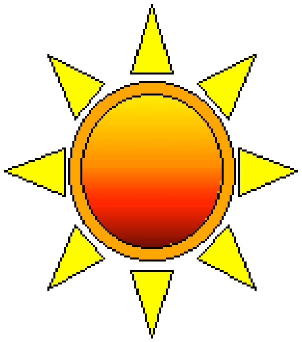

Analysis of solar hydrogen systems for use with fuel cell vehicles

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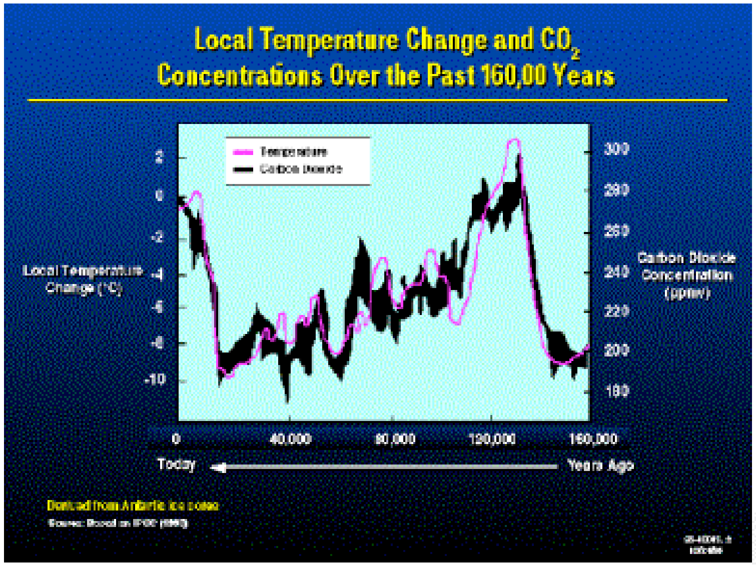
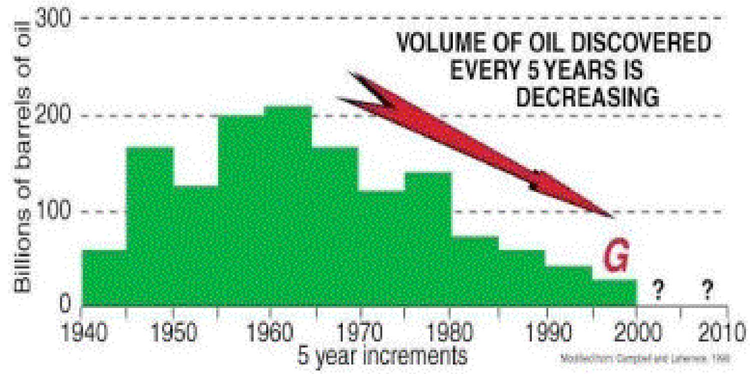
Abstract

Hydrogen has the potential of replacing fossil fuels for stationary power and transportation. Doubts about future oil production and implications of greenhouse gases provide economic and environmental reasons for a switch from petroleum. The combustion or chemical conversion of hydrogen into usable energy only produces small amounts of water vapor as a byproduct. Steam reforming of natural gas has been the main process of obtaining hydrogen, but electrolysis can provide a sustainable energy economy. Solar hydrogen systems use solar energy to split water molecules into hydrogen and oxygen, preferably for use in fuel cells. To achieve the ultimate environmentally-friendly automobile, solar hydrogen systems can be used to drastically reduce greenhouse emissions. For use with fuel cell vehicles, solar hydrogen systems can be set up at a typical suburban home or fueling station. For homes, it takes 3 to 4 years for the solar module system to offset its emissions -- coming from its production using conventional electricity. For vehicles, it would take 4 to 5 years because more energy is required to run an automobile than a typical household; however this number can be reduced by using cleaner power in the manufacture of solar modules or by increasing their efficiency. Considering that production of conventional electricity releases more greenhouse gases than gasoline, solar hydrogen systems should first address electricity use in homes and offices. The limiting paths to economic viability are the cost of efficient solar cells, electrolysis systems, and fuel cells. Technological barriers are efficiency of solar cells, hydrogen storage, and load profiling of the fuel cell. Whereas the technological barriers are likely to be overcome in the near future, solar hydrogen systems will take a longer time to be cost-effective as compared to other methods of hydrogen extraction. To be cost-competitive with fully taxed gasoline, solar module costs would have to be cut by a factor of 7 or to $0.03/kWh for a home refueling station. For larger fueling stations, solar module cost would have to be reduced by a factor of 4 or to $0.05/kWh.

Our current situation:

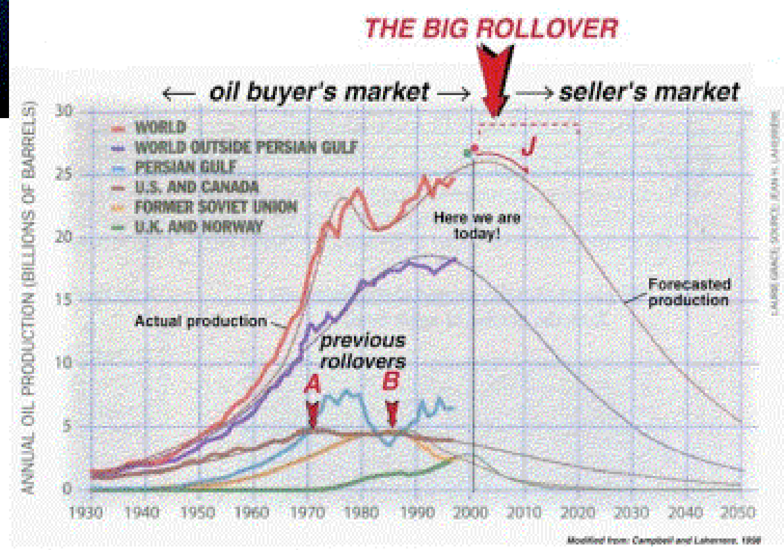


Based on IPCC 1990 [1]



Modified from Campbell and Laherrére (1998) by Les Magoon (affiliated w/ USGS) [2]

There are environmental and economic reasons for a transition from petroleum to cleaner, plentiful fuel. The relationship between temperature change and carbon dioxide concentration gives us alert to reduce our greenhouse emissions. The doubt about future oil production can cause international conflicts and unpredictable price fluctuations. Most estimates of the peaking of oil production (where supply meets demand) are between 2010 and 2020.



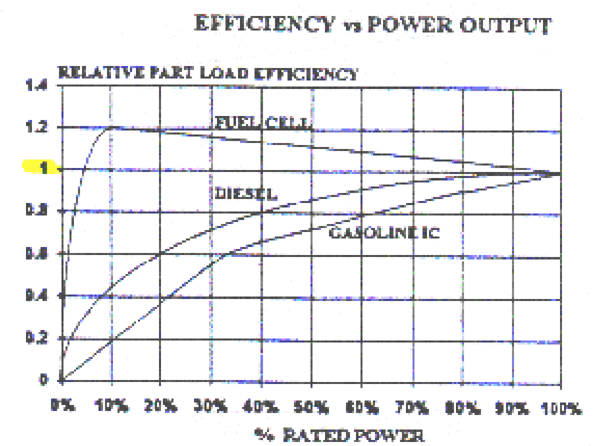
Modified from Campbell and Laherrère (1998) by Les Magoon (affiliated with USGS) [2]

Why hydrogen fuel cell?

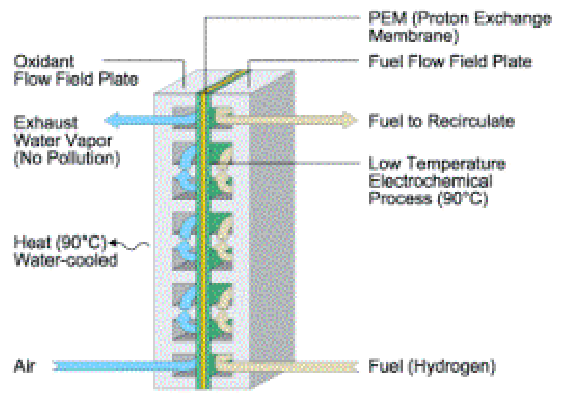
$$H_2 \Rightarrow 2H^+ + 2e^- \text{ (anode)}$$

$$2H^+ + 2e^- + \frac{1}{2} O_2 \Rightarrow 2H_2O + \text{electricity} + \text{heat (cathode)}$$

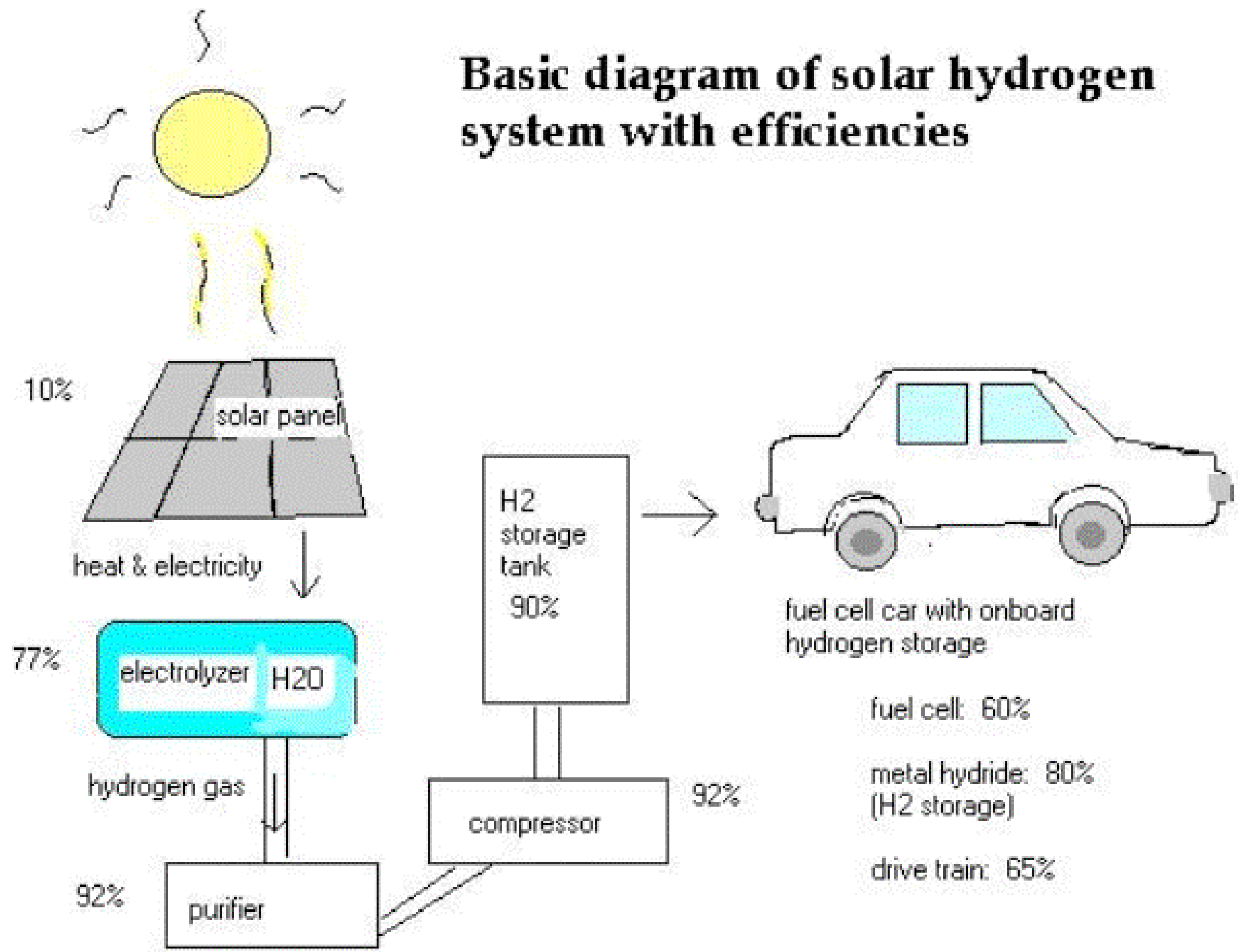
Above are the chemical reactions at the electrodes of a Proton Exchange Membrane (PEM) fuel cell. A fuel cell is an electrochemical device that conducts positive charges through the electrolyte and routes the negative charges through an external circuit before combining them at the cathode to form the byproducts. A fuel cell is more efficient than the internal combustion engine (ICE) because it doesn't rely on heat to produce mechanical power. The ICE efficiency increases when the difference in temperature between the heat source and heat sink increases. However, most of this heat is dissipated to the external environment.



Above is the load profile of an automobile during use. Since the automobile operates with 15-25% rated power most of the time, the fuel cell is more efficient than diesel or gasoline internal combustion engine. [3]

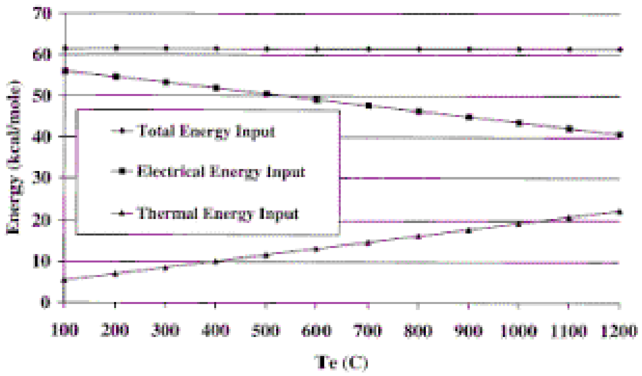


Above is a PEM fuel cell as described by Ballard Power Co. The PEM is one of several fuel cell types. The PEM is most suitable for transportation because it operates at 80 degrees Celsius and has quick response under varying load conditions. [4]



Above is what a solar hydrogen system might look like at present day. Efficiencies (especially for solar panels fuel cells, and hydrogen storage) will improve over time.

Solar module & electrolysis



Relationship between electrical energy and thermal energy requirements for electrolysis at different steam temperatures. [5]

$$H_2O \Longrightarrow H_2 + \tfrac{1}{2}\, O_2$$

The electrolysis of water requires about 68.3 kcal (286 kJ) per kmol of water. Less energy is required for steam. This energy can come from electricity and thermal energy. If the heat from the surface of the solar cells can be recovered, the amount of electricity required to electrolyze the water decreases.

Hydrogen storage & fuel cell

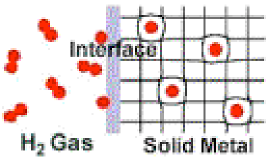
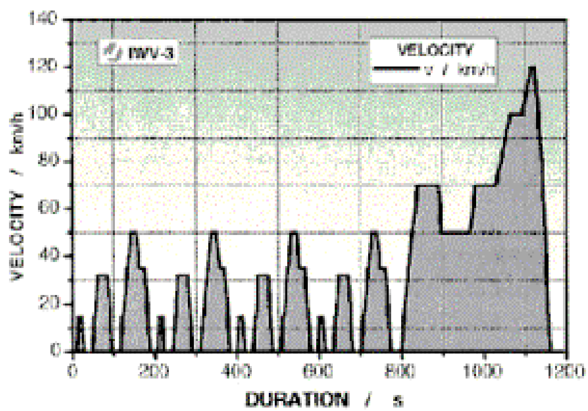


Diagram from Energy Conversion Devices, Inc. The H_2 gas takes up the unfilled electron shells of the solid metal, releasing heat. Energy Conversion Devices' metal hydride uses mainly magnesium metal and some nickel. A catalytic heater inside the metal hydride combusts the hydrogen to provide the necessary heat to release the hydrogen gas. [6]

Hydrogen gas can be stored in metal hydrides which decreases the amount of system volume needed. Currently, up to 0.07 kg of hydrogen can be stored in 1 kg of metal. The same size of metal hydride as of a 12 gallon gasoline tank (400 mi. range) can store enough energy to propel a 70 mpg-gas equivalent fuel cell vehicle for the same range. Cost and weight are barriers in its commercial introduction.

Parameters of fuel cell car

Weight	1200 kg (test drive)
Drag coefficient	0.30
Rolling resistance	0.008
Frontal area (cross-sectional)	2 m^2
At wheel energy requirement	35 MJ/ 100 km or 57 MJ/100 mi. (NEDC)
Range	400 mi.



Profile of automobile speed during New European Driving Cycle (NEDC) [7]

Energy requirements - calculations

d = Miles per year driven: 12,000

e = energy requirement at wheel: 570,000 J/mi.

s = avg. solar insolation per day: 5.1 kWh/m^2 (Atlanta, GA; fixed, tilted at same degree as latitude of location)

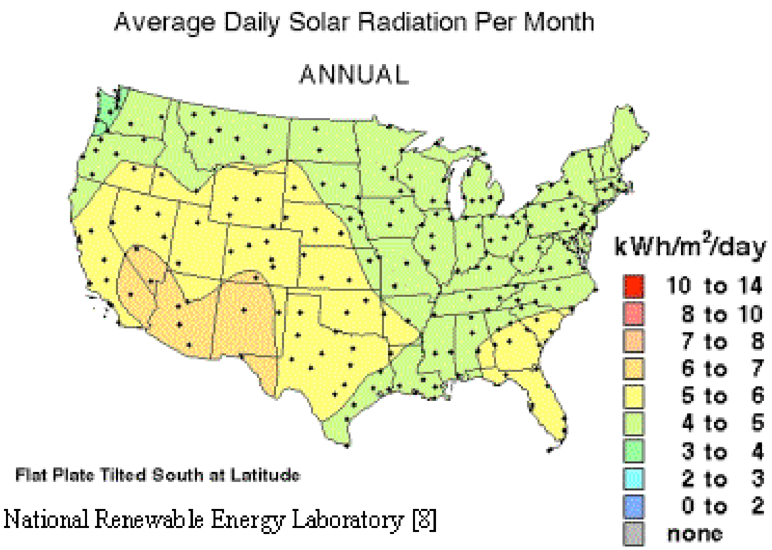
η_A = total system efficiency from solar energy capture to fueling stating hydrogen storage (solar hybrid electrical energy/heat conversion, coupling, electrolyzer, purification, compression) ~ 0.054

η_B = total system efficiency from onboard hydrogen storage to at wheel drive (onboard hydrogen storage, fuel cell, subsystem, electric engine & gear unit, peak battery) ~ 0.33

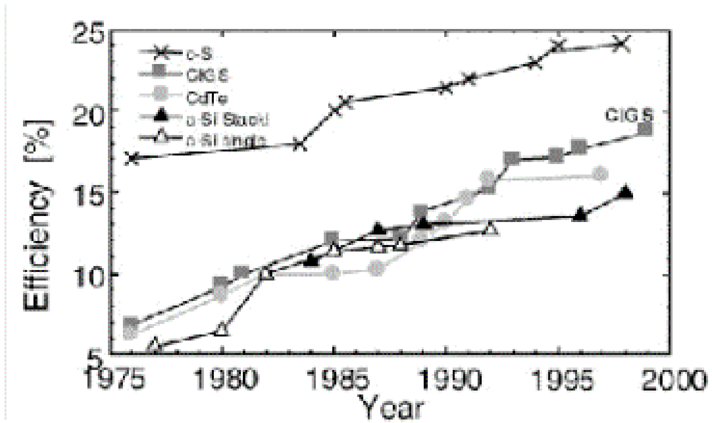
g = lower heating value of gallon of gasoline: 121.6 MJ

gas mileage equivalent (mpg)= (η_B g)/e ~ 70 mpg

Solar area requirement for fuel cell vehicle



National Renewable Energy Laboratory [8]



[9]

Calculations

solar area required (m^2) = (de)/(1.314 x 10^9 s η_A η_B)

70 mpg fuel cell car; 12 000 miles/year; Atlanta, GA; hybrid electrical/heat solar module; fixed flat plate tilted as same as latitude of location

10% solar module efficiency ~ 58 m^2

15% " " " ~ 39 m^2

20% " " " ~ 28 m^2

*** The calculations are based upon assumption that solar hydrogen fuel cell vehicle is similar to conventional passenger vehicles at approx. 1200 kg. Passenger volume may or may not be sacrificed.

The graph on left shows the improvement of efficiencies of solar cells over time. Efficiency is usually sacrificed in manufacturing in favor of lower grade, cheaper materials.

Greenhouse gas production from current methods

Greenhouse gas (GHG) emissions from manufacture of solar cells using conventional electricity

Crystalline solar cell average life span of solar module: 20 years

energy required to produce 1 m^2 of solar material: 600 kWh [26]

production of GHG per 1 kWh: 0.155 kg carbon equivalent (derived from avg. calculated from all electricity generated in U.S.)

GHG produced for production of 58 m^2 (10% solar cell eff.) : 5,400 kg carbon equivalent

" " 39 m^2 (15% solar cell eff.): 3,600 kg carbon equivalent

avg. amount emitted per year over life span of 20 years (10%): 270 kg carbon equivalent

" " " (15% solar cell eff.): 180 kg carbon equivalent

Greenhouse gas emissions (carbon equivalent) from using gasoline

2000 Honda Civic

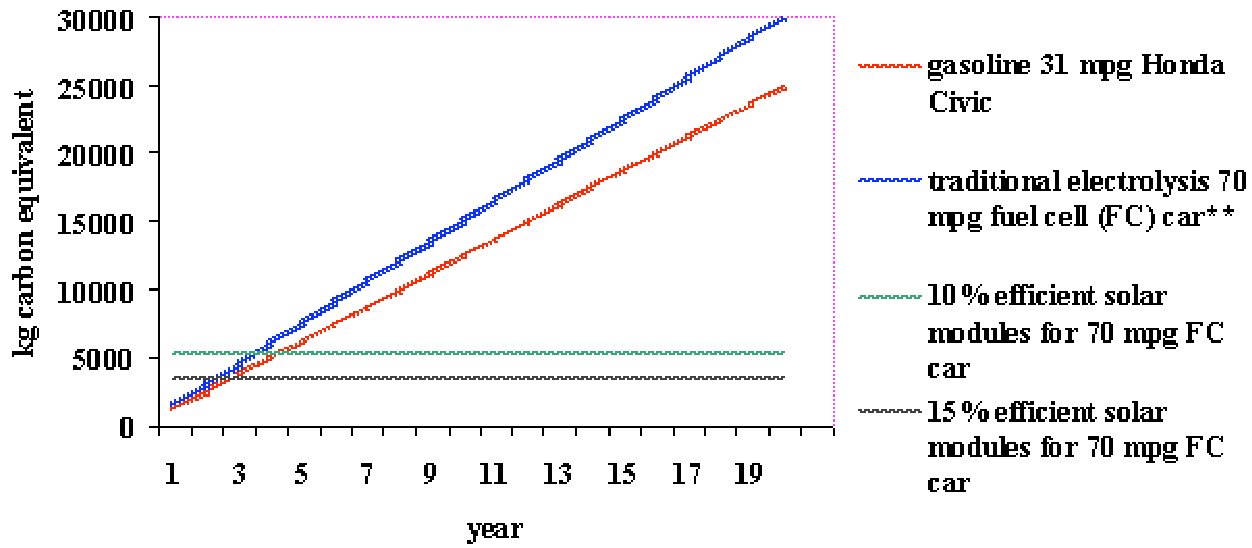
fuel economy: 31 mpg

greenhouse gas production from gasoline use (production, refining, distribution, and end use in automobile): 3.3 kg carbon equivalent per 1 gallon of gasoline

total GHG emissions (full fuel cycle) for 12,000 miles a year: 1, 250 kg carbon equivalent

Note: GHG emissions can be reduced by using recycled silicon wafers from the microelectronics industry. These calculations are based upon current electricity, of which 50% is from coal. If renewable energy is used, less GHG emissions would be produced during solar cell manufacture.

Greenhouse gas production if no change in production sources

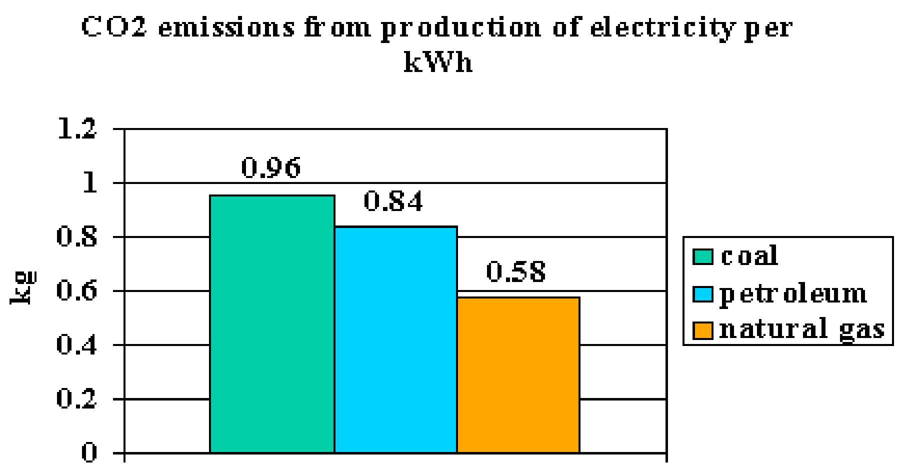


Based upon 12,000 miles of travel a year; emissions not including manufacture of car; emissions for gasoline is full fuel cycle

** Reg. Electrolysis numbers calculated from 70 mpg FC car, 77% electrolyzer efficiency, 92% purifier, 92% compressor, and 90% fueling station hydrogen storage efficiency

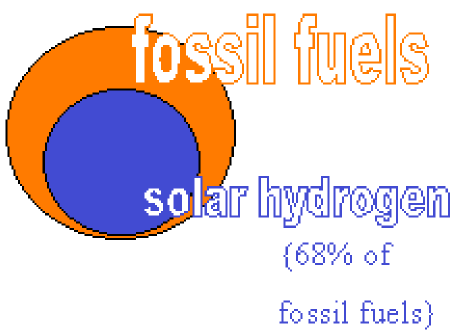
Note: using conventional electricity for electrolysis to get hydrogen for a 70 mpg fuel cell vehicle would produce more greenhouse gases than a 31 mpg gasoline automobile. Cleaner electricity sources will have to be used to justify electrolysis for transportation applications.

Greenhouse gas production



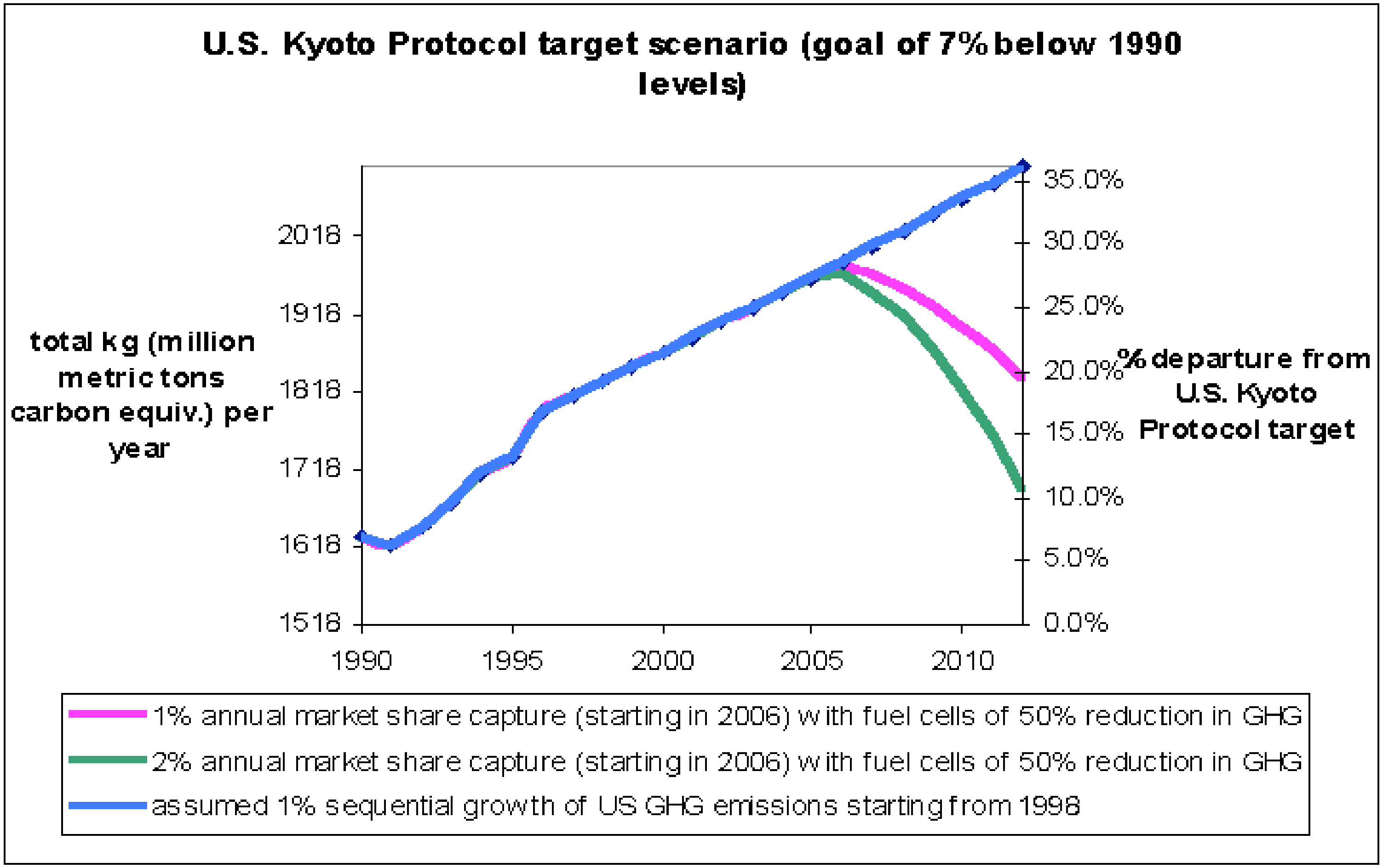
[10]

Water vapor generation



Solar cells
Wind turbines

Solar power and wind power don't directly produce greenhouse emissions. But until renewable energy is widely used, conventional electricity has to be used to produce the solar modules and wind turbines. Over 50% of electricity produced in the U.S. comes from coal. As shown on the right, coal use produces the most CO_2 of all fuels. Wind turbines displace the CO_2 production in its manufacture in 3 or 4 months in use. For solar cells for home electricity, it takes 3 to 4 years to payback the CO_2 emissions. For eventual use in solar hydrogen - fuel cell automobiles, it would take 4 to 5 years, as of present. The time can be drastically cut by a factor of two or more when manufacturing techniques improve.



Transportation produces 26% of the United States greenhouse gases. Electric utilities produce 30%. The line graph above shows the effect of commercial adoption of fuel cells (with average 50% reduction in GHG) on US emissions. Fuel cells in stationary applications will be commercially adopted in 2002. Fuel cell automobiles should be available by 2005. The cases above assume that fuel cells will adopt 1% or 2% of market share (transportation and electricity production combined) annually, beginning in 2006. The U.S. Kyoto Protocol target is 7% below 1990 levels by 2008-2012, approx. 1520 million metric tons carbon equivalent.

Conclusions

Solar hydrogen systems are an answer to reducing greenhouse emissions. They will have the most significant impact for homes, then vehicles. Since conventional electricity comes from mainly coal, replacing it with a renewable energy source will cause a drastic reduction in greenhouse gases. For fuel cell vehicles, solar hydrogen systems will payback their CO_2 emissions (for production of solar modules) within 4 to 5 years, considering the current 10% average efficiency of solar modules. Over the lifespan of 20 years, overall greenhouse emissions would be about 1/5 that of gasoline use. When manufacturing techniques and solar module efficiencies improve, solar hydrogen systems will have a much greener impact over gasoline for automobiles. Also, greenhouse emissions can be reduced during the production of solar modules by using cleaner electricity such as solar or wind power. In order to achieve the most environmental benefit from using hydrogen, clean renewable energy has to be used throughout its production process.

COST $$

Solar modules make up the majority of the cost of a solar hydrogen system. Currently, solar modules produce on average of $0.21 per kWh over their life span. To be cost-competitive with fully taxed gasoline, solar module costs would have to be cut by a factor of 7 or to $0.03/kWh for a home refueling station. For larger fueling stations, solar module cost would have to be reduced by a factor of 4 or to $0.05/kWh. (Thomas and Kuhn) [11]

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