HYDROGEN FUTURE: FACTS AND FALLACIES

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Introduction

Every now and then there have been alarming statements regarding the availability of fossil fuels especially on the liquid and gases fossil fuels. Based on the Reserve to production (R/P) ratio calculation, the estimates have been indicating only to the extent of a few decades. Secondly the situation in the oil producing countries (the so called Middle East) and Asia is creating instability for the future reliability of oil. The idea of using hydrogen- the simplest, lightest and possibly the most abundant element in the universe- as a primary form of energy is the cause for the concept of hydrogen economy.

The equation, hydroen + air = electricity + water is certainly fascinating. The conversion of hydrogen back to its natural state (water) is clean but how benigh is the fabrication and distribution of this synthetic energy carrier. However there are still many unanswered questions regading an economy based on hydrogen as energy carrier. They are:

(i) How much energy has to be expanded to split water than the theromodynamic reversible voltage to generate hydrogen?
(ii) How much energy is really consumed to make, package, distribute and transfer hydrogen?
(iii) From where does this energy come from?
(iv) How efficient is the distribution of the lightest thus most impractical of all energy gas?
(v) How much energy is needed to run a hydrogen economy?
(vi) Can the society afford such a wasteful hydrogen economy at all?

After all any new energy technology must be based on a sound platform of science, engineering and economics. It is generally presumed that the creation of a sustainable hydrogen infrastructure with a focus on fuel cells as the delivery mechanism is one of the better options available today. This emphasis is due to the fact tha the world needs a secure and equidistributable future supply of clean energy and hydroen appears to be a logical choice from the point of view of abudance. However, this logic obfuscates a number of important points and is based on some potentially slippery foundations. A key issue that is often not addressed when fuel cells and the hydrogen economy is mentioned – is where will the hydrogen actually come from? Hydrogen is only an energ carrier and not a freely available natural resource in any useale form just like the other energy carrier electricity, it needs to be produced some how. There is no dispute that hydrogen offers major benefits to the world economy and environment. Its use in transportation reduces the emission of NO_x, and SO_x pollutants, which offer significant air quality advantages in urban areas. This cannot be claimed as an advantage if hydrogen is produced from fossils, since the polluting source is shifted from tail pipe to the original source of hydrogen production.

With the exception of sequestration, it is agreed that hydrogen can never be totally clean unless it is electrolyzed using a so called renewable enegy technology such as wind turbines or solar panels. Despite losses in conversion efficiency, fuel cells also offer load levelling possibilitiesthat may bode well for renewables. Secondly this will lead to a decentralised power distribution system from the current centralised power supply system.

The hydrogen economy movement started in 1974 and from then on a variety of accomplishments have been achieved – from the acceptance of the concept as an answer to energy and environment related global problems – to research, development and commercialisation. Varieties of initiatives have been taken and a simple summary is given in **Table 1**.

Table 1 Developments in Hydrogen Movement from 1974.

Activities	Details
International conferences	THEME conference, 1974 1 WHEC, Miami Beach, 1976 2 WHEC, Zurich, 1978 3 WHEC, Tokyo, 1980 4 WHEC, Pasadena, 1982 5 WHEC, Toronto, 1984 6 WHEC, Vienna, 1986 7 WHEC, Moscow, 1988 8 WHEC, Honolulu,1990 9 WHEC, Paris,1992 10 WHEC, Cocoa Beach,1994 11 WHEC, Stuttgart, 1996 12 WHEC, Buenos Aires, 1998 13 WHEC, Beijing, 2000 14 WHEC, Montreal, Canada, 2002 15 WHEC, Yokohama, Japan, 2004 16. WHEC, Lyon, 2006 17. WHEC, Brishbane 2008 18. WHEC, Essen, 2010 19. WHEC, Toronto, 2012
Some organizations dedicated to Hydrogen Energy	Internatioanl association of Hydogen enegy HESS (Japan) National Hydrogen Association (USA) American Hydrogen Association Canadian Hydrogen association

	China Hydrogen Association German Hydrogen Association Indian Hydrogen Association Italian Hydrogen Association Koean Hydrogen Association Mexican Hydrogen Association Swedish Hydrogen Association Turkish clean Energy Association Clean air Now (USA) WCTE-CMDC (Switzerland) and many other countires have multiple associations.
Some periodicals on Hydrogen Energy	Int.J.Hydrogen Energy Hydrogen information (France) HESS Journal (Japan) The hdyrogen and fuel cell letter (USA) Hydogen Today (USA) Fuel cells Bulletin (UK) EETE (Russia) and so on
Books on Hydrogen Energy	More than 40 voluems of the proceedings of WHEC and many other books in other languages
Visual programs on Hydrogen Energy	Beyond Tomorrow Element one Energy from water Fire in the water Hydrogen: One solution Hydrogen safety Invisible Flame The Dawn of Hydrogen Age The green Car Wake up USA and so on
Some internet sites	www.iahe.org www.dwv-info.de www.ttcorp.com/nha www.cleanair.org www.h2eco.org www.fuelcells.org www.hyweb.deindex.e.html www.eren.doe.govhydrogeninfonet.html
Some Companies and	Tokio Electric Utility, Kansai Electric Power, International Fuel Cells, Toshiba, Siemens/Westinghouse

organizations involved in hydrogen, fuel cell, electric power generation	Plug Power/GE, Fuel Cell Energy Corp., EPRI
Comapies invovled in Hydrogne-fuelled vehicles (Land Vehicles)	BMW, Daimler-Chrysler, Ford, General Motors, Ballard, Energy Partners, H-Power, ZEVCO, Mazda, Honda, Toyota, Nissan
Naval applicaion of hydrogen	German Navy, Australian Navy, Canadian Navy Italian Navy
Hydrogen in space programs	U.S.S.R, U.S.A, Russia, Europe, China, Japan, India
Hydrogen in Aerospace Planes	U.S. Shuttle, Russian Shuttle, European Sanger, National aerospace plane: Boeing, Lockheed, McDonnell Douglas' Rocket dyne, Rockwell International, Pratt& Whitney
Hydrogen in Air transportation	Grumman Cheetah (Conrad Plane) Tupolev 155 German-Russian Cooperation Airbus Program Japan-Hypersonic
Hydrogen-hydride applications	Products/Developments: Batteries, Computer batteries, Electric car batteries, Airconditioning, Refrigeration, Heat pumps, Hydrogen Storage
Hydrogen catalytic combustion applications	Products/Developments: Kitchen appliances, Cookers, Ovens, Water heaters, Space heaters Companies: Fraunhofer Institute, Hydrogen Appliances

Hydrogen is not a new source of energy but merely another energy carrier. Like electricity, it provides a link between an energy source and energy consumers. The energy source may be a chemical energy carrier such as natural gas, coal, and ooil or electricity. With few exceptions, the conversion of fossil fuels into hdyrgen i.e., the transfer of chemcial energy from one substance to another can not improve overall efficienty or reduce the emission of greenhouse gases.

Energy carrier: Electrons versus Hydrogen

Renewable electricity appears more promising source of energy for the future. Like electricity from decentralized cogeneration, renewable electricity will be generated near consumers' sites to minimize transmissionlosses. Excess power generated will be supplied to the grid. Electrolysis and fue ol cells may be used for temporary energy storage with hydrogen, but for overall efficiency, renewable electricity will be transmitted directly by electrons and not by synthetic chemcial energy carriers. Today around 10% of electrical energy is lost by optimized power transmission between power plant and consumer. This figure can be lower or higher for shorter or longer transmission distances. However, if renewable electricity is converted to hydrogne and hydrogen is subsequently reconverted to electricity, then significantly more nergy is needed to drive the process. In fact only about 25% of the original electrical energy may be recovered by the consumer in stationary and mobile applications. At first glance, this may sound unbelievable, but the high losses are directly related to the two electrochemcial conversion processes and the difficulty of distributing the light energy carrier. Compared to the natural gas, packaging and distributionof hydrogen require more energy. The energy consumption associated with all significant stages of hydrogne economy was analyzed and the results surprised the hdyrogen community. The energy consumed at all the significant stages of a hydrogen economy is given in **Table 2**. For the values in this table, the energy losses are calculated using the true energy content of hydrogen, i.e., its higher heating value (HHV) of 142 MJ/kg. A hydrogen economy will be based on one or many optimized mixes of these stages. Hydrogne may be compressed to 100 bar for distribution to filling stations in piplelines and then compressed further to 850 bar for rapid trasfer inot pressure tanks of automobiles. Liquefaction may be preferred to compression in order to save transportaion energy or on site produciton of hdyrogen with less efficient electrolyzers.

Table 2 Energy consumed at stages of hydrogen economy (HHV: Higher Heating Value of Hydrogen)

Stage	Details	% of HHV	Energy consumed
AC-DC Conversion	-	5	Electricity
Electrolysis	-	35	Electricity
Compression	200 bar 800 bar	8 13	Electricity Electricity
Liquefaction	Small plants Large plants	50 30	Electricity Electricity
Chemical hdrides	CaH_2, LiH, etx	60	Electricity
Road tranport	200 km,200 bar 200 km liquid	13 3	Diesel fuel Diesel fuel
Pipeline	2000 km	20	Hydrogen
On-site generation	100 bar	50	Electricity
Transfer	100 to 850 bar	5	Electricity
Reconversion	Fuel cell, 50%	50	Hydrogen
DC-AC conversion	-	5	Electricity

The enegy cascade of a representation hydrogen option in comparison with energy transport by electrons is illustrated in **Fig.1.** Which ever scheme is chosen, a hydrogen economy will be extremely wasteful compared to today's energy system and to a sustainable energy future based on the efficient use of renewable energy, i.e., the direct use of electricity and liquid fuels from biomass.

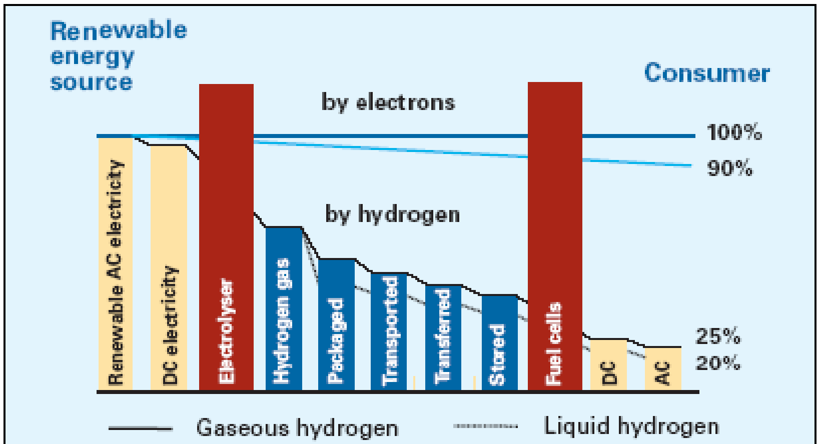

Figure 1. Energy cascade for energy transport by electrons and hydrogen

If one were to assume that the poowe routput of one of thw wind turbines is suppliede to a certain numbers of consumers by electrons i.e. by conventional electric power lines. If hydrogen is sued as the energy carrier, four wind turbines must be installed to provide these consumers with the same amount of energy. Essentially only on eof these wind turbines produces consumer benefits while the remaining three are needed to compensate the energy losses arising from the hydrogen luxury. Electrical power can be transmitted by a modestly upgraded version of the existing power distribution system. For energy transport by hydrogen, a new infrastructure must be established and in addition, the electricity grid must be extended to deliver power to all the active elements of the hydrogen infrastructure such as pumps and compressors, hydrogen liquefiers and on-site hydrogen generators.

Hence, a sustainable energy future will be based on renewable energy from various sources.With the exceptionof biomass, renewable energy is harvested as electricity, with solar, wind, hydro or ocean power plants. In addition, solar, thermal and geothermal power plants will also produce AC power. One may assume that 80% of the renewable energy becomes available as electricity while only 20% is derived from biomass or used directly for heating. This picture is acomplete reversal of today's scenario, which is characterized by 80% of energy being fossil-derived and only 20% coming from physical sources. Renewable energy will be precious and therefore should be distributed and used intelligently. Wasteful electrochemcial conversion processes such as electrolysis and fuel cells will be avoided whenever possible. Distribution losses will be minimized by local or regional energy solutions. Global energy exchange comparable to transporting oil around the world will not be practiced, because the transport of hydrogen requires too much energy compared to the low energy content of the transported commodity. This is true for the transport of the compressed or liquefied hydrogen by popelines, land vehicles and ships. In a sustainable future, nergy demand and supply will be matched by strict energy conservation in buildings, by reduced energy consumption in the transportation sector and by the use of electricity wherever and whenever possible.

Cost of Energy:

As a simple representation one can say that a customer receives only 50% o the orginal renewable electricity energy while hydrogen gas and that losses rise to 75% or higher when this hydrogen is converted back to electricity. Needless to say, the conversion is done by very efficient fuel cells. Today, natural gas prices serve as reference for the cost of electricity. Based on its energy content, grid power is about four times more expensive than natural gas. In a sustainable energy future electricity will be the price-setter. It will cost more than it does today, but it will be cheapest for of energy in the commerical market. Because of the enery losses associated with the hydrogen economy, the following energy price relations may be expected for electricity-derived hydrogen at filling stations, hydrogne will cost at least twice as much as electrical energy from the grid electricity from fuel cells will cost about four times as much as electricity from the grid. Consequently, for stationary applications such as space heating, natural gas will hardly ever be replaced by hydrogen, but small electric heaters and heat pumps will be used to condition well insulated buildings. Similarly, electaric cars may become the choice for short distance commuting, because electric power from an outlet in the garage will cost only half as much as hydrogen at the fule statin. Furthermore, the battery-to-wheel efficiency of electric cars is about 80% while the tank-to-wheel efficiceny o fuel cell cars can barely reach 40%, based on the higher heating value of hdrogen. The daily drive to work in a hydrogen fuel cell car will cost four times more than an electric or hybrid vehicle. The economica optimization clearly favours electric solutions.

Hydrogen eneconomy will be characterized by a massice increase of electric power needs. It is unlikely that this demand can be satisfed from renewable sources alone. Coal-fired and nuclear power plants will continue to be in use with all the known consequences for the environment and for safety. Therefore, before a hydrogen economy is established, the source of electric energ has ot be identified and developed. The installation of wind energ conversters, soloar power plants an dtidal power generators is essential for a sustainable energy future. Together with the rational use of energy renewable sources may be sufficient to match the reduced energy demand worldwide. However, it is unlikely; that renewable generation capacity can be stretched threefold to cover the losses of the hydrogen luxury. The conversion of electrical energy inot hydrogen is not wise at this time nor will it ever be.

Hydrogen and cogeneration

Presently, hydrogen is made from fossil fuels, i.e. from energy carriers also used in most cogeneration applications. There is no indiation that the hydrogen detour offers benefits over the direct use of hydrocarbons with respect to overall efficiency and greenhouse gas emissions. Recent well-to-wheel studies based on the true energy content of chemcial fuels, i.r. on HHV conclude that hydrogen is not a promising energy carrier. For years to come, hydrogen will not be able to beat natural gas with respect to overall efficiency, the environment and economy. Advanced hydrogen technolgoes such as fuel cells cannot compensate for the losses and energy consumption assocaited with hdyrgoen production and distribution. Polymer electrolyte fuel cell co-generators in the 200 kW class have hardly ever provided line power at lower heating value (LHV) efficency above 32%. Modern diesel engines, even micro-turbines, show better yields. But molten carbonate or solid xodie fuel cells may soon become a viable cogeneration technology. With modest fuel conditioning, these cells convert fossil fuels directly with up to 50% LHV electrical efficiency. They will compete with the conventional cogeneration equipment in a naturla gas economy. Although still too expensive, high-temperature fuel cells are clean converters of hydrocarbons into electicity. Also, high-temperature waste heat can be recovered easily for many uses. Future will witness the potential of cogeneration with high-temperature fuel cells. In a distant sustainable enegy future, with most renewable energy being harvested as electricity, the role of cogeneration must be redefined. Because of its energy efficiency, cogeneration will remain important for biomass-deried chemcial energy. This may incldue the conversion of digester ags, biogas, etc into power and heat. It may also include thermal energy obtained by combustion of wood waste, residues and farmed bio-mass in steam power plants. However, it is unlikely that hdyrogen will be produced from biomass or by electrolysis, to be subsequently converted to electricity in cogeneration facilities. Because of its inherent energy efficiency, cogenertion will continue to be one of the key power generation technologies in a sustainable energy economy. Whenever electricity is produced by Carnot processes, the unavoidable wasae heat will be utilized for space conditioning, hot water or industrial processes. Cogenration technology will be further developed and adapted to a variety of sustainable fuels from biomass.

Limitations of a Hydrogen Economy

All losses within a hydrogne economy are directly related ot the nature of hydrogen. Hence, they cannot be significantly reduced by any amount o fresearch and development. We have to accept that hydrogen is the lightest element and its physical properited do not suit the requirments of the energy market. The produciton, packaging, storage, transfer and delivery of the gas are so energy consuming that other solutions must be considered. We cannot afford to waste energy for uncertain benefits; the market economy will always seek practical solutions and as energy becomes more expensive, select the most energy-efficienty of all options. Judged by this criterion, a general Hydrogen economy can be difficult to become a reality although hdyorgen will gradually become more important as energy transport and storage medium. This presentation provides some clues for the strengths and weaknesses of hydrogne as an energy carrier. One can not deny that transporting hydrogen gas by pipeline over thousands of kilometers is difficult. Furthermore, one can not deny that compression or liquefaction of hydrogen and transport by trucks would incur large energy losses. However, hydrogen solutions may be viable for certain niche applications. For example in private buildings excess rooftop solar electricity may be used to generate hydrogen, store it at low pressure in stationary tanks for cogeneration with engines or fuel cells. Or surplus wind electicity may be stored as hydrogne for power generation during periods of calm. As stated at the beginning, hydogen generted by electrolysis may also be the best link between physical energy from renewable sources and chemcial energy. But it is questionable if hydrogen in its elemental form can ever become a dominating energy carrier.

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