
Hydrogen Economy

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Outline

- Advantages of Hydrogen
 - Disadvantages of Hydrogen
 - Hydrogen Production
 - Fossil Fuels
 - Nuclear
 - Renewable Energy Sources
 - Hydrogen Storage
 - Summary and Conclusions
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Advantages of Hydrogen

Why Hydrogen?

Think individually about what you know about hydrogen and its advantages, discuss with your neighbor(s), and be prepared to share your answer.

Disadvantages of Hydrogen

Why not hydrogen?

Think individually about what you know about hydrogen and its disadvantages, discuss with your neighbor(s), and be prepared to share your answer.

Hydrogen Production

- There is no natural source of hydrogen
 - Hydrogen can be considered as a **energy carrier**, not an energy source.
 - To supply the hydrogen for energy needs, economical processes are needed to produce hydrogen from abundant energy sources
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Hydrogen Production – Fossil Fuels

- In the short-term, hydrogen may produced from fossil fuels
 - Natural gas
 - Coal
 - Gasoline
 - Advantages:
 - Established distribution networks
 - Economical conversion processes
 - Disadvantages:
 - Finite resources
 - Shift pollution problem, but don't eliminate it!
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Hydrogen Production – Natural Gas

- Well-established technology exists to convert natural gas to hydrogen. Typically done using **steam reforming**:



High temperatures (700-1000°C) are need for high conversion.



Hydrogen plant in Tosco Corp's Avon refinery¹

¹ <http://www.airproducts.com/PhotoLibrary/restricted/photo-cpi.asp>

Hydrogen Production – Natural Gas

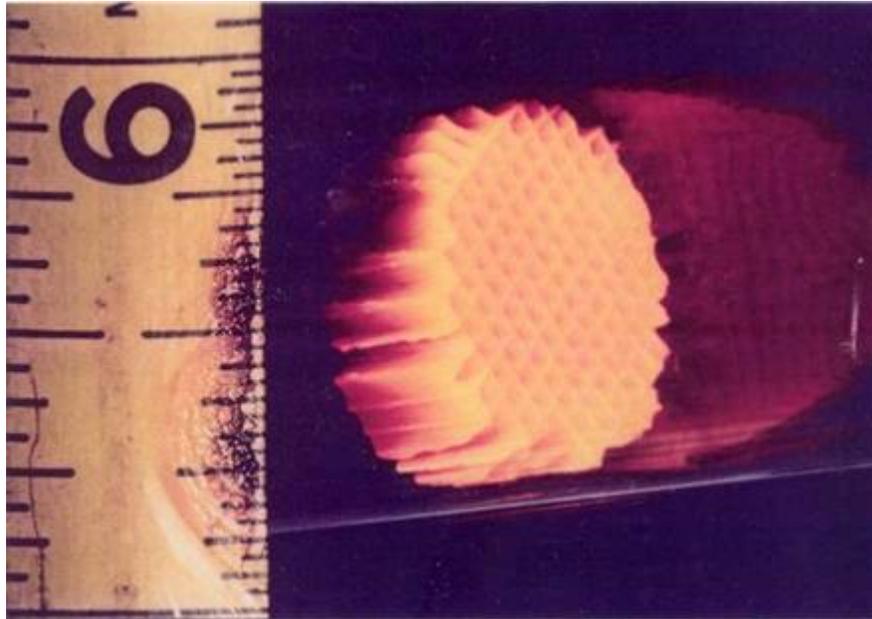
- Other conversion technologies have been commercialized or are being studied:
- Partial Oxidation



- Autothermal reforming

Combination of partial oxidation and steam reforming. Methane is partially combusted and then reformed. Combustion drives reforming reaction, so no heat needs to be added.

Hydrogen Production – Natural Gas

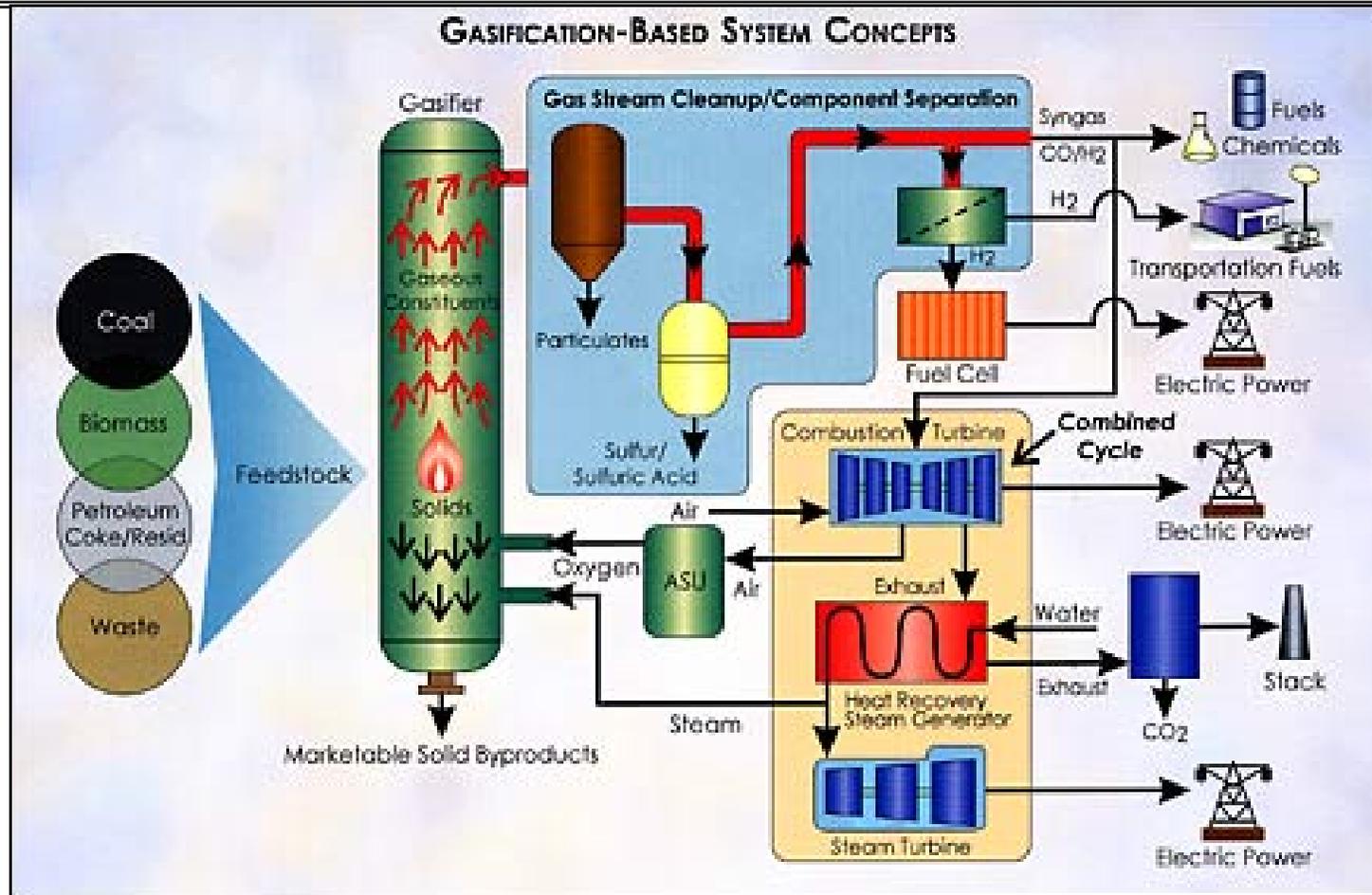


**Catalytic partial oxidation of methane over
a noble metal-coated ceramic monolith**

Hydrogen Production – Natural Gas

- Advantages
 - Pipeline system (on-site production of hydrogen?)
 - Most cost-efficient of current hydrogen-generation processes
 - Disadvantages
 - Finite resource
 - Rising natural gas prices
 - Not CO₂ neutral
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Hydrogen Production - Coal



Hydrogen Production - Coal

- Advantages
 - Can be implemented using current technology
 - U.S. has enough coal to make all of the hydrogen the economy needs for >200 years¹
 - Lowest cost for hydrogen
- Disadvantages
 - Produces more CO₂ than other technologies (carbon sequestration?)
 - Same environmental concerns as electricity generation from coal
 - Centralized production
 - Purification and separation of hydrogen at high temperatures is challenging

¹ “The Hydrogen Economy”, The National Academies Press, Washington, D.C.

Hydrogen Production - Gasoline

- For transportation needs, a short-term solution could be to convert gasoline, logistic or diesel fuel to hydrogen onboard
- Multiple steps are needed:

Conversion of gasoline to synthesis gas: $C_xH_y + H_2O + O_2 \rightarrow CO + H_2$
(steam or autothermal reforming, partial oxidation)

Water-gas shift $CO + H_2O \rightleftharpoons CO_2 + H_2$

Selective oxidation $CO + O_2 \rightarrow CO_2$
(or membrane separation)

Hydrogen Production - Gasoline

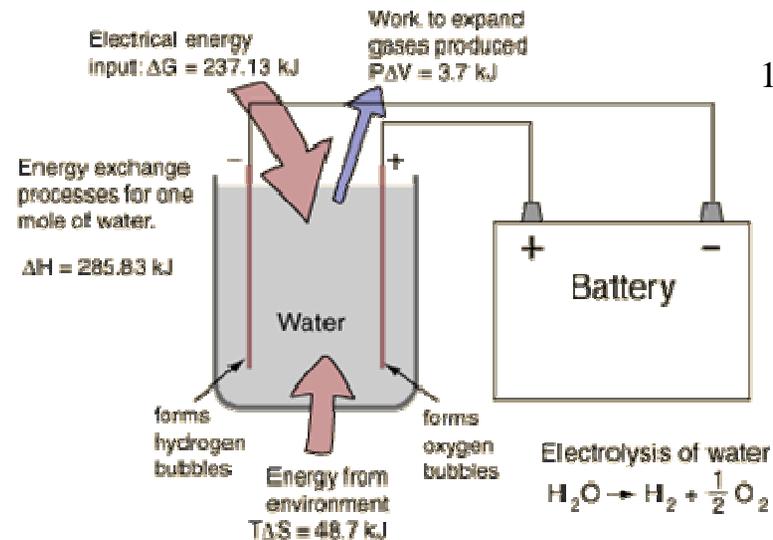
- Advantages
 - Makes use of current gasoline distribution system

 - Disadvantages
 - Difficulty with fuel impurities, particularly sulfur
 - Decreases efficiency of fuel cell system
 - Size of integrated system
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Hydrogen Production - Nuclear

- Nuclear energy can be used to produce hydrogen through two different routes:
 - Water electrolysis

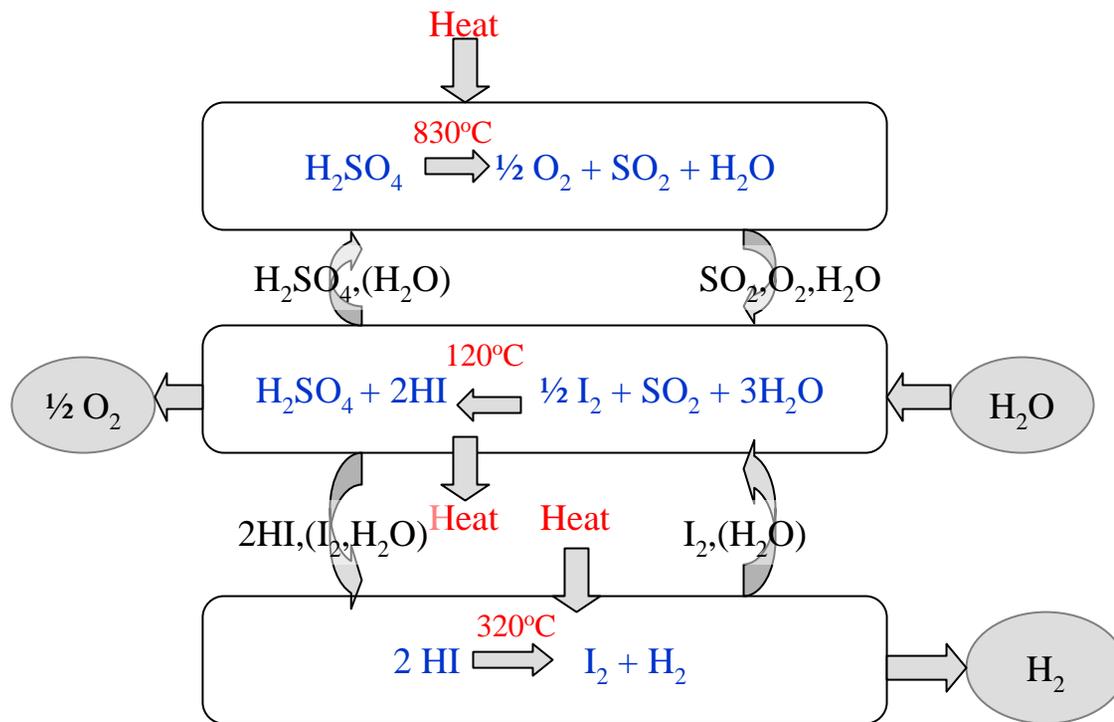
Efficiency 25-30%
(High temp, 30-40%)



- Thermochemical water-splitting
 - Split water through endothermic chemical reactions (45-50% efficiency)

Hydrogen Production - Nuclear

- Thermochemical cycles convert water to hydrogen by making use of heat from nuclear reactors (S-I, Ca-Br-Fe, Cu-Cl, Zn-O)



Hydrogen Production - Nuclear

- Advantages
 - Long-term energy resource
 - Reduced dependence on foreign energy supplies
 - No CO₂ or air pollutant emissions
 - Disadvantages
 - Nuclear waste
 - Public acceptance
 - Material issues at high temperatures
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Hydrogen Production – Renewable Resources

- For a true hydrogen economy (no net carbon emissions), renewable resources must be used.
 - Possible renewable resources include:
 - Water electrolysis
 - Biomass conversion
 - Biogenesis
 - Solar Energy
 - Wind Energy
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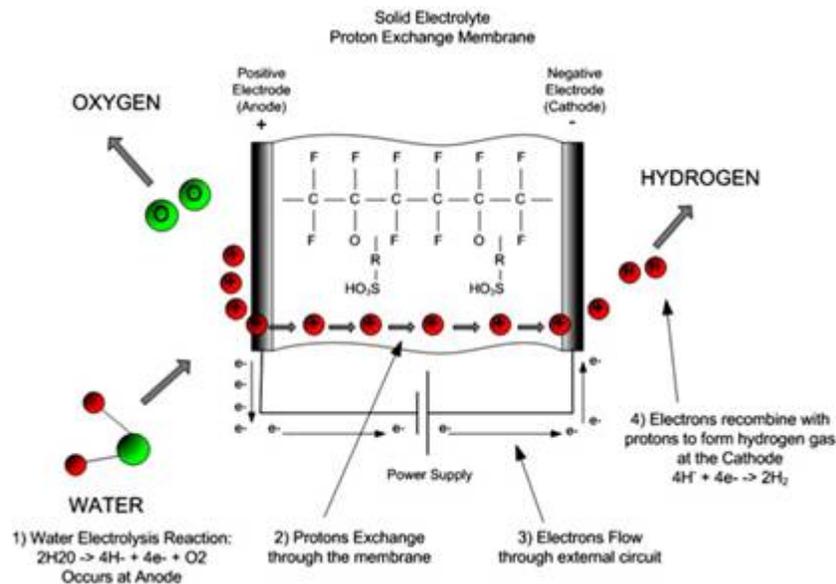
Hydrogen Production - Electrolysis

- Electrolysis can be achieved using:

- Proton exchange membrane (PEM)

- Liquid electrolyte (KOH)

Caustic solution functions as the electrolyte instead of a membrane



Hydrogen Production - Electrolysis

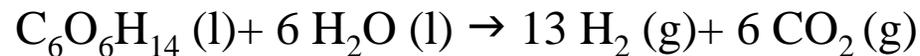
- Advantages
 - No CO₂ production
 - Distributed hydrogen generation
 - Disadvantages
 - Expensive
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Hydrogen Production - Biomass

- Gasification, analogous to coal gasification, can turn crops or crop residues to hydrogen
 - Advantages:
 - CO₂-neutral
 - Decreased dependence on foreign energy sources
 - Disadvantages
 - Very inefficient
 - Large amounts of land required (40% of current U.S. cropland would be needed to power all cars)
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Hydrogen Production - Biomass

- Catalysts can also be used to converted bio-derived molecules to hydrogen¹



Platinum and nickel-based catalysts have been found to catalyze this reaction at 500 K in aqueous solution

This could be a route to convert carbohydrates, which are extracted from renewable biomass and biomass waste streams, to hydrogen

¹Cortwright, R.D., Davda, R.R, and Dumesic, J. A., *Nature* **418** (2002), 964-967.

Hydrogen Production - Biogenesis

- Biogenesis uses microorganisms to generate hydrogen. Bacteria can take organic wastes (proteins and carbohydrates) and generate hydrogen. For example, members of the *Thermotogales* family produce hydrogen¹.
- Advantages:
 - Environmentally benign
 - Moderate processing conditions
- Disadvantages
 - Large-scale production has not been proven

Hydrogen Production – Solar Energy

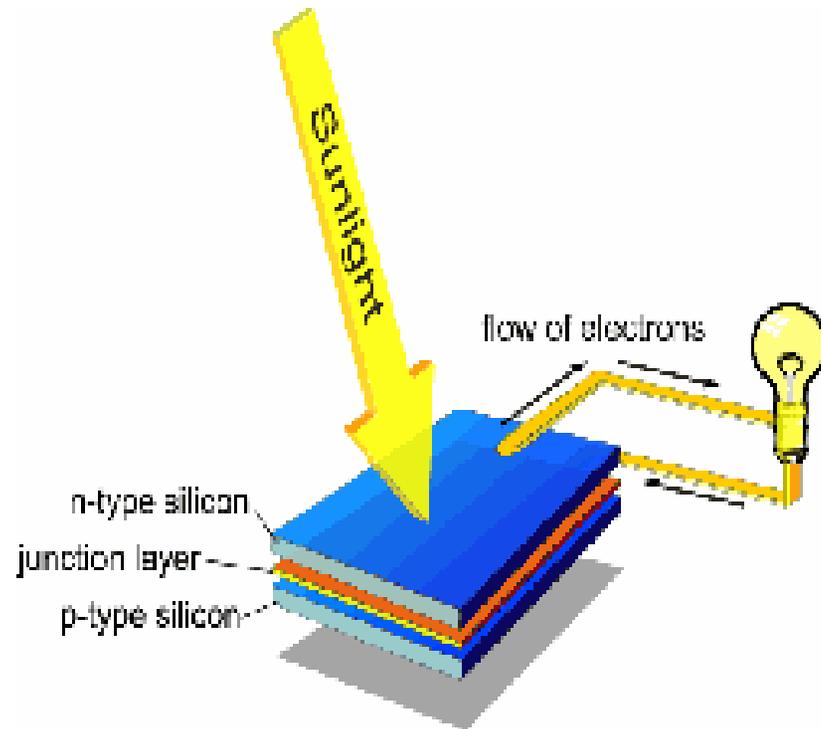
- Solar energy can be harnessed to produce hydrogen in several ways:
 - Photovoltaic cells: solar energy is converted to electricity which drives water electrolysis
 - Photoelectrochemical methods
 - Thermochemical methods
 - Use heat from a solar collector to drive a cycle which converts water to hydrogen
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Hydrogen Production – Solar Energy

Photovoltaic cell

Solar energy creates electron-hole pairs, which create electricity

Electricity then drives electrolysis



Hydrogen Production – Solar Energy

- Recent work has studied the combination of these two processes in a single nanoscale process. Photon absorption creates a local electron-hole pair that electrochemically splits a neighboring water molecule
 - This requires a material that is both stable in aqueous environments and has a small bandgap so that solar energy can be absorbed.
 - Possible solutions:
 - Dye-sensitized photocells that accumulate energy from multiple low-energy photons to inject higher-energy photons into semiconductor
 - Doped oxide semiconductors with reduced bandgaps
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Hydrogen Production – Solar Energy

- Advantages:
 - Distribute hydrogen generation
 - No pollution
 - Disadvantages:
 - Expensive
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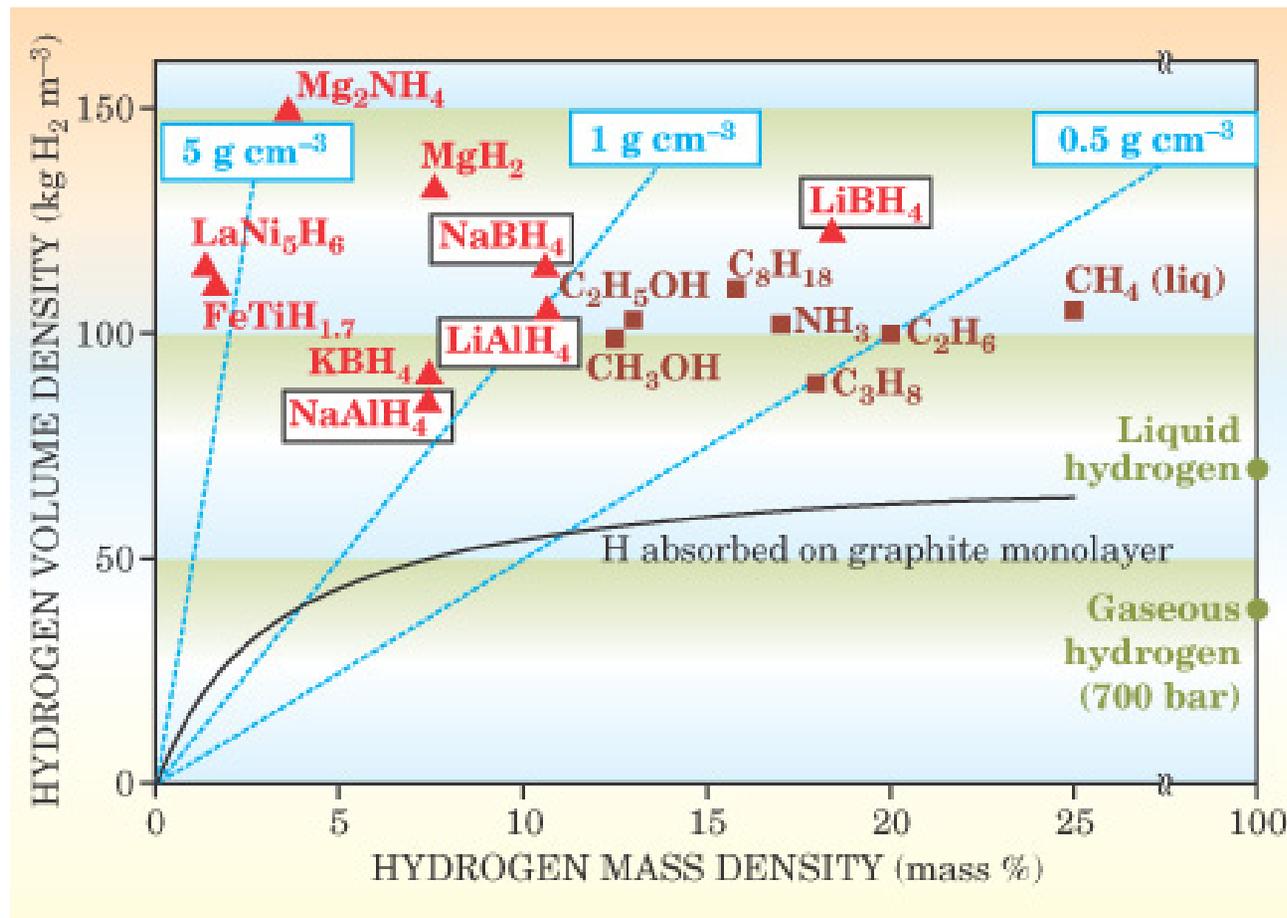
Hydrogen Production – Wind Energy

- Wind-turbine electricity can electrolyze water to produce hydrogen
 - Advantages:
 - No emissions
 - Cost-competitive
 - Domestic source of energy
 - Disadvantages
 - Environmental and siting issues
 - Hydrogen only produced intermittently
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Hydrogen Storage

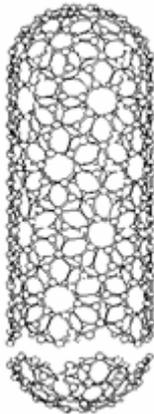
- Storing hydrogen in a high energy-density form is a key part of the hydrogen economy
 - Liquefaction of hydrogen is prohibitively expensive (~30% of energy content is lost in liquefaction). Compression to 10,000 psi costs ~11% of hydrogen's energy content.
 - Hydrogen storage media are required that store a lot of hydrogen in a small volume and can easily desorb hydrogen on demand
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Hydrogen Storage

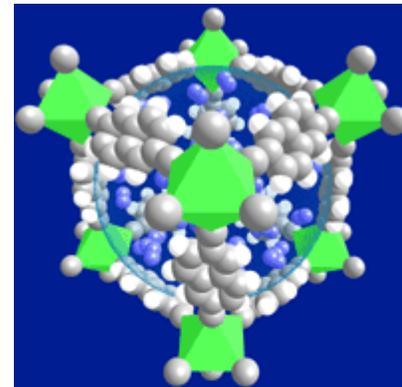


Hydrogen Storage

- Some of the most promising materials for hydrogen storage include:
 - Metal hydrides (LaNi_5H_6 , Mg_2NH_4 , $\text{Na}^+(\text{BH}_4)^-$, LiBH_4)
 - Carbon nanotubes
 - Zeolites
 - Metal-organic framework materials



Carbon nanotube¹



Source: University of Michigan

This graphic depicts a metal-organic framework, a molecular structure that can store hydrogen. The hydrogen atoms are represented by blue spheres.

¹ <http://www.research.ibm.com/nanoscience/nanotubes.html>

² http://www.trnmag.com/Stories/2003/052103/Hydrogen_storage_eased_052103.html

Summary and Conclusions

- Hydrogen is extremely attractive because of its environmental implications, and because use of hydrogen in fuel cells is efficient
 - Many options are being considered for hydrogen production. Production from renewable sources is the most attractive long-term, but has the most technical barriers at the current time
 - Hydrogen storage is a critical issue that needs to be overcome for implementation of hydrogen in transportation applications
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References

Crabtree, G.W., Dresselhaus, M.S., and Buchanon, M.V., *Physics Today*
57(2004), 39-56.

“The Hydrogen Economy”, The National Academies Press, Washington, D.C.
