HYDROGEN FUTURE: FACTS AND FALLACIES

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Abstract: A transition to a 'hydrogen economy' is a sea change in our energy infrastructure and is not to be taken lightly. As an energy carrier, hydrogen is to be compared to electricity, the only wide spread and viable alternative. When hydrogen is employed to transmit renewable electricity, only 50% can reach the end user due to losses in electrolysis, hydrogen compression and the fuel cell. The rush into a hydrogen economy is neither supported by energy efficiency arguments nor justified with respect to economy or ecology. In fact, it appears that hydrogen will not play an important role in a sustainable energy economy because the synthetic energy carrier cannot be more efficient than the energy from which it is made. Renewable electricity is better distributed by electrons than by hydrogen. Consequently, the hasty introduction of hydrogen as an energy carrier cannot be a stepping stone into a sustainable energy future. The opposite may be true. Because of the wastefulness of a hydrogen economy, the promotion of hydrogen may counteract all reasonable measures of energy conservation. Even worse, the forced transition to a hydrogen economy may prevent the establishment of a sustainable energy economy based on an intelligent use of precious renewable resources. This article is meant to direct attention to some fundamental problems of a Hydrogen Economy.

Key words: Hydrogen economy, hydrogen energy

Introduction

It is interesting to watch the growing debate over the future of energy. Many forecasts predict that the demand for energy will grow by 50 percent over the next two decades. Natural gas reserves are becoming a concern in many nations. The situation in the Middle East and Asia is to put it mildly, creating instability for the future reliability of oil. United States and Ontario has focused attention on problems with the grid that feeds our growing appetite for electricity. Continued technological advances in renewables and distributed generation options are new possibilities and options. The idea of using hydrogen - the simplest, lightest and most abundant element in the universe - as a primary form of energy is beginning to move from the pages of science fiction and into the speeches of industry executives. Greenery, innovation and market forces are shaping the future of our industry and propelling us inexorably toward hydrogen energy.

Consequently, hydrogen is the topic of the day. The 'Hydrogen Initiative' led politicians from many countries to follow suit without questioning the promises of the hydrogen enthusiasts. Hydrogen is presented as the ultimate solution to all energy problems. The equation: 'hydrogen + air = electricity + drinking water' is certainly fascinating. Representatives from industry or the public are seen on television drinking the drip-off from tail pipes of hydrogen fuel cell vehicles. Indeed, the conversion of hydrogen back to its natural state (water) is clean, but how benign is the fabrication and distribution of this synthetic energy carrier? Certainly, hydrogen is the most abundant element in the biosphere. Unfortunately, it appears only in chemical compounds such as hydrogen oxide, commonly known as water. More energy is needed to split water than can ever be retrieved from the generated hydrogen. How much energy is really consumed to make, package, distribute and transfer hydrogen? Where does the energy come from? How efficient is the distribution of the lightest, thus most impractical of all energy gases? How much energy is needed to run a hydrogen economy? Can we afford such a wasteful hydrogen economy at all? These questions need to be answered before investments are made in a hydrogen future. It will cost trillions of dollars to convert the entire energy system to hydrogen. Thus, it is simply due diligence to question the optimistic claims of the hydrogen promoters before tax money is spent on research, development and hardware. Any new energy technology must be based on a sound platform of science, engineering and economics.

World governments have committed billions of dollars/euros to the development of a hydrogen infrastructure, with a focus on fuel cells as the delivery mechanism. This decision to forge a transition to hydrogen has been made, and it is unlikely that the evolution could be stopped now, even if people wanted. The logic: the world needs a secure future supply of clean energy, and hydrogen is the most abundant element in nature. 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 are mentioned - is where will the hydrogen actually come from? Hydrogen is an energy carrier and not a freely available natural resource in any useable form - just like the other energy carrier electricity it has to be produced somehow. Advocates of renewable energy would be well advised to examine the issues and to ensure that solar and wind technologies are not over-looked or under-valued in the years to come as a source of hydrogen.

There is no dispute that hydrogen offers major benefits to the world economy and environment. Its use in transportation reduces the emission of NOx and SOx pollutants, which offers significant air quality advantages in urban areas. However, if the original source of hydrogen is produced from conventional sources such as fossils then in reality these emissions and other pollutants are technically just shifting from the tail pipe to the original source of hydrogen production.

Natural gas has been already referred as a ‘clean’ fuel (since it is ‘cleaner than coal’), so the use of gas as a feedstock for hydrogen means the resulting energy is ‘cleaner’ at point of consumption. With the exception of sequestration it is agreed that hydrogen can never be totally ‘clean’ unless it is electrolyzed using a renewable energy technology, such as wind turbines or solar panels. Despite losses in conversion efficiency, fuel cells also offer load levelling possibilities that may bode well for renewables. Few people forecast the use of fuel cells in centralized energy plexes, and it is safe to suggest that any paradigm shift which encourages society to break away from the mold of large centralized generating facilities in favor of distributed generation (DG) options is bound to encourage greater uptake of renewables.

Thirty years were passed since the beginning of the Hydrogen Energy Movement in 1974. Over the past three decades, there have been accomplishments on every front - from the acceptance of the concept as an answer to energy and environment related global problems - to research, development and commercialization. The Hydrogen Energy System has now taken firm roots. Activities towards the implementation are accelerating. The various activities and accomplishments over this period are listed in **Table. 1**. Hydrogen may yet to find an important place in our energy future. We are focusing on building the knowledge and capabilities that will be needed in the future should hydrogen enter the supply chain as a transportation fuel. However, the surge of interest in a ‘hydrogen economy’ is based on visions than on facts. Since, hydrogen economy would be based on two electrolytic processes both associated with heavy energy losses: electrolysis and fuel cells. For a secured energy future, we need new energy sources, not new energy carriers. Because the investment in infrastructure is substantial and therefore irreversible, it is important that the choice we make is a proper one for the future.

Unfortunately, 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 oil, or electricity. With few exceptions, the conversion of fossil fuels into hydrogen, i.e. the transfer of chemical energy from one substance to another, cannot improve overall efficiency or reduce the emission of greenhouse gases. Carbon dioxide is released into the atmosphere when natural gas is reformed to hydrogen or when natural gas is burnt in furnaces. Hydrogen is clean only if it is made from renewable electricity. However, electricity from any source, conventional or renewable, can be transmitted to the consumer by power lines, pollution-free and with a relatively high efficiency. So why use electricity to split water by electrolysis, spend more electricity to package hydrogen by compression or liquefaction to make it marketable, use energy to distribute it to the consumer and convert it back, with considerable losses, to electricity in stationary or mobile fuel cells? In a sustainable future, cheaper power will come from the grid. Also, renewable electricity will soon replace fossil fuels which are now used for stationary power generation or space conditioning. The replaced oil will probably be sold at fuelling stations to power vehicles. For many years this substitution process will dominate the transition within the energy market from stationary to mobile applications of fuels. The most important source of petroleum fuel will be the improvement of building thermal standards. For years to come, hydrogen has to compete with replaced fossil fuels. But will hydrogen be a promising option after the depletion of oil wells, when renewable energy has become abundant?

Energy carrier: Electrons vs. 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 transmission losses. Excess power generated will be supplied to the grid. Electrolysis and fuel cells may be used

Table 1. Developments in Hydrogen Movement from 1974 - 2004

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
Concepts	Acceptance of Hydrogen Energy, Hydrogen Economy & Hydrogen Energy System
Organizations dedicated to Hydrogen Energy	I.A.H.E, H.E.S.S. (Japan) National Hydrogen Association (USA) American Hydrogen Association Canadian Hydrogen Association China Hydrogen Association German Hydrogen Association Indian Hydrogen Association Italian Hydrogen Association Korean Hydrogen Association Mexican Hydrogen Association Swedish Hydrogen Association Turkish Clean Energy Association Clean Air Now (USA) WCTC-CMDC (Switzerland)
Periodicals on Hydrogen Energy	Int. J. Hydrogen Energy Hydrogen Information (France) H.E.S.S. Journal (Japan) The Hydrogen & Fuel cell letter (USA) Hydrogen Today (USA) Fuel Cells Bulletin (U.K) E.E.T.E. (Russia)
Books on Hydrogen Energy	Proceedings: WHEC (>40 Vols) Books in: English, Japanese, German, Russian, French, Italian, Spanish, Polish, Portuguese, Turkish, etc.,
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, U.S.A
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
Companies and Organization involved in Hydrogen, Fuel Cell Electric Power Generation	Tokio Electric Utility, Kansai Electric Power, International Fuel Cells, Toshiba, Siemens/Westinghouse Plug Power/GE, Fuel Cell Energy Corp., EPRI
Companies involved in Hydrogen-Fuelled Vehicles (Land Vehicles)	BMW, Daimler-Chrysler, Ford, General Motors, Ballard, Energy Partners, H-Power, ZEVCO, Mazda, Honda, Toyota, Nissan
Naval Application 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, Air-conditioning, Refrigeration, Heat pumps, Hydrogen Storage
Hydrogen Catalytic Combustion Applications	Products/Developments: Kitchen appliances, Cookers, Ovens, Water heaters, Space heaters Companies: Fraunhofer Institute, Hydrogen Appliances

for temporary energy storage with hydrogen, but, for overall efficiency, renewable electricity will be transmitted directly by electrons and not by synthetic chemical energy carriers. Today, around 10% of electrical energy is lost by optimized power transmission between power plant and consumer. This figure is lower for shorter transmission distances. However, if renewable electricity is converted to hydrogen, and hydrogen is subsequently reconverted to electricity, then significantly more energy 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 electrochemical conversion processes and the difficulty of distributing the light energy carrier. Compared to natural gas, packaging and distribution of hydrogen requires much more energy. The energy consumption associated with all significant stages of a hydrogen economy was analyzed and the results surprised the hydrogen community worldwide. The energy consumed at all the significant stages of a hydrogen economy is given in **Table 2.** In most of the cases, electricity is consumed. nergy losses were 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. Hydrogen may be compressed to 100 bar for distribution to filling stations in pipelines, and then compressed further to 850 bar for rapid transfer into pressure tanks of automobiles. Liquefaction of hydrogen may be preferred to compression in order to save transportation energy, or on-site production of hydrogen with less efficient electrolyzers may offer economic advantages over hydrogen production in large centralized plants and distribution by pipelines. There are no general solutions. The energy cascade of a representative hydrogen option in comparison with energy transport 'by electrons' is illustrated in **Fig. 1**. Whichever 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.

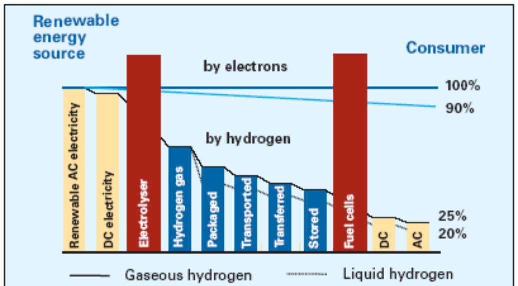

Figure 1. Energy cascade for energy transport by electrons and hydrogen

In **Fig 2**, renewable electricity is symbolized by wind turbines. Let us assume that the power output of one wind turbines is supplied to a certain number of consumers by electrons, i.e. by conventional electric power lines. If hydrogen is used as the energy carrier, four wind turbines must be installed to provide these consumers with the same amount of energy. Essentially, only one of 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 exception of biomass, renewable energy is harvested as electricity, with solar, wind, hydro or ocean power plants. In addition, solar

Table 2 Energy Consumed at stages of a hydrogen Economy (HHV: Higher Heating Value of Hydrogen)

Stage	Deatils	% 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 hydrides	CaH_2, LiH, etc.	60	Electricity
Road Transport	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
Re-conversion	Fuel cell, 50%	50	Hydrogen
DC-AC conversion	-	5	Electricity

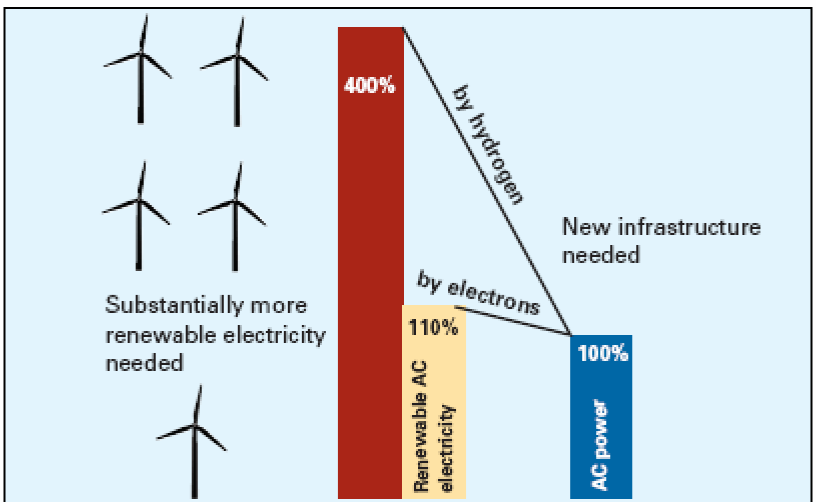

Figure 2. Renewable electricity generators needed for energy transport by electrons and by hydrogen

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 a complete 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 electrochemical 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 compressed or liquefied hydrogen by pipelines, land vehicles and ships. In a sustainable future, energy 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% of the original renewable electricity energy with 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 the cheapest form of energy in the commercial market. Because of the energy losses associated with the hydrogen economy, the following energy price relations may be expected for electricity-derived hydrogen: at filling stations, hydrogen will cost at least twice as much as electrical energy from the grid electricity from hydrogen 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, electric 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 fuel station. Furthermore, the 'battery-to-wheel' efficiency of electric cars is about 80%, while the 'tank-to-wheel' efficiency of fuel cell cars can barely reach 40%, based on the higher heating value of hydrogen. The daily drive to work in a hydrogen fuel cell car will cost four times more than in an electric or hybrid vehicle. The economic optimization clearly favours electric solutions.

A hydrogen economy will be characterized by a massive increase of electric power needs. It is unlikely that this demand can be satisfied 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 electrical energy has to be identified and developed. The installation of wind energy converters, solar power plants and tidal 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 into 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 indication 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 chemical fuels, i.e. 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 technologies such as fuel cells cannot compensate for the losses and energy consumption associated with hydrogen 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) efficiency above 32%. Modern diesel engines, even micro turbines, show better yields. But molten carbonate or solid oxide 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 conventional cogeneration equipment in a natural gas economy. Although still too expensive, high-temperature fuel cells are clean converters of hydrocarbons into electricity. 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 energy 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-derived chemical energy. This may include the conversion of digester gas, 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 hydrogen will be produced from biomass or by electrolysis,to be subsequently converted to electricity in cogeneration facilities. Because of its inherent energy efficiency, cogeneration will continue to be one of the key power generation technologies in asustainableenergyeconomy. Whenever electricity is produced by Carnot processes, the unavoidable waste heat will be utilized for space conditioning, hot water or industrial processes. Cogeneration technology will be further developed and adapted to a variety of sustainable fuels from biomass.

Limitations of a Hydrogen Economy: All losses within a Hydrogen Economy are directly related to the nature of hydrogen. Hence they cannot be significantly reduced by any amount of research and development. We have to accept that hydrogen is the lightest element and its physical properties do not suit the requirements of the energy market. The production, 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-efficient of all options. Judged by this criterion, a general "Hydrogen Economy" can never become a reality, although hydrogen will gradually become more important as energy transport and storage medium. This article provides some clues for the strengths and weaknesses of hydrogen as an energy carrier. Certainly the proportion of energy lost depends on the application. 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 the 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 electricity may be stored as hydrogen for power generation during periods of calm. As stated at the beginning, hydrogen generated by electrolysis may also be the best link between physical energy from renewable sources and chemical energy. But it is questionable if hydrogen in its elemental form will ever become a dominating energy carrier.

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