Does a Hydrogen Economy Make Sense?

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Introduction

The establishment of a sustainable energy future is one of the most pressing tasks of mankind. With the exhaustion of fossil resources the energy economy will change from a chemical to an electrical base. This transition is one of physics, but proven technology and existing engineering experience come in useful. Actions must be taken soon to start a transition process which will take many years to complete.

Unfortunately, politics seems to listen to the advice of visionaries [1], lobby groups and environmental activists, all presenting qualitative arguments, but hardly ever based their arguments on facts and laws of physics. A secure sustainable energy future cannot be based on shaky arguments, hype and political activism, but has to be built on solid grounds of established science.

This article is in part a response to false claims of hydrogen promoters. Although most particular claims are correct, in total they do not properly consider the energy conservation principle, one of the fundamental laws of physics. Hydrogen is not a new energy, but only an artificial synthetic energy carrier. It has to be made from high grade energy like electricity or natural gas. Before the technology of a hydrogen economy is developed or put in place, the fundamental question needs to be addressed. Where does the energy come from that is to be delivered to the consumer attached to hydrogen? How much of the original energy is needed to satisfy the energy needs of society? How much energy is lost in the distribution system? Are there other ways to bring the energy to the people?

These questions have been studied in detail [2]. This publication builds on the results of this energy analysis of a hydrogen economy. It translates the results into a wider perspective and draws conclusions that are devastating for a hydrogen economy. A hydrogen economy will never make sense.

The Sustainable Energy Future

Two postulates need to be satisfied to make the energy system sustainable.

1. All energy must come from sustainably managed renewable sources
2. Energy must be distributed and used with highest efficiency.

In this context "sustainable" is used in its original meaning. In the late 18th century, the mandate of sustainability was created by the Prussian forest administration to mean "never take more wood out of a forest than nature can replenish between two harvesting periods." This rule applies to all interactions between man and nature. In the energy area, it involved the harvest of energy on the input end of the energy chain as well as the release of reaction products into the environment at the other end. Nature's ability to release or absorb is limiting the use of energy from geological resources.

Clearly, fossil fuels and nuclear (fusion and fission) energy do not satisfy these criteria on both ends of the energy chain. Resources are finite and the release of geo-carbon-dioxide or radioactive waste cannot be absorbed by nature. Biomass is not sustainable per se, but its growth and harvest must be managed in a sustainable way like forests in parts of Europe. Also, the sustainability of some hydro power projects could be questioned. Artificial lakes are gradually filled with silt and become useless with time. Also, the damage caused by flooding fertile valleys may be in conflict with the sustainability mandate.

However, most hydro power, solar energy, wind power, ocean energy or geothermal installations harvest renewable energy in a sustainable way. Add energy obtained from sustainably managed biomass and organic waste to complete the list of renewable energy. After depletion of fossil and uranium deposits energy must come from these sources. There are no other sustainable energy sources that could possibly contribute substantially to the energy needs of mankind. However, the conversion of renewable energy into commercial energy commodities is not trivial. It will take years to switch from today's fossil-based energy system to a new platform built on physical energy harvested from nature in a sustainable way.

Onset and speed of this transition to sustainability depend on

- availability of hydropower, wind, sun, geothermal heat and biomass
- climatic conditions for harvesting solar, wind and biomass
- topology along shorelines for harvesting ocean energy
- availability of land and sites for renewable energy installations
- proximity of such installations to urban areas
- established energy efficiency and standards of energy use
- political leadership with sound visions

But the transition may also be slowed by local availability of fossil resources, existence of conventional power plants or strong business interests.

Countries without fossil resources like Switzerland and Denmark are already moving towards sustainability. Countries with rich fossil deposits like Saudi Arabia, USA or Russia finally begin to recognize the challenges. There is no global road map to sustainability, but regional solutions are needed to reflect local situations. Road maps and international agreements may slow the process in lead countries while established energy economies may discourage changes.

Renewable Energy and the Energy Market

For a planned transition from today's to a sustainable energy base one needs to consider the properties of renewable energy supplied by nature. Without any question, the energy demand of mankind can be satisfied from renewable sources. The sun supplies many thousand times more energy globally than required to satisfy mankind's energy needs. However, meteorological fluctuations, variations by climate zones, availability of sites etc. need to be considered and site-specific solutions must be found. Energy from renewable sources is already competitive in some areas. The number of attractive sites is rapidly increasing with rising oil prices and further development of green energy technologies. Wind energy has become attractive on windy sites of all continents. There is no global distribution problem for energy from renewable sources. Renewable energy is available where people live: wind in the Chicago area ("Windy City"), sun in Arizona, forest biomass in the eastern parts of the United States.

However, with the exception of biomass, renewable energy is harvested as physical energy, some as heat, but the vast bulk as electricity. Consider the following compilation:

Solar energy	photovoltaic	DC **electricity**
	solar collectors	hot water, space heating
	Solar concentrators	AC **electricity**
Wind energy		AC **electricity**
Hydropower		AC **electricity**
Ocean energy	waves	AC **electricity**
	tides	AC **electricity**
Geothermal	low-temperature heat	hot water, space heating
	high-temperature heat	AC **electricity**
Biomass	chemical conversion	synthetic liquid fuels
	low-temperature heat	hot water, space heating etc.
	high-temperature heat	AC **electricity**
Organic waste	chemical conversion	synthetic liquid fuels
	high-temperature heat	AC **electricity**

Today, about 80% of the energy is derived from chemical and only 20% from physical sources, the future will see just the opposite. About 80% will be harvested as energy electricity or low-temperature heat with about 20% being available from organic resources.

On first sight the significantly different distribution of the energy spectrum appears frightening. A closer look, however, reveals that the future energy supply is much better matched to the energy demand of consumers. People need chemical energy only for food. All other energy services are supplied in form of physical energy: motion of cars, heat or cold for indoor climate and cooking, artificial lighting, communication, etc. Today, chemical energy is converted to satisfy these physical energy needs. In future, electricity could be used directly to assure comfort and living standard of people. Fortunately, consumer needs of energy services are better matched in a sustainable energy than in today's chemical energy world.

The change from chemical energy to electricity is certainly much less difficult than a change in the other direction would be. We have to part from one well-established chemical energy tradition and switch to another, equally well established electrical energy society. It is certainly easier to gradually extend the use of electricity than to create chemical energy from electricity to continue with the heritage of James Watt and Carnot. Certainly, the energy end use technologies and consumer habits need to be adapted to electricity, the base energy of a sustainable future.

Inversion of the Energy System

Because of the dominance of electrical energy and the relatively weak position of chemical energy in as sustainable future, our energy supply system will undergo significant changes.

Today's energy system is dominated by chemical carriers like coal, oil and gas. Electrical and transportation energy are derived from chemical energy by thermal power plants, heat engines, or fuel cells. During the last two centuries scientists and engineers have developed fascinating thermal energy conversion devices and related theories. From oil wells to driving on highways, much of today's economy is directly related to the conversion of chemical energy of fossil origin into energy services of physical nature.

With the end of fossil reserves the era of chemical energy conversion is bound to come to an end. This development is irreversible. It can only be slowed, but never stopped by politics, energy wars, or the introduction of synthetic energy carriers like hydrogen. We have to face the future and prepare for it.

What does the future look like? The sustainable energy future will be dominated to perhaps 80% by electrical energy from renewable sources. Renewable electricity will be transmitted directly to the user via existing and new power lines. Chemical energy must be derived from electricity, e.g. by electrolysis of water. Therefore, electricity-derived hydrogen is unlikely to be converted back to electricity by thermal power plants or fuel cells. Renewable electricity will gradually replace fossil fuels. Electricity will become the base of our energy system. It does not make sense to continue with chemical energy technologies by converting good electricity into hydrogen for use in steam power plants.

The inversion of the energy system will affect our entire energy world and change our energy system. Many chemical energy conversion technologies may become obsolete. Coal, oil or gas fired power plants and internal combustion engines will "run out of fuel". Electric heat pumps will become real energy multipliers. Without Carnot losses, the overall efficiency of the energy system may reach 50%. Efficient electrical transmission and appliances will replace inefficient chemical energy conversion and distribution technologies. Green electricity, combined with an efficient energy distribution and use, will be the base of a sustainable energy world. Because of the improved overall efficiency, even a growing demand of energy services can be satisfied from renewable sources.

The transition from a chemical to an electrical energy base is too complex to be analyzed in detail. We have to face the need for change and get to work without fruitless debates about costs and economic consequences. The cost of future renewable electricity cannot be compared to the present cost of electricity generated by converting coal to electricity in amortized, but inefficient and dirty thermal power plants. Future options may be compared with each other. Also, the suitability of renewable energy sites should be assessed with care. But as such, renewable energy is free, forever, while oil and gas prices climb with demand and depletion. By this argument investments in optimized and lasting renewable energy equipment should eventually become extremely profitable.

Energy Strategy Options

There are two main options for the delivery of sustainable energy to the consumer. Both of them are free of "geocarbon", thus environmentally clean. Both start with renewable electricity and provide energy users with the same energy services. These options differ only with respect to the choice of base energy, chemical or electrical.

At this time the favored and more convenient option is to maintain the chemical energy base. Fossil fuels are replaced by synthetic hydrogen and the energy business is continued as usual. Oil companies become hydrogen suppliers, roadside fuelling stations pump hydrogen instead of gasoline, and cars are powered by hydrogen and fuel cells. This option, termed "hydrogen economy", can certainly be realized. The necessary technology is available or can be developed in time.

The second option is a controlled transition from today's chemical to an electrical energy base. Renewable energy it brought to the people in form of electricity. The necessary technology is available or can be developed in time. This option, termed "electron economy", can certainly be realized.

Both options require additional research and development. New storage technologies are needed for hydrogen as well as for electrons. But a hydrogen infrastructure must be built from scratch while the electric power grid only needs a modest extension in most parts of the world. In fact, the electron option may be much closer to today's energy technology and, therefore, much easier implemented than the hydrogen option.

In simple terms, a "hydrogen economy" has to compete with an "electron economy". Both options deliver renewable electricity to the people, but by use of different energy carriers. Winner will be the option with the lower energy losses between energy source and energy services. The situation is illustrated in the following picture. The competition between hydrogen and electricity is determined by the respective overall energy efficiency between renewable source and end use.

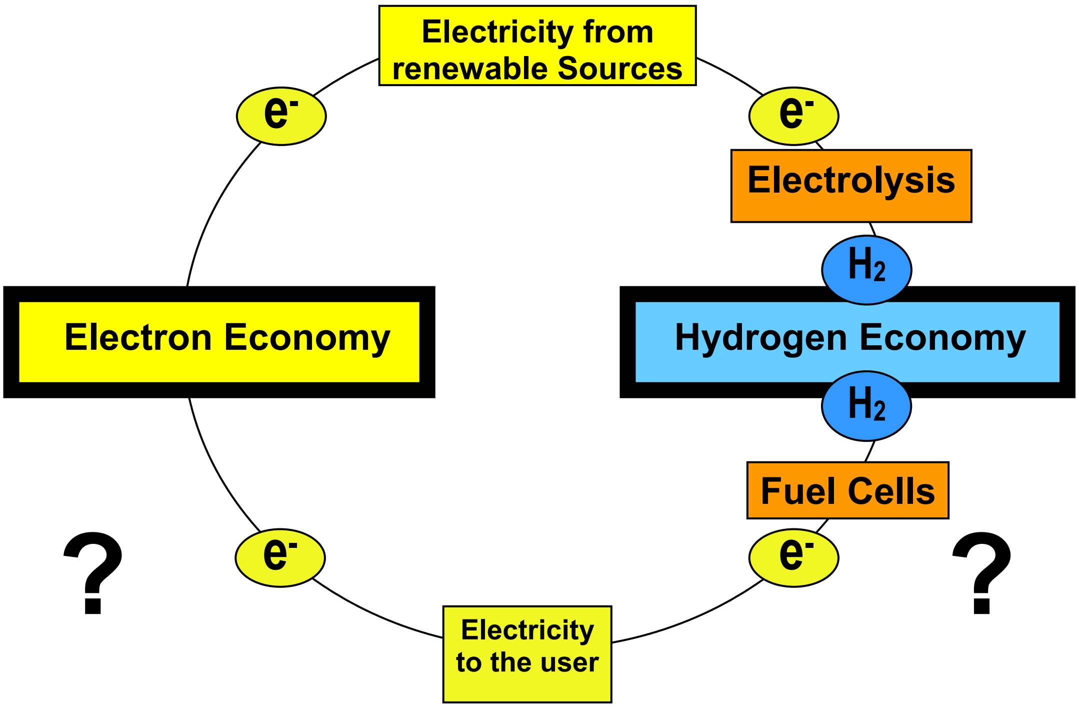

Figure 1 Energy distribution options in a sustainable energy future

The Myth of "Hydrogen Energy"

Hydrogen is promoted (e.g. [1]) as a new source of energy. This is certainly nonsense, to be clear. It is true that hydrogen is the most abundant element of our universe, but it exists only in chemical compounds like water, fossil fuels or living biomass. Furthermore, the abundance of hydrogen cannot be a sales argument, because hydrogen atoms are not destroyed by their energetic use. The gas is obtained by splitting water with the help of electrical energy into hydrogen and oxygen. The invested energy is later recovered, unfortunately only partially, when hydrogen and oxygen are recombined and the original amount of water is regained. Hydrogen is not an energy source, but an energy carrier much like water in a hydronic heating system.

1. From water by electrolysis

$$H_2O \Rightarrow H_2 + \tfrac{1}{2} O_2$$

electrical energy + H_2O = energy in H_2 + ½ O_2
286 kJ/mol = 286 kJ/mol
100% = 100%

Reality: 130% energy input = 100% energy in H_2 + 30% losses

2. From natural gas by reforming

$$CH_4 + 2\ H_2O \Rightarrow 4\ H_2 + CO_2$$

Methane energy + heat + H_2O = energy in H_2 + CO_2
890 kJ/mol + 254 kJ/mol = (4 x 286 kJ/mol =) 1,144 kJ/mol
78% + 22% = 100%

Reality: 110% energy input = 100% energy in H_2 + 10% losses

12

Figure 2 Hydrogen production by electrolysis and reforming

Hydrogen may be extracted from natural gas by steam reforming or from water by electrolysis, Figure 2. In both cases, more energy is needed to liberate hydrogen from its chemical bounds than can ever be recovered by oxidizing the energy carrier for energy release. The equation: "hydrogen plus air = energy plus drinking water" reflects simplified views of laymen. It seems that the energetic base of hydrogen generation and use are not properly considered in the ongoing hydrogen debate. Where does the energy come from to make hydrogen?

Energy Losses within a Hydrogen Economy

The energy losses of optimized and efficient electrical grids (not yet installed in most parts of the world) are tolerable. For modest distribution distances about 90% of the generated electricity is available for end use. The energy losses of all important stages of a hydrogen economy have only recently been analyzed by the author and his colleagues [2] ("The Future of the Hydrogen Economy: Bright or Bleak", www.efcf.com/reports). The most significant results are presented below.

A hydrogen economy involves more stages than the two obvious conversion processes of electrolyzer and fuel cell. Even before water can be split into hydrogen and oxygen, high-voltage AC power has to be converted to low voltage DC current, water has to be cleaned, demineralized, distilled, pumped and pressurized. Electrolysis involves significant energy losses. The generated hydrogen needs to be packaged by compression, liquefaction or chemical processes to make it marketable. Then the synthetic chemical energy carrier has to be transported to the user by road, rail or ship, as well as pipelines. Hydrogen may also be lost by leakages. Because of the physical properties of hydrogen, all these stages require much more energy than is needed for the distribution of liquid fuels to consumers. Storage of hydrogen, in particular in the liquid state, and transfer into vehicle tanks also requires energy. Finally, the re-conversion of hydrogen to DC electricity fuel cells and the subsequent DC/AC conversion are associated with heavy energy losses. These processes cannot be made much more efficient by additional research and development. The main losses reflect the physics of hydrogen. Only a small fraction of the original renewable electricity can be recovered by consumers with efficient hydrogen fuel cells.

The results of the cited report [2] are presented for six significant stages. The energy losses or the parasitic energy consumption is presented in percent of the Higher Heating Value HHV of the delivered hydrogen. Furthermore, the results of this engineering analysis are presented as curves to allow readers to find answers for parameters of his choice. As assumptions and equations are contained in the original study, only the most essential graphs are presented here.

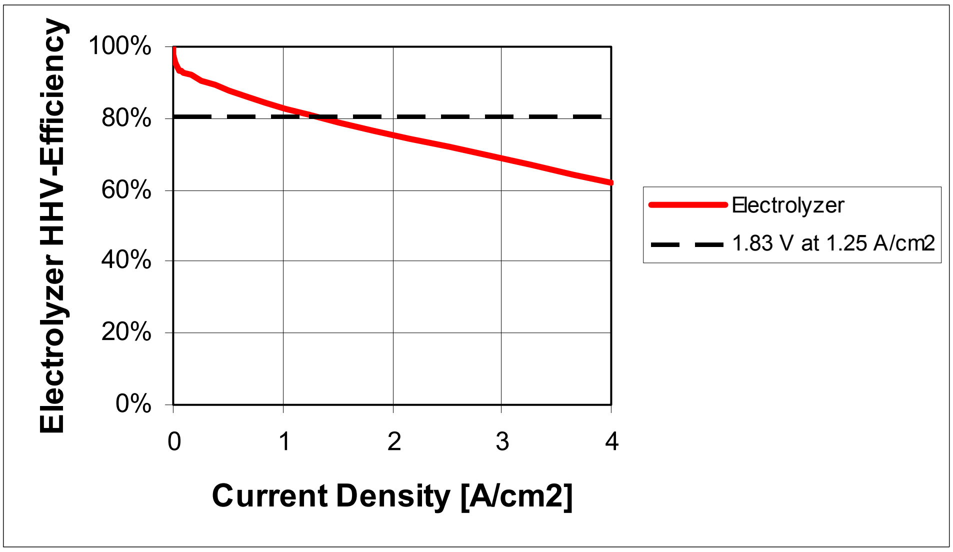

Figure 3 Energy losses of hydrogen production by electrolysis.

The energy losses are directly related to the operational parameters of an electrolyzer. Internal Ohmic ("IR") losses are proportional to the electric current. Current densities between one and two Amperes per cm^2 are standard resulting in power losses in the range of 30%. Higher efficiencies can be obtained for lower current densities and lower output. Electrolyzer optimization is a matter of economics, not physics.

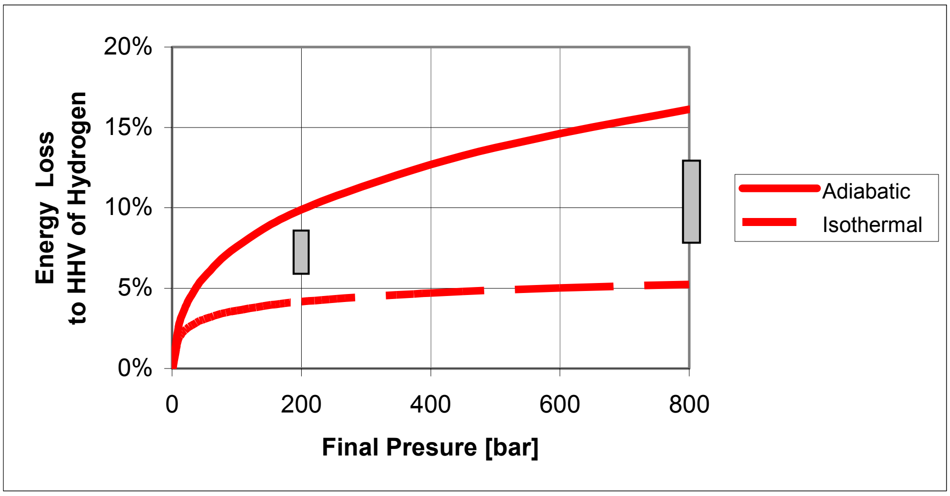

Figure 4 Compression of hydrogen gas

Because of its low molecular weight, the compression of hydrogen requires eight times more energy than the compression of natural gas and 15 times more than the compression of air. Multistage compressors with intercoolers are needed to compress hydrogen close to the ideal isothermal limit. Still, depending on final pressure the compression energy needed amounts to 8 to 15% of the energy contained in the hydrogen gas.

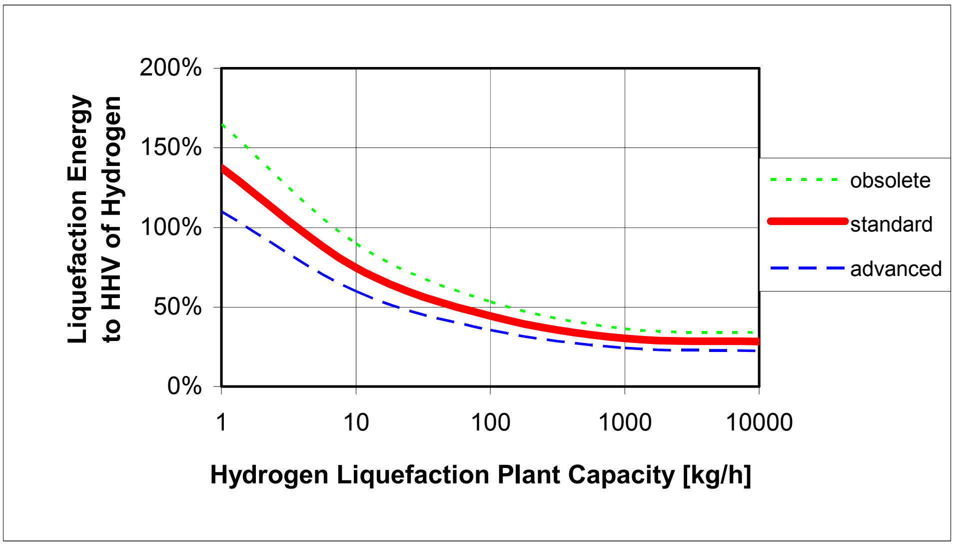

Figure 5 Liquefaction of hydrogen gas

Much electrical energy is required to liquefy hydrogen. The low temperature of about 20K is reached by multistage counter flow expansion. But hydrogen gas has to be cooled first with liquid nitrogen to temperatures below its Joule Thompson point. Hydrogen liquefaction will always remain an energy-intensive process.

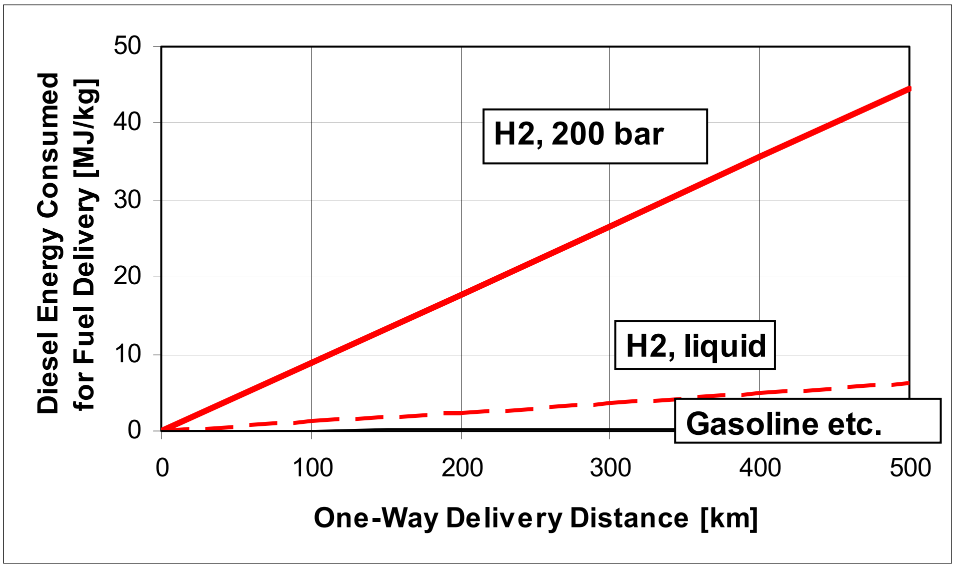

Figure 6 Road delivery of hydrogen

A 40-tonne hydrogen transporter carries about 350 kg of hydrogen gas at 200 bar (3,500 psi) or 3,500 kg of liquid hydrogen at cryogenic 20K. It takes 22 tube trailers (200 bar) or 4.5 liquid hydrogen trucks to transport the energy contained in a single gasoline tanker of the same gross weight.

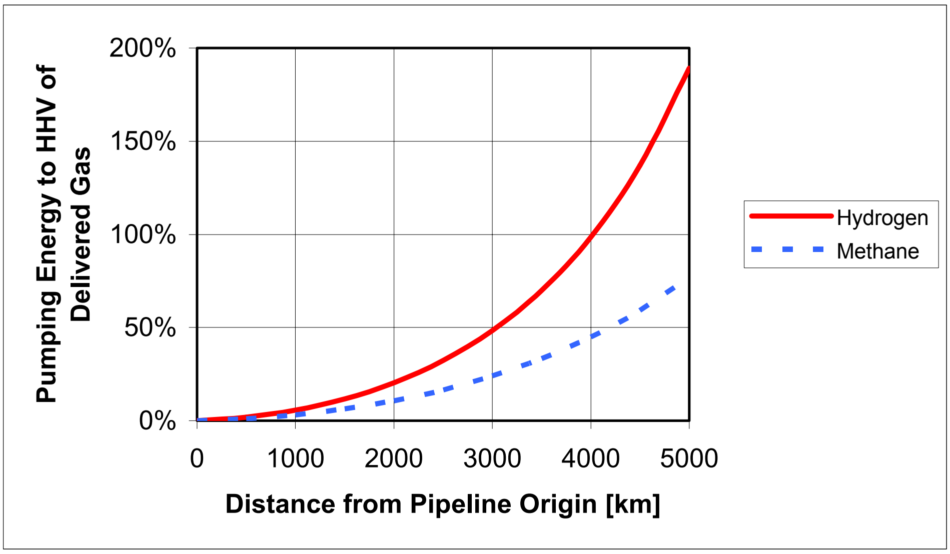

Figure 7 Long distance transport of hydrogen through pipelines

Pumps are energized by hydrogen taken from the gas flow. As a consequence, the lines are exponentially curved. Only a small fraction of hydrogen generated in North Africa would arrive in London or Hamburg. Pipeline transport of natural gas requires less energy.

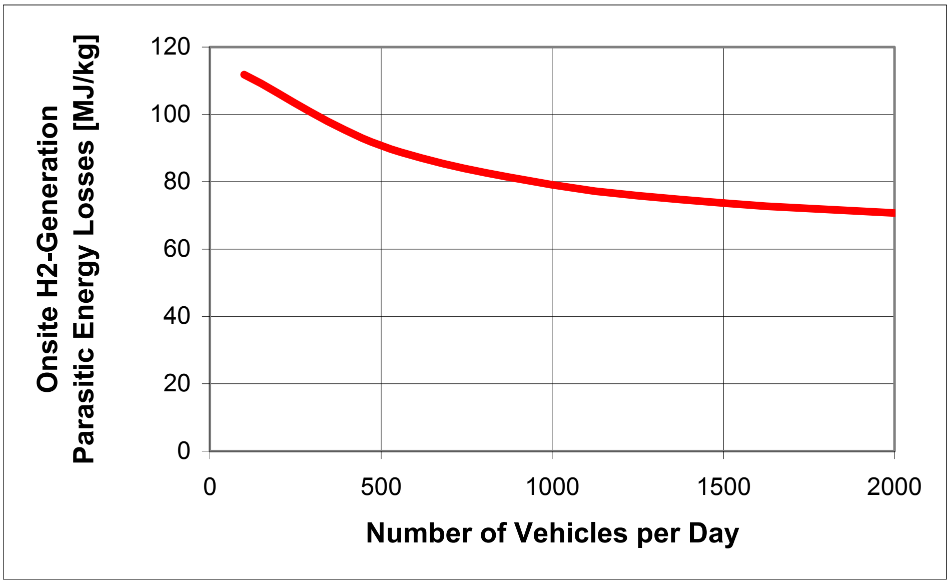

Figure 8 Onsite production of hydrogen by electrolysis at filling stations

This option requires not only much energy for water make-up, electrolysis, gas compression and transfer, but local availability of electricity and water. To serve 1,000 vehicles per day, continuous electric power of at least 30 MW is needed at a water consumption of 110 m^3 per day. There are many highway sites where these conditions cannot be met.

For the ongoing hydrogen debate the following results are presented for a selection of representative operational parameters:

Hydrogen from electricity and water by electrolysis		25%
Compression	to 200 bar	8%
	to 800 bar	13%
Liquefaction	in small plants	50%
	in large plants	30%
Chemical hydrides		60%
200 km road delivery (Diesel)	at 200 bar	13%
	as liquid	3%
2000 km pipeline		20%
Onsite generation (electrolysis)		50%
Transfer from 100 bar storage to 700 bar tank		8%
Re-conversion to electricity and water by fuel cells		50%

The initial publication of these numbers has caused irritation among hydrogen promoters. However, our analysis has been checked by renowned institutions and withstood all criticism. In fact, the results of our study confirm the findings of published well-to-wheel studies of hydrogen groups. The only difference is that we compare a future hydrogen economy with a future electron economy while our critics compare the future hydrogen economy with the present fossil fuel situation. Needless to say, in our study the reduction of greenhouse gas emissions cannot be addressed as carbon is not involved in either one of the two alternatives.

The tabulated numbers have been used for the illustration of the loss cascades presentation of energy transport by electrons and hydrogen.

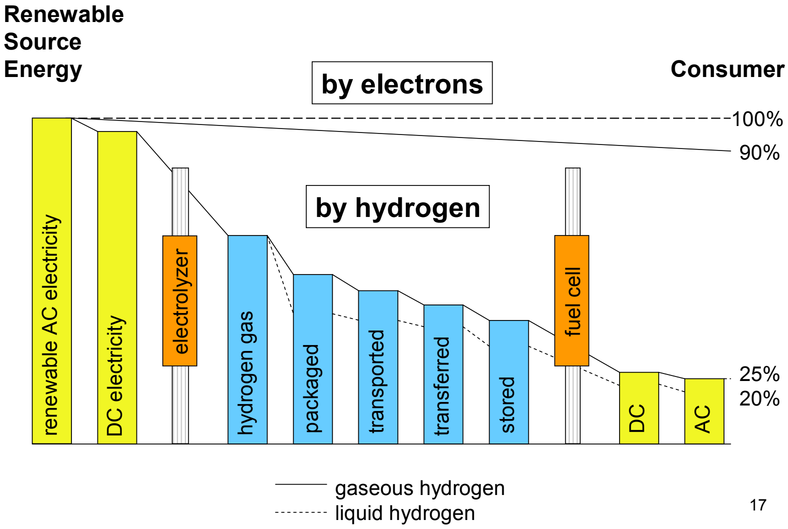

Figure 9 Transport of renewable electricity by electrons and by hydrogen. 25% of the original energy become useful for the hydrogen path

While with modern power grids distribution over modest distances may achieve about 90% efficiency, only 20 to 25% can be put to use when hydrogen is used as transport medium. This is certainly in conflict with the efficiency mandate of a sustainable energy future. Promoters of hydrogen point out that the present use of hydrocarbons is equally inefficient. However, this is a misleading claim as it compares the poor efficiency of a future hydrogen economy with the equally poor efficiency of today's energy technologies. Nevertheless, the comparison reveals that high efficiency cannot be obtained when chemical energy is used as source carrier. In a sustainable energy future chemical hydrogen has to compete with physical electrons. The results of our study identify the winner. Hydrogen can never compete with its own energy source, with electricity.

The illustration borrows from the energy cascade of electrical systems where voltage is lost by Ohmic resistance along the path of energy flow. The hydrogen case is more complex, but difficult to schematize. In a gas-tight system, the hydrogen flow remains unchanged between electrolyzer and fuel cell, unless some of the transported hydrogen is used for propulsion of hydrogen carriers or to energize compressors in pipeline systems. Between electrolyzer and fuel cell, parasitic energy, in particular electricity must be supplied to power liquefaction plants, compressors, pumps, fuel delivery trucks etc. to deliver hydrogen to the user. Depending on the chosen distribution technology, the parasitic power requirements may amount to 50% or more of the energy content (higher heating value HHV) of the hydrogen delivered to the fuel cell at the end of the line. In addition to the electric power grid has to be extended to deliver hydrogen to the consumer. Transporting hydrogen over long distances may never be profitable. In particular, intercontinental ocean transport of liquid hydrogen requires so much energy that a global hydrogen economy may never emerge. The suggestion of hydrogen promoters, to derive hydrogen from the strong and steady winds in Patagonia, may remain a dream forever. Only a small fraction of the hydrogen filled into the cryogenic containers at Cape Horn will eventually reach the energy markets in North America or Europe, certainly not enough for a viable energy business.

Two Questions Need Answers

The difference between energy distribution by electrons and by hydrogen is so striking that two more questions have to be addressed. First, as consumers receive not more than one fourth of the original electricity via the hydrogen path, about four times more renewable energy must be generated than required for an efficient energy distribution by electrons. While only one of four renewable power generators produces useful electricity, the other three are needed to overcome losses and to provide parasitic power to the distribution system. The number of four is based on a fuel efficiency of 50%. It will be higher for less efficient hydrogen conversion appliances. In the following illustration historic Dutch wind mills are used to make the point. Wind is certainly one good option, but as said before, renewable electricity can also be derived from solar, hydro, ocean, geothermal or biomass energy sources.

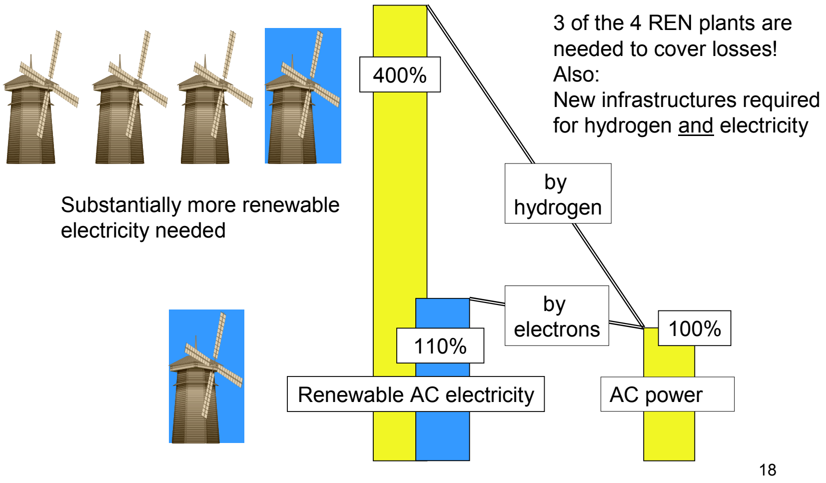

Figure 10 Renewable power plants needed for energy transport by electrons and hydrogen. Necessary extension of the power grid is not shown

The second question is related to the consumer cost of energy. It must be assumed that transmission losses are charged to the customer, as practiced today. Electricity form hydrogen, be it for stationary, mobile or portable applications, will be at least four times more expensive than power from he grid. If capital amortization and cost of operation are included, the factor may be much higher. Who wants to pay for expensive hydrogen when electricity is much cheaper? Again, hydrogen being an artificial energy carrier cannot compete with its own energy source. In a sustainable energy future hydrogen from renewable electricity is challenged by renewable electricity itself. It is no longer competing with fossil fuels, but it is running against electrons in the competition of energy transport media.

Consumer Response

As energy distribution losses will be charged to the customer, the following price structure can be derived from physics:

- Energy purchased in the form of hydrogen will be at least twice as expensive, as energy delivered by the grid.
- Electricity derived from hydrogen with fuel cells in stationary or mobile applications will be at least four times more expensive than energy from the grid.

For many portable applications hydrogen-derived electricity has to compete with electricity from batteries. This situation cannot be generalized in this context.

Consumers will continue to look for bargains. Considering the significant price differences it is realistic to expect the following:

- Rather than switching from natural gas to hydrogen, home owners will reduce the energy consumption of their houses by active and passive means. They are likely to install electric heater or electric heat pumps to meet the remaining heating and cooling requirements.
- For commuting and local driving small, simple, efficient and inexpensive electric cars will be preferred to complex and expensive hydrogen fuel cell vehicles.
- Liquid synthetic fuels from biomass will be used for long distance driving, trucks, air and ocean transport, as synthetic hydrogen will not only be more expensive than biomass-derived liquid fuels, but it cannot be stored economically in quantities required for long distance travel.

Most of these arguments put forth are derived from the physical properties of hydrogen and the laws of physics governing the key processes of a hydrogen economy. Neither the nature of hydrogen nor the physics involved can be changed by further research, by majority votes of committees, but legislation of parliaments or by initiatives of political leaders. The speculations about the establishment of a hydrogen economy as a sustainable solution of our energy problems should be terminated as soon as possible.

But will hydrogen ever find a sustainable market? The honest answer is no. However, hydrogen may be used in local or regional niche applications. But it may never become a commercial energy commodity like gasoline as projected by the supporters of a hydrogen economy.

From Now to Sustainability

Unless caused by political shocks, war or OPEC decisions changes in the energy sector proceed slowly. But trends are apparent and ongoing, perhaps too small to be noticed on the yearly energy statistics, but accumulating changes over the years. They are caused by supply and demand, by new energy technologies, by the emergence of powerful economies (e.g. China and India), by depletion of resources, by air quality legislation and similar developments.

The growing demand and declining resources have led to rising energy prices with the following noticeable effects:

In the stationary sector, the demand of heating fuels is declining as a result of

- improved thermal insulation of buildings,
- more efficient HVAC appliances,
- use of biofuels like wood, wood chips and pellets,
- use of electricity for direct heating and heat pumps.

In the mobile sector the total fuel consumption is still growing as a result of an increasing number and more powerful cars on the road. However, the fuel consumption expressed in passenger mile per gallon is declining as a result of

- improved efficiency of IC engines,
- introduction of hybrid electric vehicles,
- substitution of fossil fuels by synthetic hydrocarbons or biogas,
- use of small battery-electric cars and scooters for commuting.

The overall efficiency of our energy system is increased by

- higher conversion efficiency of power plants or IC engines,
- higher efficiency of the electrical energy distribution system,
- rising energy awareness and change in consumer behavior,
- growing supply of electricity from renewable sources.

The transition to electricity is already in progress. Electricity is gaining market shares against fossil fuels. Electricity is gaining acceptance. A "hydrogen economy" may never catch up with the ongoing transition to an "electron economy".

Conclusions

For the establishment of a sustainable energy future the present energy system has to undergo significant changes, not just minor adaptations or modifications. The key point is the transition from a chemical energy base built on fossil fuels to a physical energy base built mainly on electricity from renewable sources. This transition is predetermined by the laws of physics. It cannot be avoided or significantly delayed by politics. However, the transition will proceed more smoothly, if all players agree to move into the same direction.

Without the slightest doubt, the technology for a hydrogen economy exists or can be developed in reasonable time. Also, hydrogen is an appropriate energy carrier for particular niche applications, or it may become an important medium for electricity storage with reversible fuel cells. But hydrogen can never establish itself as a dominant energy carrier. It has to be fabricated from high grade energy and it has to compete with high grad energy in the marketplace. Hydrogen cannot win this fight against its own energy source.

Therefore, the answer to the question: "Does a Hydrogen Economy make Sense?" is an unconditional "NEVER". A global hydrogen economy has no past, present or future!

References

[1] "The Hydrogen Economy", Jeremy Rifkin, Penguin Putman, 2002

[2] "The Future of the Hydrogen Economy, Bright or Bleak?" by Ulf Bossel, Baldur Eliasson and Gordon Taylor, April 2003, www.efcf.com/reports)

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Born 1936 in Germany, studied Mechanical Engineering in Darmstadt (Germany) and at the Swiss Federal Institute of Technology in Zurich with Diploma Degree (thermodynamics, fluid mechanics) in 1961. Short work period at Brown Boveri & Cie, then graduate education at the University of California at Berkeley with Ph.D. degree in 1968 for experimental research in the area of space aerodynamics. Two years Assistant Professor at Syracuse University, return to Germany, head of the free molecular flow research group at the DLR in Göttingen. Left field for solar energy in 1976, founder and first president of the German Solar Energy Society, started his own R&D consulting firm for renewable energy technologies in 1979. Called by Brown Boveri & Cie in 1986 to join their New Technology Group in Switzerland. Since 1987 involved in fuel cells, since 1989 manager of ABB's fuel cell development efforts worldwide. Left ABB in 1990 to become a freelance fuel cell consultant, with clients in Europe, Japan and the US. Many patents and publications related to fuel cells. He has created, and is still in charge of the annual fuel cell conference series of the European Fuel Cell Forum in Lucerne.