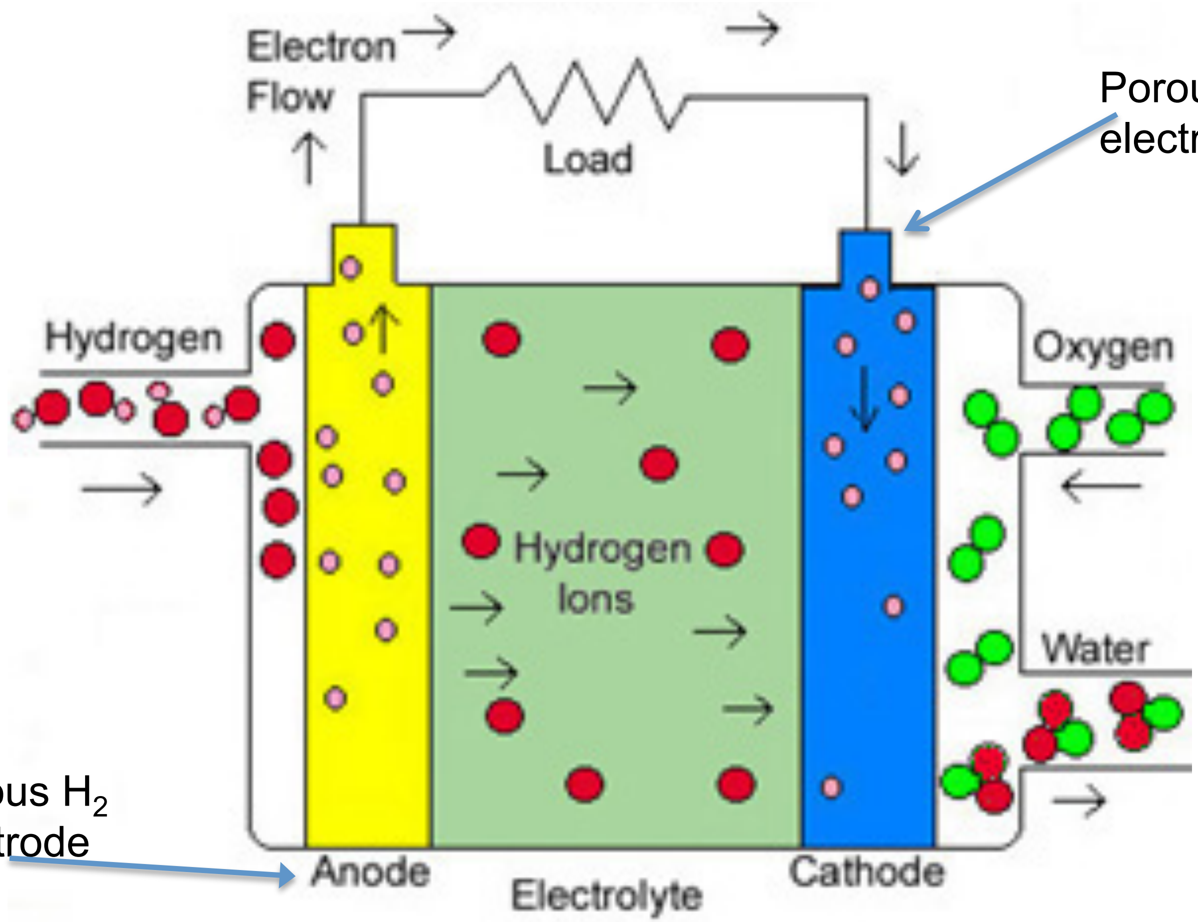
Fuel Cells



Porous O_2 electrode

Porous H_2 electrode

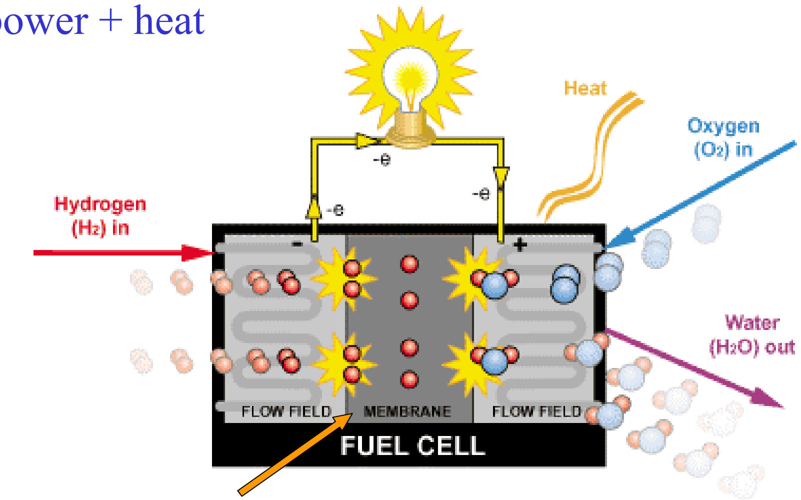
Eg. mixture of KOH and H_2O) at lower pressure than ends

$H_2 + 0.5O_2 \rightarrow H_2O$ + electrical energy + heat

Fuel Cells and Novel Fuel Cell Materials Panel

<u>Panel Chairs:</u> Frank DiSalvo (Cornell), Tom Zawodzinski (Case Western Reserve)

$2H_2 + O_2 \rightarrow 2H_2O$ + electrical power + heat



Membrane conducts protons from anode to cathode
proton exchange membrane (PEM)

Current status:

Limits to performance are materials, which have not changed much in 15 years.

Challenges:

Membranes

Operation in lower humidity, more strength, durability and higher ionic conductivity.

Cathodes

Materials with lower overpotential and resistance to impurities.

Low temperature operation needs cheaper (non- Pt) materials.

Tolerance to impurities: S, hydrocarbons, Cl.

Anodes

Tolerance to impurities: CO, S, Cl.

Cheaper (non or low Pt) catalysts.

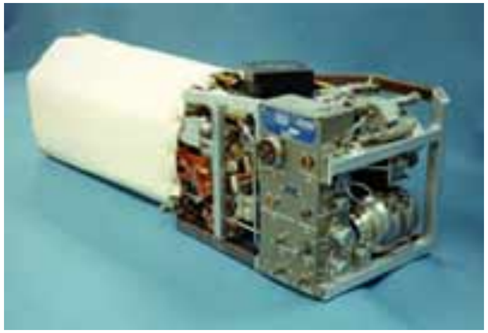
Reformers

Need low temperature and inexpensive reformer catalysts.

M. S. Dresselhaus, MIT

Types of Fuel Cells

Phosphoric Acid FC
(PAFC), 250 kW
United Technologies



Alkaline Fuel Cell
(AFC), Space Shuttle
12 kW
United Technologies

Low-Temp

High Temp

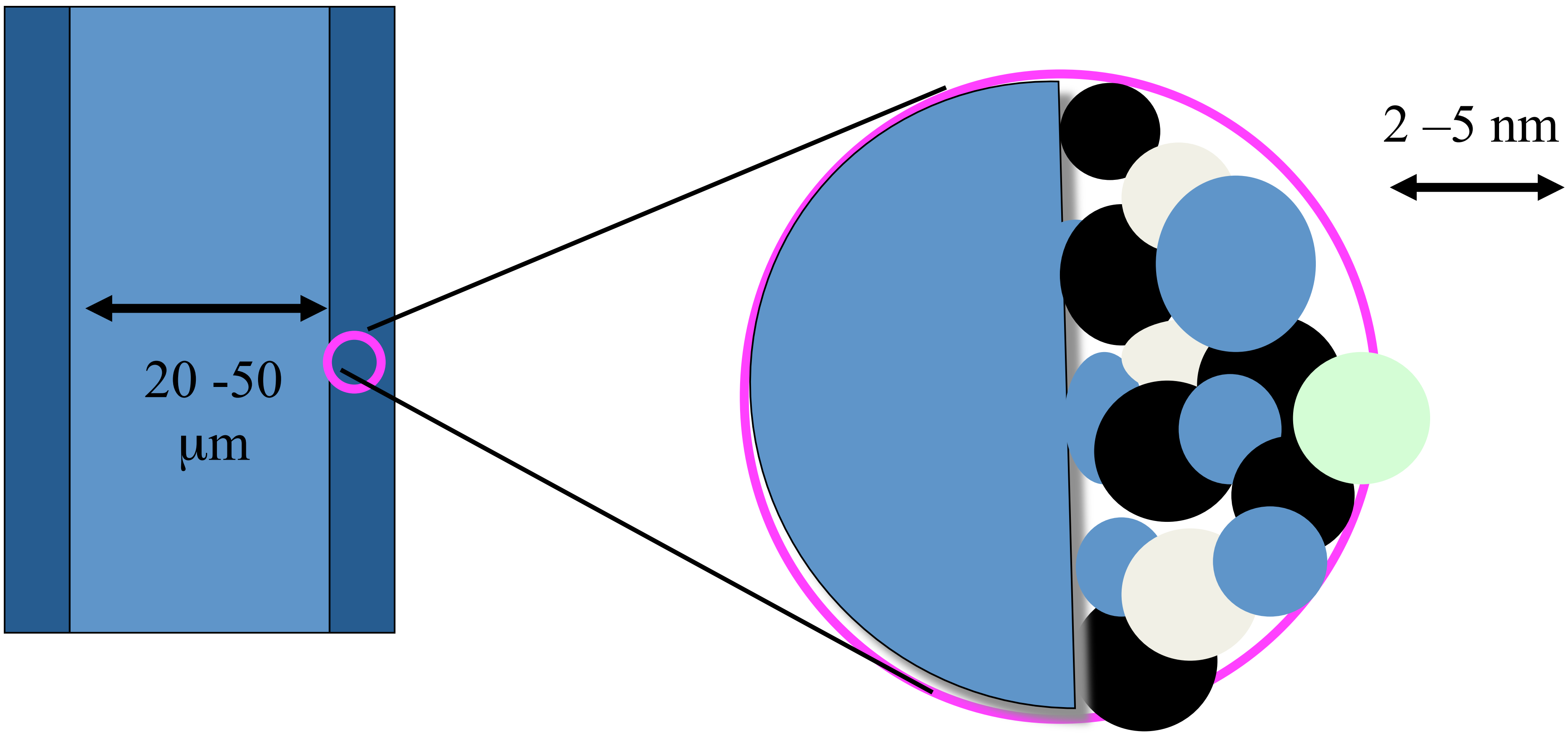
Proton Exchange
Membrane (PEM)
50 kW, Ballard

Solid Oxide FC
(SOFC) 100 kW
Siemens-
Westinghouse

Molten Carbonate FC
(MCFC) 250 kW
FuelCell Energy,

Electrode/Membrane Design

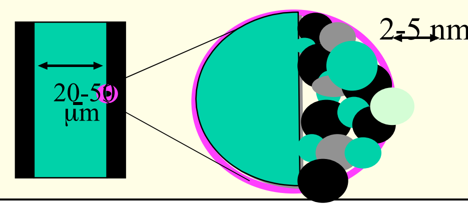
Very challenging. Electrodes need to support three percolation networks: electronic, ionic, fuel/oxidizer/product access/egress.



Priority Research Areas in Fuel Cells

Electrocatalysts and Membranes

Oxygen reduction cathodes, minimize rare metal usage in cathodes and anodes, synthesis and processing of designed triple percolation electrodes

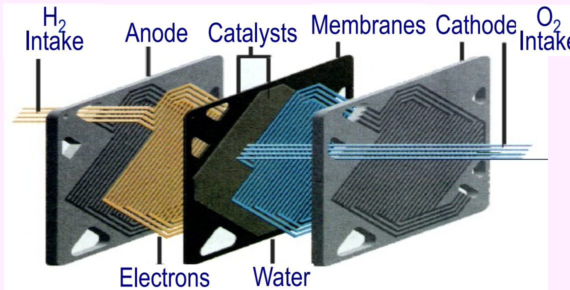


Controlled design of triple percolation nanoscale networks: ions, electrons, and porosity for gases

Low Temperature Fuel Cells

'Higher' temperature proton conducting membranes, degradation mechanisms, functionalizing materials with tailored nano-structures

Internal view of a PEM fuel cell

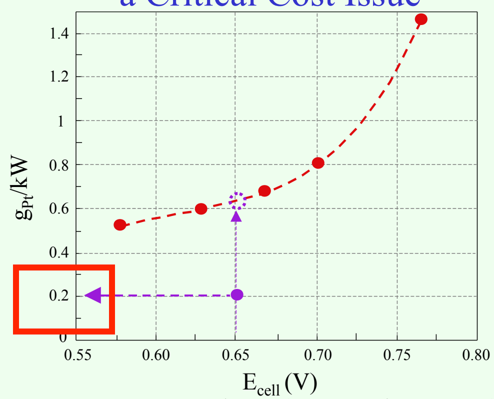


Source: T. Zawodzinski (CWRU)

Solid Oxide Fuel Cells

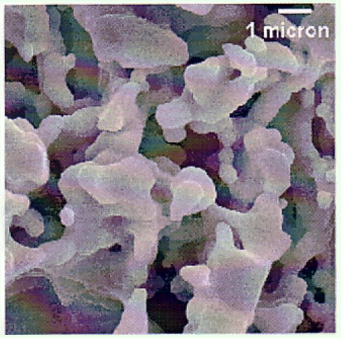
Theory, modeling and simulation, validated by experiment, for electrochemical materials and processes, new materials-all components, novel synthesis routes for optimized architectures, advanced in-situ analytical tools

Mass of Pt Used in the Fuel Cell — a Critical Cost Issue



Source: H. Gasteiger (General Motors)

YSZ Electrolyte for SOFCs



Porosity can be tailored

Source: R. Gorte (U. Penn)

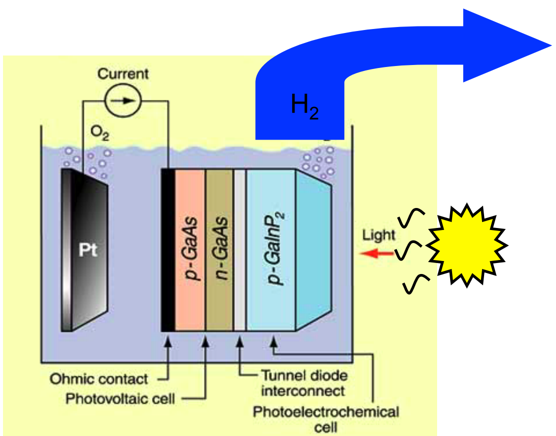
M. S. Dresselhaus, MIT

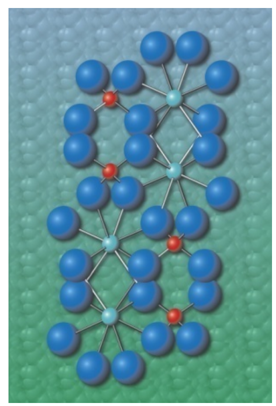
High Priority Research Directions for Hydrogen Economy

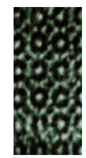
- Low-cost and efficient renewable (solar) energy production of hydrogen
- Nanoscale catalyst design
- Biological, biomimetic, and bio-inspired materials and processes
- Complex hydride materials for hydrogen storage
- Nanostructured / novel hydrogen storage materials
- Low-cost, highly active, durable cathodes for low-temperature fuel cells
- Membranes and separations processes for hydrogen production and fuel cells

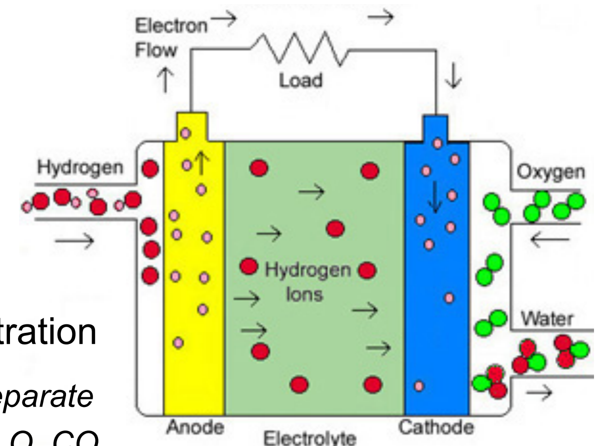
Cross-cutting Issue - Materials

the challenge: to understand and control the interaction of hydrogen with materials









sunlight + $H_2O \rightarrow H_2 + O_2$

transparent semiconductor layers
nanoscale catalysts
nanostructured interfaces

$H_2 \rightarrow NaAlH_4$

new H storage materials
catalytic reactions
nanoscale texture

molecular filtration

membranes separate
H_2 , O_2 , CO, H_2O, CO_2
nanoscale size selection

$H_2 + O_2 \rightarrow H_2O$

fuel cell catalysts
ionic membranes
nanoscale architecture

catalysts, nano-materials, membranes needed throughout

M. S. Dresselhaus, MIT

http://www.driveclean.ca.gov/Search_and_Explore/Technologies_and_Fuel_Types/Hydrogen_Fuel_Cell.ph

- http://www.fuelcells.org/uploads/carchart.pdf

www.fuelcells.org

Fuel Cell Vehicles

(From Auto Manufacturers)

Automaker	Vehicle Type	Year Shown	Engine Type	Fuel Cell Size/type	Fuel Cell Mfr.	Range (mi/km)	MPG Equivalent*	Max. Speed	Fuel Type	Commercial Intro.	Picture
Audi	Q5 HFC	2010	Fuel cell/ battery hybrid	98 kW PEM	N/a	N/a	N/a	N/a	Compress. Hydrogen @ 700 bar	Prototype	
	A2	2004	Fuel cell/ battery hybrid	66 kW PEM	Ballard	137 mi 220 km	N/a	109 mph 175 km/h	Compress. hydrogen		
AVL List GmbH	AVL FCC: 4-5 persons commuter for company internal usage or private fields	2010	EV with FC range extender	3 kW PEM	N/a	94 mi/150 km (at full load and traveling 12.5 mph/20 km/h)	N/a	19 mph 30 km/h	34L CGH @ 200bar	Prototype serves for technology demonstration and as research platform. Developed in cooperation with Tongji University	
AvtoVAZ	Lada Antel-2	2003	Fuel cell/ battery hybrid	Alkaline fuel cell	N/a	219 mi 350 km	N/a	N/a	Compress. hydrogen @ 400 bar	Debuted at the 2003 Moscow Auto Show.	
	Lada Antel-1	2001	Fuel cell/ battery hybrid	Alkaline fuel cell	N/a	155 mi 250 km	N/a	50 mph 80 km/h	Compress. hydrogen @ 250 atm.		
										Prototype. 4-cylinder gas engine for high speed	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RIDGELINE
CLARITY
CLARITY
FUEL CELL
ZERO EMISSIONS. INFINITE POSSIBILITIES.
Coming Winter 2016
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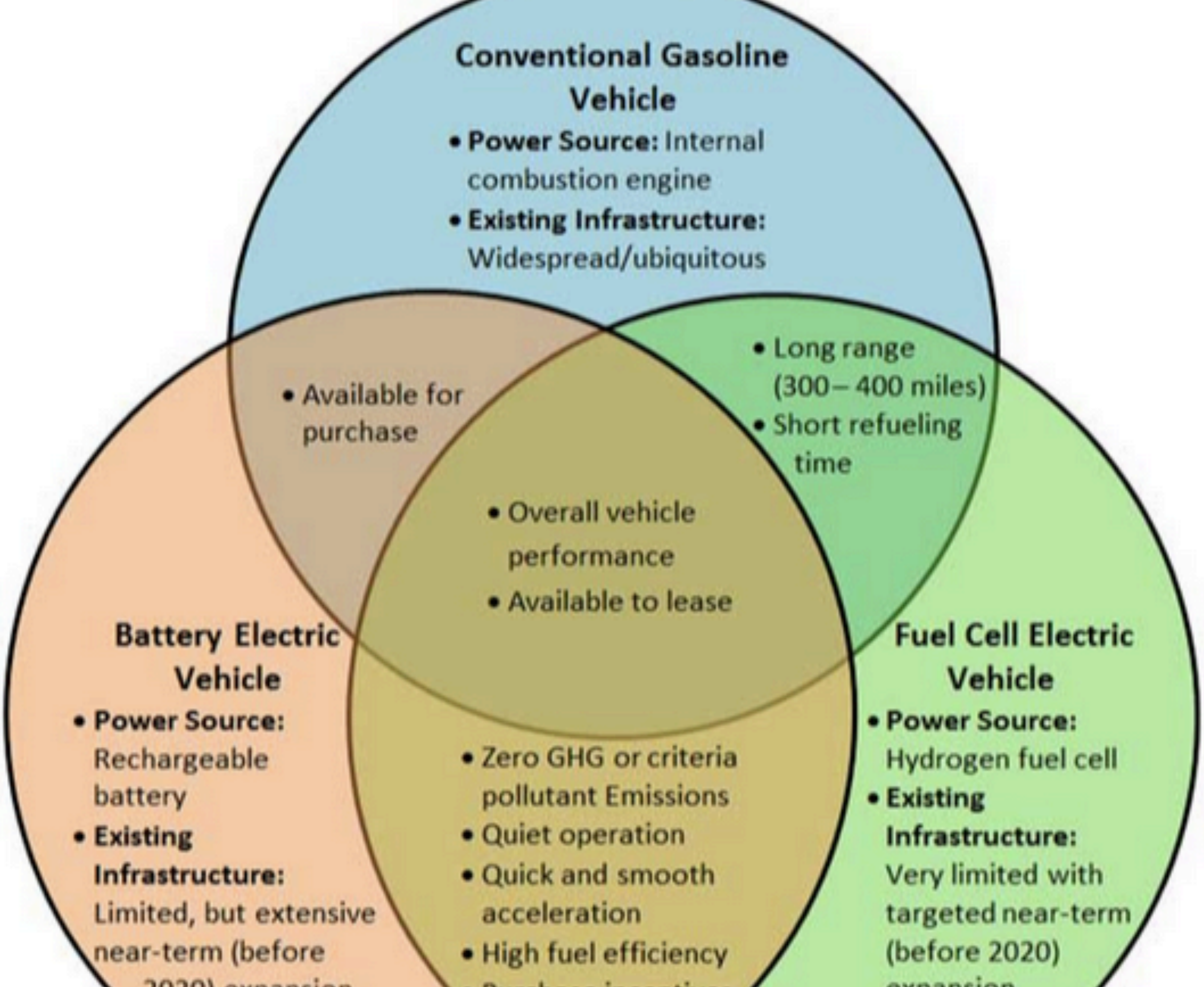
05
FCHV-BUS


Conventional Gasoline Vehicle
• Power Source: Internal combustion engine
• Existing Infrastructure: Widespread/ubiquitous
• Available for purchase
• Long range (300 – 400 miles)
• Short refueling time
• Overall vehicle performance
• Available to lease
Battery Electric Vehicle
• Power Source: Rechargeable battery
• Existing Infrastructure: Limited, but extensive near-term (before
• Zero GHG or criteria pollutant Emissions
• Quiet operation
• Quick and smooth acceleration
• High fuel efficiency
Fuel Cell Electric Vehicle
• Power Source: Hydrogen fuel cell
• Existing Infrastructure: Very limited with targeted near-term (before 2020)