Hydrogen Economy

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A hydrogen economy is a hypothetical future economy in which the primary form of stored energy for mobile applications and load balancing is hydrogen (H_2). In particular hydrogen is proposed as a fuel to replace the gasoline and diesel fuels currently used in automobiles.

The hydrogen fuel cycle to be implemented by the hydrogen economy. Contents

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The present

Hydrogen production is a large and growing industry. Globally, about 50 million metric tons of hydrogen were produced in 2004; the growth rate is about 10% per year. The energy in the current flow corresponds to about 200 gigawatts. Within the U.S., production was about 11 million metric tons, or 48 GW (10.8% of the average U.S. total electric production of 442 GW in 2003). Because hydrogen storage and transport are so expensive, most hydrogen is currently produced locally, and used immediately, generally by the same company producing it. As of 2005, the economic value of all hydrogen produced is about $135 billion per year.

48% of current hydrogen production is from natural gas, 30% is from oil, 18% is from coal, and electrolysis accounts for about 4%.

There are two primary uses for hydrogen today. About half is used to produce ammonia (NH_3) via the Haber process, which is then primarily used directly or indirectly as fertilizer. The other half of current hydrogen production is used to convert heavy petroleum sources into lighter fractions suitable for use as fuels. This latter process is known as hydrocracking.

Because the world population and the intensive agriculture used to support it are both growing, ammonia demand is growing. Hydrocracking represents an even larger growth area, as rising oil prices encourage oil companies to extract poorer source material, such as tar sands and oil shale. [edit]

The short-term future

The large market and sharply rising prices have also stimulated great interest in alternate, cheaper means of hydrogen production. One particular method that has gained considerable commercial interest and U.S. government funding is high-temperature thermochemical electrolysis of water (H_2O). Some prototype nuclear reactors operate at 850 to 1000 degrees Celsius, considerably hotter than existing commercial plants. Thermochemical electrolysis of water at these temperatures converts more of the initial heat energy into chemical energy (hydrogen), potentially doubling efficiency, to about 50%. Such electrolysis has been demonstrated in a laboratory, but not at a commercial scale.

The potential savings, just for the existing hydrogen market, could be substantial. General Atomics predicts that hydrogen produced in a High Temperature Gas Cooled Reactor (HTGR) would cost $1.53/kg. In 2003, steam reforming of natural gas yielded hydrogen at $1.40/kg, making the new scheme unattractive. At 2005 gas prices, hydrogen cost $2.70/kg, so a savings of tens of billions of dollars per year is possible with the nuclear-powered supply. Much of this savings would translate into reduced oil and natural gas imports.

One side benefit of a nuclear reactor that produces both electricity and hydrogen is that it can shift production between the two. For instance, the plant might produce electricity during the day and hydrogen at night, matching its electrical generation profile to the daily variation in demand. If the hydrogen can be produced economically, this scheme would compete favorably with existing grid energy storage schemes. What is more, there is sufficient hydrogen demand in the United States that all daily peak generation could be handled by such plants. [edit]

Rationale

Electricity has revolutionized the quality of human life since the late 19th century by enabling easier use of available energy sources. Inventions such as the dynamo and electric lighting sparked its growth on direct current. Later the alternator and alternating current enabled electric power transmission over long distances in a grand scale.

Currently, grid load balancing is done by varying the output of generators. However, electricity is hard to store efficiently for future use. The most cost-efficient and widespread system for large-scale grid energy storage is pumped storage, which consists of pumping water up to a dam reservoir and generating electricity on demand from that via hydropower. However such systems will not scale down to portable applications. Smaller storage alternatives such as capacitors have very low energy density. Batteries have low energy density and are slow to charge and discharge.

Around the time electricity started to come in use, another portable energy source was born. With internal combustion engines burning hydrocarbon fuels automobiles came into use. Internal combustion engines beat the competition at the time, such as compressed air, or electric automobiles powered by batteries, because they provided better range, by virtue of the efficiency of the internal combustion engine and high energy density of the hydrocarbon fuel. The high power-to-weight ratio of internal combustion engines also made it possible to build aircraft that have a higher density than air.

Present concerns regarding the long term availability of hydrocarbon fuels and global warming due to carbon dioxide (CO_2) tailpipe emissions have given rise to a search for an alternative to hydrocarbon fossil fuels which does not have these problems.

Some think that fuel cells, using hydrogen as a fuel, are tomorrow's equivalent to the internal combustion engines of old.

Hydrogen is the most abundant element in the universe. It also has an excellent energy density by weight, which leads to it being used for spaceships like the space shuttle. Emissions of a hydrogen-oxygen fuel cell, in theory, consist of pure water. The fuel cell is also more efficient than an internal combustion engine. [edit]

Envisioned centralized hydrogen sources

Large rural high efficiency generators combined with a distribution system (like the natural gas distribution system but able to meet hydrogen's additional transport challenges) and fuel cells that run on hydrogen might be able to replace today's electrical distribution and generation systems, and fuel vehicles. Similar systems are currently used with natural gas to produce electricity, such as large urban developents with cogeneration facilities. The energy source could be nuclear, or fossil fuel. Large generators that produced hydrogen from fossil fuel energy sources would generate huge amounts of pollution, but centralize emissions, so emission control systems would be easier to inspect and hence perhaps better maintained than systems on automobiles owned by individuals. However there are several technological "showstoppers" that stand in the way.

Unfortunately, pure hydrogen is not widely available on our planet. Most of it is locked in water or hydrocarbon fuels. It can be produced using other high-energy fuels, i.e. fossil fuels, but such methods require fossil fuels and generate CO2 to a greater extent than conventional engines. It can also be produced using huge amounts of energy and water. Nuclear power can provide the energy, but has well known disadvantages. Some 'Green' energy sources are capable of generating energy in a cost effective way if the externalities of conventional energy sources are factored in, but the policies of the world's major governments do not factor them in. This is called the production problem.

Hydrogen also has a poor energy density per volume. This means you need a large tank to store it, even when additional energy is used to compress it, and the high pressure compounds safety issues. The large tank reduces the fuel efficiency of the vehicle. Because it is a small energetic molecule, hydrogen tends to diffuse through any liner material intended to contain it, leading to the embrittlement, or weakening of its container. This is called the storage problem.

Other proponents envision local hydrogen sources, however the challenges large, rural high efficiency hydrogen generators face are far more acute when in an urban environment.

Fuel cells are still expensive. Some require expensive platinum group metals. Many have a low service life. They also used to be pretty bulky, but this is improving. Some think improved knowledge of nanotechnology and mass production will eventually solve this problem. [edit]

Production

The production and distribution of hydrogen for the purpose of transportation is being tested in limited markets around the world, particularly in Iceland, Germany, California, Japan and Canada. There are several processes which can yield hydrogen via water splitting using various energy sources at different efficiencies and costs. As of 2005, 48% of hydrogen production (for industrial processes) is from natural gas, 30% is from oil, 18% is from coal, and 4% is from electrolysis. [edit]

Fossil fuels [edit]

Steam reforming

Commercial bulk hydrogen is usually produced by the steam reforming of natural gas. At high temperatures (700–1100 °C), steam (H2O) reacts with methane (CH4) to yield syngas. CH4 + H2O → CO + 3 H2 [edit]

Carbon monoxide

Additional hydrogen can be recovered from the carbon monoxide (CO) through the lower-temperature water gas shift reaction, performed at about 130 °C: CO + H2O → CO2 + H2

Essentially, the oxygen (O) atom is stripped from the water (steam) to oxidize the carbon (C), liberating the hydrogen formerly bound to the carbon and oxygen. [edit]

Coal

Coal can be converted into syngas and methane, also known as town gas, via coal gasification. [edit]

Electrolysis

Electrolysis is an alternative to using fossil fuels directly to create hydrogen. The only requirements are electricity and water, and electrolysis produces just hydrogen and oxygen, assuming the water is pure and non-reactive electrodes are used. However, electricity is much more expensive per unit of energy than methane, and hence the process is uneconomic for large scale production.

Research into high-temperature electrolysis may eventually lead to a viable process that is cost-competitive with natural gas steam reforming. In the high temperature electrolysis process, some of the energy is supplied in the form of heat, which is cheaper than electricity, and can be cheaper than natural gas. If a large enough fraction of the input energy is supplied in the form of heat, and if it is cheap enough, high-temperature electrolysis could be cheaper than steam reforming of natural gas.

An example of a CO2 emission-free system, possible with near-term technology, would be if renewable energy sources such as concentrated solar thermal power collectors and wind turbines were used to produce hydrogen from water, using high-temperature electrolysis. [edit]

Thermochemical production

Some thermochemical processes, such as the sulfur-iodine cycle, can produce hydrogen and oxygen from water and heat without using electricity. Since all the input energy for such processes is heat, they can be much more efficient than high-temperature electrolysis.

None of the thermochemical hydrogen production processes have been demonstrated at production levels, although several have been demonstrated in laboratories.

Many sources of high-temperature heat have been proposed. The most promising is a high temperature nuclear reactor. Concentrating solar collectors might also be used. Coal is not generally considered, because the syngas route is already reasonably efficient. [edit]

Other methods

- Nanotechnology research on photosynthesis may lead to more efficient direct solar production of hydrogen, or perhaps carbon dioxide neutral synthetic hydrocarbon fuels.
- Hydridic Earth theory suggests that hydrogen could be mined for. [edit]

Storage

Storage is the main technological problem of a viable hydrogen economy. Some attention has been given to the role of hydrogen to provide grid energy storage for unpredictable energy sources, like wind power. The primary difficulty with using hydrogen for grid energy storage is that converting power to hydrogen and back is not cheap.

Hydrocarbons are stored extensively at the point of use, be it in the gasoline tanks of automobiles or propane tanks hung on the side of barbecue grills. Hydrogen, in comparison, is quite expensive to store or transport with current technology. Hydrogen gas has good energy density per weight, but poor energy density per volume versus hydrocarbons, hence it requires a larger tank to store. A large hydrogen tank will be heavier than the small hydrocarbon tank used to store the same amount of energy, all other factors remaining equal. Increasing gas pressure would improve the energy density per volume, making for smaller, but not lighter container tanks (see pressure vessel). Compressing a gas will require energy to power the compressor. Higher compression will mean more energy lost to the compression step. Alternatively, higher volumetric energy density liquid hydrogen may be used (like the Space Shuttle). However liquid hydrogen is cryogenic and boils around 20.268 K (–252.882 °C or -423.188 °F). Hence its liquefaction imposes a large energy loss, used to cool it down to that temperature. The tanks must also be well insulated to prevent boil off. Ice may form around the tank and help corrode it further if the insulation fails. Insulation for liquid hydrogen tanks is usually expensive and delicate. Assuming all of that is solvable, the density problem remains. Even liquid hydrogen has worse energy density per volume than hydrocarbon fuels such as gasoline by approximately a factor of four. [edit]

Ammonia storage

Ammonia (NH3) can be used to store hydrogen chemically and then release it in a catalytic reformer. Ammonia provides exceptionally high hydrogen storage densities as a liquid with mild pressurization and cryogenic constraints. It can also be stored as a liquid at room temperature and pressure when mixed with water. Ammonia is the second most commonly produced chemical in the world and a large infrastructure for making, transporting and distributing ammonia already exists. Ammonia can be reformed to produce hydrogen with no harmful waste, or can mix with existing fuels and burned efficiently. Pure ammonia burns poorly and is not a suitable fuel for most combustion engines. Ammonia is very energy expensive to make. Existing infrastructure would have to be greatly enlarged to handle replacing transportation energy needs. Ammonia is a toxic gas at normal temperature and pressure and has a potent odor. [edit]

Metal hydrides

There are proposals to use metal hydrides as the carrier for hydrogen instead of pure hydrogen. Hydrides can be coerced, in varying degrees of ease, into releasing and absorbing hydrogen. Some are easy to fuel liquids at ambient temperature and pressure, others are solids which could be turned into pellets. Proposed hydrides for use in a hydrogen economy include boron and lithium hydrides. These have good energy density per volume, although their energy density per weight is often worse than the leading hydrocarbon fuels.

Solid hydride storage is a leading contender for automotive storage. A hydride tank is about three times larger and four times heavier than a gasoline tank holding the same energy. For a standard car, that's about 45 US gallons (0.17 m³) of space and 600 pounds (270 kg) versus 15 US gallons (0.057 m³) and 150 pounds (70 kg). A standard gasoline tank weighs a few dozen pounds (tens of kilograms) and is made of steel costing less than a dollar a pound ($2.20/kg). Lithium, the primary constituent by weight of a hydride storage vessel, currently costs over $40 a pound ($90/kg). Any hydride will need to be recycled or recharged with hydrogen, either on board the automobile or at a recycling plant.

Often hydrides react by combusting rather violently upon exposure to moist air, and are quite toxic to humans in contact with the skin or eyes, hence cumbersome to handle (see borane, lithium aluminium hydride). This is why such fuels, despite being proposed and vigorously researched by the space launch industry, have never been used in any actual launch vehicle.

Few hydrides provide low reactivity (high safety) and high hydrogen storage densities (above 10% per weight). Leading candidates are sodium borohydride, lithium aluminium hydride and ammonia borane. Sodium borohydride and ammonia borane can be stored as a liquid when mixed with water, but must be stored at very high concentrations to produce desirable hydrogen densities, thus requiring complicated water recycling systems in a fuel cell. As a liquid, sodium borohydride provides the advantage of being able to react directly in a fuel cell, allowing the production of cheaper, more efficient and more powerful fuels cells that do not need platinum catalysts. Recycling sodium borohydride is energy expensive and would require recycling plants. More energy efficient means of recycling sodium borohydride are still experimental. Recycling ammonia borane by any means is still experimental. [edit]

Synthesized hydrocarbons

An alternative to hydrides is to use regular hydrocarbon fuels as the hydrogen carrier. Then a small hydrogen reformer would extract the hydrogen as needed by the fuel cell. The problem is reformers are slow and given the energy losses involved plus the extra cost of the fuel cell you were probably better off burning it in a cheap internal combustion engine to begin with.

Direct methanol fuel cells do not require a reformer, but provide lower efficiencies and power densities compared to conventional fuel cells, although this could be counter balanced with the much better energy densities of ethanol and methanol over hydrogen. Alcohol fuel is a renewable resource.

Solid-oxide fuel cells can run on light hydrocarbons such as propane and methane with out a reformer, or can run on higher hydrocarbons with only partial reforming, but the high temperature and slow startup time of these fuel cells makes then prohibitive for automobiles. [edit]

Other methods

More exotic hydrogen carriers based on nanotechnology have been proposed, such as carbon buckyballs and nanotubes, but these are still in the early research stage. [edit]

Transportation

Hydrogen seems unlikely to be the cheapest carrier of energy over long distances in the near future. Advances in electrolysis and fuel cell technology have not addressed the underlying cost problem yet.

As of 2005, the cheapest method to move energy around the planet is in uranium by rail, but nuclear power has received negative responses. The next cheapest and currently most widely used is in the form of oil in a pipeline or supertanker, or coal by rail or bulk carrier vessel. Natural gas pipelines and liquified natural gas tankers are much more expensive in comparison, which explains why natural gas from Alaska's North Slope is currently reinjected into the ground rather than shipped to the lower 48 states where it would be worth a fortune. Electric power lines move energy at even higher cost than natural gas pipelines; therefore, power stations are generally located within 100 miles (160 km) of the loads they serve. Long-distance power lines are used to average out imbalances between local electrical supply and demand, by moving a small portion of the total electricity generated. For example, California burns an average of about 30 gigawatts of electricity, and has a north-south transmission capacity bottleneck (the 500 kV Path 15) of 5.4 gigawatts.

Hydrogen pipelines are unfortunately more expensive than even long-distance electric lines. Hydrogen is about three times bulkier in volume than natural gas for the same energy delivered, and hydrogen accelerates the cracking of steel (hydrogen embrittlement), which increases maintenance costs, leakage rates, and material costs. The difference in cost is likely to expand with newer technology: wires suspended in air can utilize higher voltage with only marginally increased material costs, but higher pressure pipes require proportionally more material. [edit]

Environmental concerns

48% of hydrogen gas is created through the natural gas steam reforming/water gas shift reaction method, outlined above. This creates carbon dioxide (CO2), a greenhouse gas, as a byproduct. This is usually released into the atmosphere, although there has also been some research into interning it underground or undersea.

Recently, there have also been some concerns over possible problems related to hydrogen gas leakage. Molecular hydrogen leaks slowly from most containment vessels. It has been hypothesized that if significant amounts of hydrogen gas (H2) escape. Hydrogen gas may, due to ultraviolet radiation, form free radicals (H) in the stratosphere. These free radicals would then be able to act as catalysts for ozone depletion. A large enough increase in stratospheric hydrogen from leaked H2 could exacerbate the depletion process. However, the effect of these leakage problems may not be significant. The amount of hydrogen that leaks today is much lower (by a factor of 10-100) than the estimated 10%-20% figure conjectured by some researchers; in Germany, for example, the leakage rate is only 0.1% (less than the natural gas leak rate of 0.7%). At most, such leakage would likely be no more than 1-2% even with widespread hydrogen use, using present technology. Additionally, present estimates indicate that it would take at least 50 years for a mature hydrogen economy to develop, and new technology developed in this period could further reduce the leakage rate. [edit]

Consumption [edit]

Chemical feed

Hydrogen is used in chemical reactions - the Haber process and hydrocracking - as described in "The present" above. [edit]

Energy source

The underlying premise of a hydrogen economy is that fuel cells will replace internal combustion engines and turbines as the primary way to convert chemical power into motive and electrical power. The reason to expect this changeover is that fuel cells, being electrochemical, can be more efficient than heat engines. Currently, fuel cells are very expensive, but there is active research to bring down fuel cell prices.

Fuel cells work with hydrocarbon fuels as well as pure hydrogen. If and when fuel cells become cost-competitive with internal combustion engines and turbines, one of the first adopters will be large gas-fired powerplants. These are currently being built in large numbers by a highly competitive industry, their owners can work with operational constraints (tight temperature ranges, low shock, slow power ramps, etc), power to weight is not an issue, and even small efficiency gains are worth quite a lot. If reforming natural gas into hydrogen and then using that hydrogen in a fuel cell is somehow more efficient than burning the natural gas, gas-fired powerplants will do that instead. But there is no known "serious" discussion of fuel-cell powerplants.

Much of the popular interest in hydrogen seems to attach to the idea of using fuel cells in automobiles. The cells can have a good power-to-weight ratio, are more efficient than internal combustion engines, and produce no damaging emissions. If cheap fuel cells can be manufactured, they may be economically viable in an advanced hybrid automobile (hybrid in the sense of fuel-cell/battery combination).

So long as methane is the primary source of hydrogen, it will make more sense to fill specialized car tanks with compressed methane and run the fuel cells directly off that. The resulting system uses the methane energy more efficiently, produces less total CO2, and requires less new infrastructure. A further advantage is that methane is much easier to transport and handle than hydrogen. Methane used for fuel cells cannot have traces of methanethiol or ethanethiol, which are smelly chemicals injected into natural gas distributions to help users find leaks. The sulfur component of the odorant will destroy the membranes of the fuel cell. Since the technology for running internal combustion engines directly from methane is well developed, low polluting, and leads to long engine life, it is more likely that compressed natural gas (CNG) will be used for transportation in this way rather than in fuel cells for the near future. [edit]

Problems

The most common way to store hydrogen, and really the only way to do it efficiently is to compress it to around 10,000 PSI. Many people believe that the energy needed to compress the gas is one of the major faults in the idea of a hydrogen based economy. For example, if one considers the entire world using hydrogen just in their cars, then a massive amount of energy would be needed to be compressed and stored. Thus, if it were not used in any way, the net energy used to compress it would be wasted. These types of fuel cells are very expensive, typically 100 times more expensive per kW output than conventional internal combustion engines. It has further been suggested that cars powered by Li-on or Li-polymer batteries are capable of being more efficient than hydrogen-based cars would ever be, and that they just need to be mass produced to become cost effective. [edit]

Examples

Several domestic US automobile manufactures have committed to develop vehicles using hydrogen. (They had previously committed to producing electric vehicles in California, a program now defunct at their behest.) Critics argue this "commitment" is merely a ploy to sidestep current calls for increased efficiency in gasoline and diesel fuel powered vehicles.

Some hospitals have installed combined electrolyzer-storage-fuel cell units for local emergency power. These are advantageous for emergency use due to their low maintenance requirement and ease of location compared to internal combustion driven generators.

The North Atlantic island country of Iceland has committed to becoming the world's first hydrogen economy by the year 2050. Iceland is in a unique position: at present, it imports all the petroleum products necessary to power its automobiles and fishing fleet. But Iceland has large geothermal and hydroelectric resources, so much so that the local price of electricity actually is lower than the price of the hydrocarbons that could be used to produce that electricity.

Iceland already converts its surplus electricity into exportable goods and hydrocarbon replacements. In 2002, it produced 2000 tons of hydrogen gas by electrolysis, primarily for the production of ammonia (NH3) for fertilizer. Ammonia is produced, transported, and used throughout the world, and 90% of the cost of ammonia is the cost of the energy to produce it. Iceland is also developing an aluminum-smelting industry - aluminum costs are primarily driven by the cost of the electricity to run the smelters. Either of these industries could effectively export all of Iceland's potential geothermal electricity.

But neither directly replaces hydrocarbons. Reykjavik has a small pilot fleet of city busses runing on compressed hydrogen [1], and research on powering the nation's fishing fleet with hydrogen is underway. For practicality, Iceland may end up processing imported oil with hydrogen to extend it, rather than to replace it altogether.

A pilot project demonstrating a hydrogen economy is operational on the Norwegian island of Utsira. The installation combines wind power and hydrogen power. In periods when there is surplus wind energy, the excess power is used for generating hydrogen by electrolysis. The hydrogen is stored, and is available for power generation in periods where there is little wind.

The Hydrogen Expedition is currently working on creating a hydrogen fuel cell-powered ship and using it to circumnavigate the globe, as a way to demonstrate the capability of hydrogen fuel cells. [edit]

See also

- Future energy development
- Hydrogen car
- Amory Lovins
- Rocky Mountain Institute
- Sabatier process
- Grid energy storage
- Methanol economy [edit]

External links

- European Fuel Cell Forum - Papers by a set of fuel cell engineers, many concerning the hydrogen economy.
- 20 Hydrogen myths - Published by the Rocky Mountain Institute, a major hydrogen economy proponent.
- Transmitting 4,000MW of New Windpower from North Dakota to Chicago: New HVDC Electric Lines or Hydrogen Pipelines - Paper study comparing projected costs.
- Hydrogen Use - News about the use of hydrogen as a clean fuel.
- FreedomCAR - U.S. hydrogen powered car initiative.
- Hydrogen Pathways Program - Hydrogen transportation research and graduate program at the Institute of Transportation Studies at UC Davis.
- Hypercar Concept
- PolyFuel - Commercial methanol fuel cell technology.
- www.physicstoday.org article - Summary of avenues of research into lower-cost hydrogen production, better storage, and lower-cost fuel cells.
- Bottling the hydrogen genie - Article from The Industrial Physicist.
- Article advocating the use of nuclear power to produce hydrogen
- "Boron: a better energy carrier than hydrogen?" paper by Graham Cowan
- The Hydrogen Expedition - an organization attempting to circumnavigate the globe in a hydrogen-powered ship.
- NOVA scienceNOW - A 14 minute video of the NOVA broadcast about hydrogen fuel cell cars that aired on PBS, July 26, 2005. Hosted by Robert Krulwich with guests, Ray and Tom Magliozzi, the Car Talk brothers.
- Hydrogen Hopes - Scientific American Frontiers
- Shell's hydrogen powered bus in Amsterdam [edit]

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