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The Physics of the Hydrogen Economy

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Abstract

In a "Hydrogen Economy" hydrogen will be a vehicle for the transport of electric energy. The source of the energy carrier is electricity and so is the output of a fuel cell on the other end of the hydrogen distribution network. Consequently, the emerging hydrogen infrastructure has to compete with an electric power system. For most stationary applications, already existing wires are unlikely to be replaced by a hydrogen pipeline. Electric cars offer advantages over fuel cell vehicles in commuting traffic and advanced batteries compete with hydrogen fuel cell power sources in most portable applications. Therefore, any investment in a hydrogen infrastructure ought to be based on a careful assessment of the two options for the transportation of electricity. This publication is meant to direct attention to some fundamental problems of a Hydrogen Economy.

At present, the solution for a sustainable energy future is seen in production and use of hydrogen assuming that it is just another gaseous fuel and can be handled much like natural gas in today's energy economy. But this is not the case. The recent study "The Future of the Hydrogen Economy: Bright or Bleak?" (www.efcf.com) analyzes the physics of the Hydrogen Economy. In particular, the energy required to package, distribute, store and transfer hydrogen is assessed. The results reveal that an energy economy based on pure hydrogen suffers from high parasitic energy losses. As a consequence, the Hydrogen Economy will not emerge as envisioned by the hydrogen promoters, in particular, as better options exist for a sustainable future based on renewable energy and environmentally benign technologies.

The study does not consider hydrogen derived chemically from natural gas or other hydrocarbons, as this option does not provide obvious advantages with respect to energy and environment.

Hydrogen "Economy"

Hydrogen by itself is a synthetic energy carrier. In distant future most energy will be derived from renewable sources. All of these are of physical nature: radiation from the sun, kinetic energy from wind, water and waves, or geothermal heat from the ground. All of them are first converted to electricity that may then be used directly for many, mostly stationary applications, or it can be used to synthesize hydrogen from water by electrolysis. Hydrogen may be the only meaningful link between physical and chemical energy.

But in a Hydrogen Economy the lightest of all gases has to be processed like any other market commodity. It has to be packaged by compression or liquefaction, transported by surface vehicles or pipelines, stored, and transferred to the end user. There it can be converted back into electricity by fuel cells or other conversion devices. High-grade electricity from renewable or nuclear sources is needed not only to generate hydrogen by electrolysis, but also for almost all essential marketing stages. At the end of the chain much less electricity becomes available than has been invested upstream in the process of generation and marketing hydrogen.

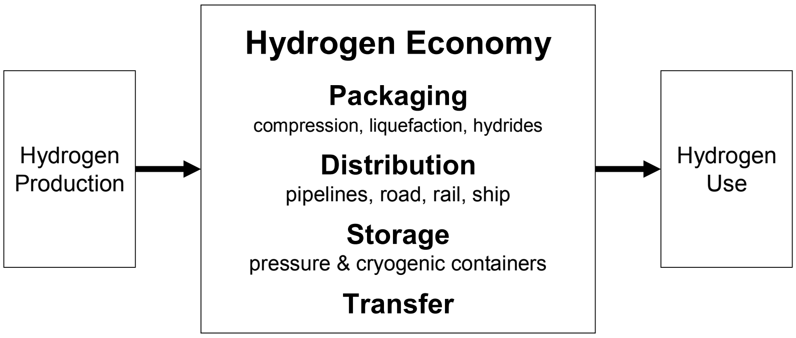

Figure 1 Schematic Representation of a "Hydrogen Economy"

Because of the molecular structure of hydrogen, the handling of hydrogen is much more energy-consuming than the handling of natural gas or liquid fuels. For a fair analysis the higher heating value "HHV" is used throughout in accordance with the energy conservation principle or the first law of thermodynamics. In contrast, the lower heating value LHV is a practical engineering convention with no immediate link to fundamental physics. At least the enthalpy of formation (or the higher heating value HHV) has to be invested to split water by electrolysis. Consequently, for a correct energy analysis, the use of hydrogen must also be based on the higher heating value in recognition of the energy conservation principle. The lower heating value was created for engineering convenience to account for limitations imposed by the sulfur-rich coal of the late 1800s. The difference between HHV and LHV is 18.3% for hydrogen, 10.4 for natural gas and 6.4% for gasoline.

Electrolysis

Producing hydrogen from water is an energy-intensive process. Below the temperature of self-ignition of hydrogen and oxygen, water can be split only in the presence of noble metal catalysts. A penalty of about 0.25 Volts has to be paid for forcing nature to break the chemical bond already at room temperature. As a consequence, the apparent open circuit voltage of an electrolyzer is not 1.23 but around 1.48 Volts. However, under normal operating conditions an electrolyzer is operated at 700 mA/cm^2 and 1.76 Volt DC. The true electrolyzer voltage efficiency is 1.23V / 1.76V = 70%. In practice, at least 1.43 electrical energy units must be invested to obtain 1 HHV unit of hydrogen. In terms of energy, 1.43 x 142 MJ/kg or 206 MJ are consumed to produce one kilogram of hydrogen by electrolysis, but only 142 MJ/kg are contained in the synthesized energy carrier. In total, 64 MJ/kg or 45% of the HHV content are lost for each kilogram of hydrogen delivered. Considering all losses associated with power generation and transmission, this number would be much higher.

Compression of Hydrogen

The compression of gas requires energy, and the compression work depends on the thermodynamics of the compression process. The energy consumption of a multi-stage hydrogen compressor is about half-way between the two theoretical limits of an isothermal and an adiabatic compression process.

As shown in Figure 2, the energy required for the compression of atmospheric hydrogen depends on the final pressure as well as on the chosen compression technology. For a state-of-the-art multistage process around 10 and 17 MJ are needed to compress 1 kg of hydrogen form atmospheric pressure to 20 and 80 MPa (200 and 800 bar), respectively. This is between 8 and 13% of the HHV energy content of hydrogen. The heavier methane can be compressed at a seven times lower consumption of energy.

Our analysis does not include parasitic compression losses, general energy consumption of the compressor station, or losses associated with the generation and distribution of electrical power. In total, between 15 and 20 MJ of electrical energy are needed for the compression of 1 kg hydrogen to 200 or 800 bar. Pressure electrolysis does not eliminate the compression energy requirement, but only reduces the energy consumption to that for isothermal compression.

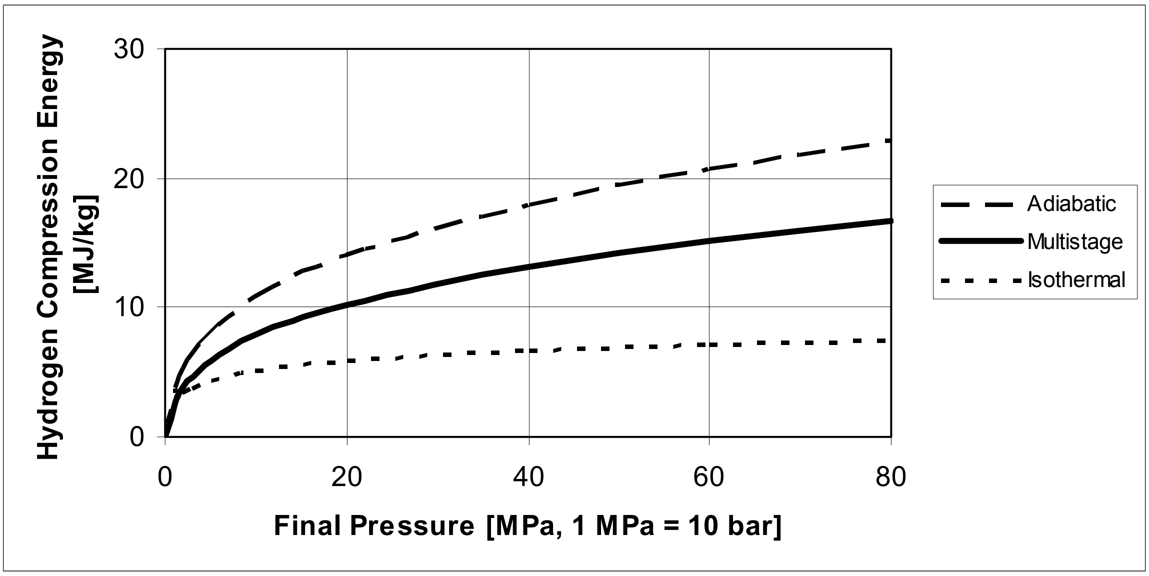

Figure 2 Energy required for the compression of hydrogen

Liquefaction of Hydrogen

Even more energy is needed to compact hydrogen by liquefaction. Because of the complexity of the liquefaction process, the analysis is based on operating experience of existing hydrogen liquefaction plants. Typically, small plants are less energy-efficient than large facilities. The medium size liquefaction plant of Linde Gas AG at Ingolstadt in Germany produces 182 kg/h at a specific energy consumption of about 54 MJ/kg, while much larger plants in the US require 36 MJ/kg to liquefy hydrogen. A Japanese feasibility study reveals that a plant for 300 metric tons of liquid hydrogen per day (12,500 kg/h) consumes at least 30.3 MJ of electricity for the liquefaction of 1 kg hydrogen. This plant would be about 6 times larger than any existing facility, but its output could only satisfy the demand of about 1,000 fuel cell vehicles per hour or serve ten filling stations on a major highway.

The curve in Figure 3 represents the median energy consumption of existing hydrogen liquefaction plants. In a Hydrogen Economy one would consider plants in the 10,000 kg/h size range with a total specific electric energy consumption of at least 30 MJ per kilogram of liquid hydrogen. The electric power requirement of such a liquefaction plant would be 83 MW. Also, as much as 21% of the HHV energy content of the liquefied hydrogen would be consumed. This parasitic energy consumption does not include upstream losses related to the electric power supply.

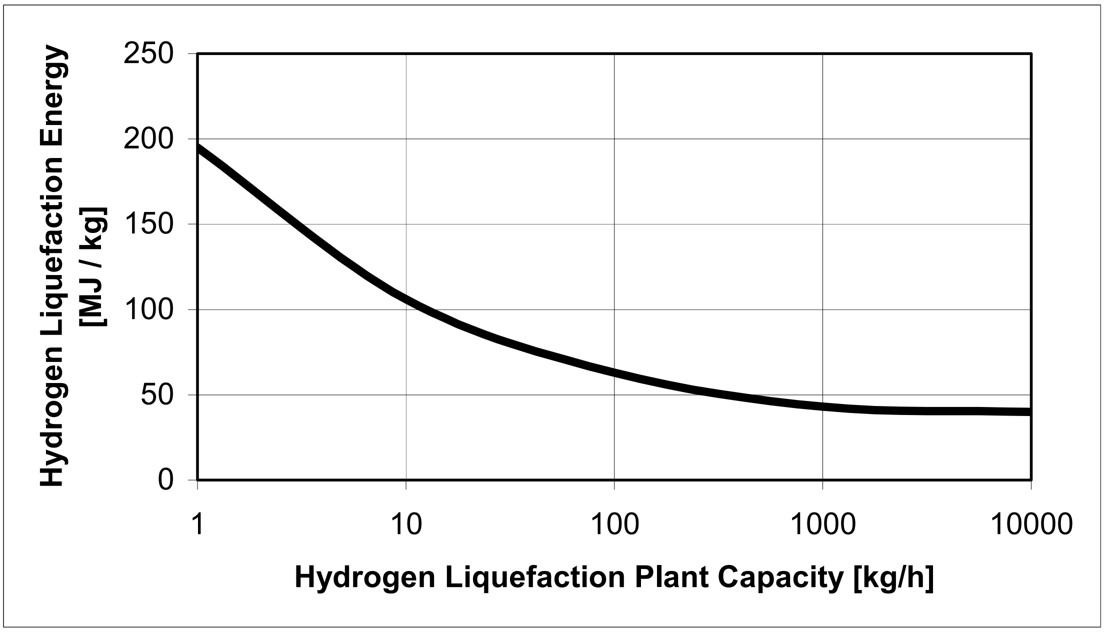

Figure 3 Specific liquefaction energy relative of hydrogen versus plant size

Moreover, liquid hydrogen storage systems lose hydrogen gas by boil-off. This is due to unavoidable heat leakage, and must be permitted for safety reasons. The loss rate depends on the size and design of the cryogenic storage tank, but would be significant for those used in vehicles, and may amount to 3 to 4 per cent a day. While the boil-off gas may be used when the vehicle is operated, it would have to be vented if the vehicle was parked. For example, if parked at an airport for 14 days, the loss of hydrogen could be 50 to 60 per cent of a full tank.

Physical Metal Hydrides

Hydrogen may be stored physically, e.g. by adsorption in porous matrices of special alloys such as physical metal hydrides. The hydrogen forms a very close, but not perfect, bond with alloys like $LaNi_5$ or $ZrCr_2$. As for any adsorption process, higher pressure and cooling are essential for the loading process, while heat must be added at lower pressure to recover the stored hydrogen. Each storage media has its own temperature-pressure characteristic. Commercial metal hydride storage cartridges are loaded at pressures of about 3 MPa (30 bar). Energy is needed to produce and compress hydrogen. Much of this energy input is lost in form of waste heat during the filling process. For rapid discharge heat transfer from the ambient may not suffice, but external heat sources must be used to drive the hydrogen out of the storage container. Waste heat from the fuel cell may be used for this purpose, but it is lost for cogeneration applications.

The overall energy consumption depends on the storage material and the features of the storage system. However, compression of hydrogen to 30 bar would require about 5 MJ/kg or 3% of its HHV energy content.

The storage density of metal hydrides is limited. Today, about 1 g of hydrogen can be stored in 100 g of metal hydride substance. Thus, the HHV hydrogen energy content of such metal hydride storage vessel is 1.42 MJ/kg. Typically, 50% of that or 0.71 MJ/kg or 200 Wh/kg can be converted to electricity by a fuel cell. Advanced batteries store up to 300 Wh/kg of battery weight and provide electricity directly without the need for electrochemical conversion equipment. Additional research may increase the energy storage capacity of hydrogen adsorption devices as well as batteries. Both technologies are in competition with each other.

Chemical Metal Hydrides

Hydrogen may also be stored chemically in alkali metal hydrides. There are many options like LiH, NaH, KH, CaH_2. Complex binary hydride compounds like $LiBH_4$, $NaBH_4$, KBH_4, $LiAlH_4$ or $NaAlH_4$ have also been proposed for hydrogen storage. None of these compounds can be found in nature. All have to be synthesized from metals and hydrogen.

For example, calcium hydride CaH2 is obtained by combining calcium metal with pure hydrogen at 480°C. Energy is needed to extract calcium from calcium carbonate (limestone) or other minerals, and hydrogen from water by electrolysis. Then both elements are heated to about 480°C and combined to calcium hydride. Hydrogen is released when the hydride is oxidized with water by a vigorous exergetic reaction. For each hydrogen atom of the hydride two hydrogen atoms are liberated from the water. In most cases, the reaction heat is lost in the process.

Counting only the heat of formation for the chain of chemical processes, about 1.6 energy units must be invested to obtain one HHV energy unit of hydrogen. At least 227 MJ of (mostly electrical) energy is consumed for each kilogram of hydrogen delivered by calcium hydride. About 85 MJ/kg or 60% of the HHV energy content of hydrogen are lost in the process. A similar energy balance is obtained for other hydride materials.

Road Delivery of Hydrogen

A Hydrogen Economy would involve hydrogen transport by trucks, trains and ships. There are other options for hydrogen distribution, but road transport would always play a role, be it to serve remote locations or to provide back-up supply to dispersed hydrogen generators at times of peak demand.

The cited analysis is based on information and operating experience of the leading truckers of industrial gases and liquid fuels in Germany and Switzerland. The energy required to deliver the energy equivalent of 26 tons of gasoline over a given distance are assessed for hydrogen gas at 20 MPa (= 200 bar), liquid hydrogen, methanol, ethanol, propane and gasoline. Trucks with a gross weight of 40 metric tones (30 metric tons for liquid hydrogen) are fitted with suitable tanks or pressure vessels. Also, at full load the fuel consumption is 40 kg of diesel oil per

100 km. This is equivalent to 1 kg per 100 km per metric ton gross weight. For the return run with emptied tanks, the fuel consumption is reduced accordingly. We assume the same engine efficiency for all trucks.

The 40 metric ton tanker trucks are designed to carry a maximum of fuel. For gasoline, ethanol and methanol, the payload is about 26 metric tons. All of it is delivered to the customer.

Today, 20 MPa (200 bar) pressurized hydrogen is delivered in tube trailer trucks. The tubes are emptied only to about 4.2 MPa (42 bar) when discharging to a receiver at 4 MPa (40 bar). Such pressure cascades are standard practice today. Consequently, such pressurized gas carriers deliver only 80% of their payload, while 20% of the load remains in the tanks and is returned to the gas plant.

At 200 bar pressure a modern tube-trailer truck carries 3,000 kg of methane, but only 350 kg of hydrogen of which only 288 kg can be transferred to the customer. Compressors would be required to completely empty the contents of the delivery tank into higher-pressure storage vessels. However, in anticipation of technical developments, the analysis considers road transport of hydrogen at 350 bar pressure. This raises the load to 500 kg and the hydrogen payload to 400 kg per truck.

Because of its low density of only 70 kg/m^3 the transport of liquid hydrogen is limited by volume, not weight. Only about 30 m^3 or 2,100 kg of the light liquid can be stored on a truck of allowed dimensions. For the analysis we assume the gross weight of such a voluminous liquid hydrogen carrier to be only 30 metric tons. Although this reduces the diesel oil consumption, trucking of liquid hydrogen remains expensive, because despite its small payload, the vehicle has to be financed, maintained, registered, insured, and operated by a certified driver.

According to our analysis 22 hydrogen tube trailers or three liquid hydrogen trucks would be required to carry the same amount of energy as a single gasoline truck. However, as the tank-to-wheel efficiency of fuel cell vehicles is likely to surpass that of conventional fossil-fuelled IC engines by factor 1.5, the number of hydrogen carriers would be reduced from 22 to perhaps 15. This is still an unacceptable number for many reasons.

In Figure 4, the energy needed to transport 1 kg of pressurized (20 MPa = 200 bar) hydrogen over a given distance is compared to the energy consumption to transport other fuels. It takes about 9 MJ to transport 1 kg of compressed hydrogen over a distance of 100 km. Shipment of liquid hydrogen would require 1.23 MJ/kg, while gasoline can be shipped over the same distance for only 0.09 MJ/kg, or at 100 times lower energy consumption than for compressed hydrogen.

Figure 4 Specific energy needed for the road delivery of fuels

The energy needed to transport any of the liquid hydrocarbon fuels is reasonably small. However, the relative energy consumption of pressurized hydrogen transport becomes unacceptable at almost any distance. For an average delivery range of 200 km the consumption of diesel oil energy could become 18 MJ/kg for compressed and 6 MJ/kg for liquid hydrogen delivered. The numbers correspond to 12.7% and 4.2% of the HHV energy content of the delivered energy carrier.

Pipeline Delivery of Hydrogen

Hydrogen pipelines exist today, but they are used to transport a chemical commodity from one production site to another. The energy required to move the gas is of secondary importance, because energy consumption is part of the production cost. However, energy consumption must be considered for hydrogen energy transport through pipelines.

The assessment of the energy required to pump hydrogen through pipelines is derived from natural gas pipeline operating experience. For comparison we assume that the same amount of energy is delivered through the same pipeline. In reality, existing pipelines cannot be used for hydrogen, because of diffusion losses, brittleness of materials and seals, incompatibility of compressors with hydrogen and other technical issues. Also, hydrogen pipelines will be larger in diameter to reduce the energy requirement for pumping. Definite answers must be left to the hydrogen pipeline designer.

For comparison with hydrogen (ρ = 0.09 kg/m^3, HHV = 142 MJ/kg), "natural gas" is substituted by methane (ρ = 0.72 kg/m^3, HHV = 55.6 MJ/kg). Also, we assume a pipeline diameter of 1 m and an internal pressure of 1 MPa (10 bar). The reference energy flow becomes 3,144 MJ/s or 3.144 GW. Because of the equal energy flow requirement the hydrogen gas has to be moved at 31.4 m/s. This speed is certainly on the high end of gas pipeline operation indicating that pipelines of larger diameter must be installed for hydrogen. In both cases, the flow is turbulent. Hence, for given energy flow rate and pipeline geometry, moving hydrogen requires about 3.85 times more energy than moving natural gas.

Typically, to transport natural gas through a pipeline at 10 m/s, a compressor is installed every 150 km. They are often fuelled from the gas stream, with each compressor consuming about 0.3% of the energy flow. Applying this model to the transport of hydrogen through given pipeline, we find that the specific energy consumption to move the gases over a pipeline distance of 1 km is 10.9 kJ/kg for hydrogen, but only 1.1 kJ/kg or about 10 times less for methane.

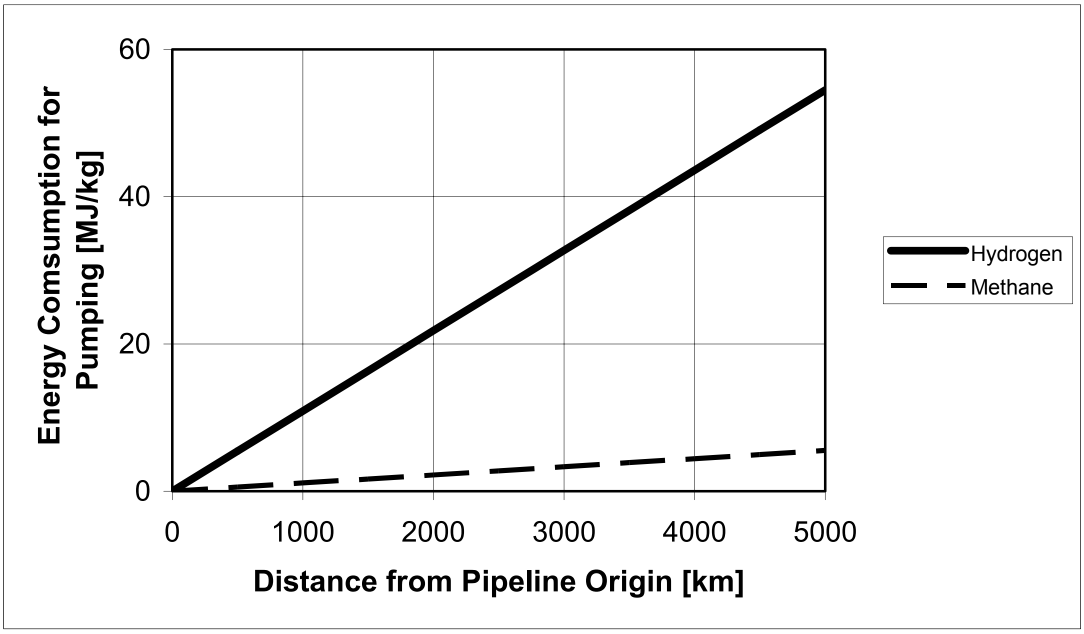

Figure 5 Energy consumption for pumping hydrogen and natural gas through a given pipeline

The results are shown in Figure 5. Apparently, much more energy is needed to pump hydrogen over a given distance compared to natural gas. But, the equal energy flow assumption requires an unreasonable high flow velocity for hydrogen. Reducing the energy flow or increasing the pipe diameter provide obvious solutions, but is associated with higher costs for equipment and operation of hydrogen pipelines.

Nevertheless, for given energy flow, if hydrogen would be pumped through an existing natural gas pipeline of 2000 km length, the pumping energy consumption is estimated to be about 25 MJ/kg or 17.6% of the HHV energy content of the delivered hydrogen.

On-site Generation of Hydrogen

One option for providing hydrogen at filling stations and dispersed depots is on-site generation of the gas by electrolysis. Again, the energy needed to generate, compress, and deliver hydrogen by this scheme is assessed. For reasons stated earlier we do not consider onsite hydrogen generation by reforming of natural gas or other hydrocarbon energy carriers. All of them can be used with higher overall efficiency in vehicles with advanced conventional IC engines.

The analysis is done for filling stations supplying an average of 60 liters (= 50 kg) of gasoline or diesel oil to 1,000 conventional cars and trucks per day. The energy equivalent would be 17,000 kg of hydrogen per day. However, as the tank-to-wheel efficiency of fuel cell cars is higher than that of IC engine vehicles, the hydrogen requirement is reduced to 70% of the energetic equivalent.

We further assume that the electrolyzer efficiency of 80%. Also, we account for electricity lost by AC-DC power conversion at the electrolyzer station, for energy required by pumps and compressors, or consumed for water make-up and supply.

On a 24-hour average about 25 MW of electric power would be required for the hydrogen production by electrolysis, up to 1.5 MW for the water make-up, about 4.5 MW for the compression of hydrogen to 10 MPa (100 bar) for on-site storage and 40 MPa (400 bar) for rapid transfer to vehicle tanks at 35 MPa (350 bar). In all, to generate and store hydrogen for 1,000 vehicles per day, the filling station must be supplied with continuous electric power of at least 30 MW. Also, the water consumption for the electrolysis alone would be 107 m^3 per day or about 1.25 liters per second.

For the analyzed case, about 220 MJ/kg are consumed to obtain 142 MJ/kg HHV units of hydrogen. The parasitic power losses associated with an onsite production of hydrogen by electrolysis are of the order of 80 MJ/kg or 56% of the HHV energy content of the delivered hydrogen.

Transfer of Hydrogen

Liquids can be drained from a full into an empty container by action of gravity. No additional energy is required, unless the liquid is transferred from a lower to a higher elevation, or at accelerated flow rates.

However, the transfer of gases is always associated with a loss of pressure, i.e. a loss of energy. The energy losses depend on the specifics of the hydrogen transfer. In our study we find that at least 5 MJ/kg are required to pump hydrogen at filling stations from a large storage tank at 10 MPa (100 bar) into a small vehicle tank at 35 MPa (350 bar). At least 10 MJ/kg of electrical energy is needed to fill hydrogen gas from a 10 MPa storage tank into a 70 MPa tank onboard a hydrogen vehicle. The hydrogen transfer itself may consume up to 8% of the HHV energy content of the gas.

Summary of the Hydrogen Results

The intent of this presentation of the physics of hydrogen and related engineering results is to create an awareness of the fundamental weaknesses of a Hydrogen Economy. As far as we could determine, the upstream energy needed to operate a Hydrogen Economy has not previously been fully assessed. However, the energy cost of producing, packaging, distributing, storing and transferring hydrogen may have been analyzed elsewhere in other contexts. If so, the findings of such studies may be used to confirm or correct our results. Furthermore, readers of this study are invited to refine and extend the analysis.

We summarize our analysis by applying the results to four representative supply paths within a Hydrogen Economy.

A Hydrogen is produced by electrolysis, compressed to 20 MPa and distributed by road to filling stations, stored at 10 MPa, then compressed to 40 MPa for rapid transfer to vehicles at 35 MPa.

B Hydrogen is produced by electrolysis in centralized plants, liquefied and distributed by road to filling stations or consumers, then transferred to vehicles.

C Hydrogen is produced by electrolysis on-site at filling stations or consumers, stored at 10 MPa, then compressed to 40 MPa for rapid transfer to vehicles at 35 MPa.

D Hydrogen is produced by electrolysis and stored in chemical metal hydrides.

Table 1 Parasitic energy consumption for different hydrogen delivery paths

	Energy cost per stage [MJ/kg]	Path A gas [MJ/kg]	Path B liquid [MJ/kg]	Path C onsite [MJ/kg]	Path D hydride [MJ/kg]
Production of H_2					
Electrolysis, central*	64	64	64		32***
Electrolysis, onsite**	80			80	
Packaging					
Compression 20 MPa	10	10			
Liquefaction	30		30		
Chemical hydrides	85				85****
Distribution					
Road, 20 MPa H_2, 200 km	18	18			
Road, liquid H_2, 200 km	6		6		
Transfer					
10 MPa to 40 MPa	5	5		5	
Delivered to User					
Parasitic energy consumption		97	100	85	117
Energy Input / HHV of H_2	142	168%	170%	160%	182%

* Without water makeup, gas compression, electrical losses etc.
** Including water makeup, gas compression, electrical losses etc.
*** Only 50% of the hydrogen released comes from electrolysis
**** Excluding energy needed to produce alkali metals

The analysis reveals that even for idealized processes considerable losses occur between the electrical source energy and the hydrogen energy delivered to the consumer. For road delivery of compressed hydrogen (Path A) the energy input exceeds the HHV energy of the delivered hydrogen by a factor of at least 1.68. In the case of liquid hydrogen (Path B) the factor is 1.70. For on-site hydrogen production (Path C) the factor is 1.60. For delivery of hydrogen by chemical hydrides (Path D) the factor is 1.82. It is unlikely that any of these options would be attractive. Hence pure hydrogen may provide practical solutions for some niche markets, but it may never become the dominant energy vector in a future energy economy, in particular, as options exist for an equally clean sustainable energy future.

Today, the losses between oil wells and filling stations, i.e. the energy required for transportation, refining and distribution, are about 12% giving a well-to-tank efficiency of 88% for the delivery of gasoline. In other terms, 1.14 energy units must be extracted from oil wells to put one energy unit into the tank of a car. In a Hydrogen Economy, at least 1.70 units of energy are consumed to deliver one HHV unit of hydrogen energy to the customer. Most of the energy input is high grade electricity. If generated in coal-fired steam power plants, more than five energy units must be extracted from mines to provide one HHV unit of hydrogen energy to the customer. Hence even in the best attainable case, on an HHV basis the power-plant-to-tank efficiency cannot be much above 50%.

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. Mankind 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 study provides some clues for the strengths and weaknesses of hydrogen as an energy carrier. Certainly the proportion of energy lost depends on the application. The analysis shows that transporting hydrogen gas by pipeline over thousands of kilometers is difficult. Furthermore, the analysis shows 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 co-generation 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. With respect to fuel cells the following fact should be observed.

1. For all portable fuel cell devices the hydrogen energy supply is seriously limited by weight and volume of the hydrogen storage device. The small commercial hydride cartridges weight 250 g, but only contain hydrogen for the generation of 10 Watts DC electricity during one hour with an efficient fuel cell. As stated before, advanced batteries have a similar energy storage density. Also, methanol would be the better energy carrier for portable applications.

2. For all stationary applications energy distribution by wires is far superior to conversion of electricity into hydrogen, transport of the energy gas to the consumer and re-conversion of hydrogen to electricity by fuel cells. While over 90% of the original electric power can be put to use by consumer today, only 20 to 30% would be utilized in case of hydrogen. Even over long distances energy transport in DC cables may prove to be more efficient than the hydrogen solution.

3. For transportation applications, additional difficulties not considered in the foregoing analysis are related to the onboard storage of hydrogen. All standard liquid hydrocarbons fuels carry much more energy and more hydrogen per volume

than 80 MPa or liquefied hydrogen. Liquid hydrocarbons are far superior to hydrogen. Synthetic liquid hydrocarbons like methanol, ethanol or DME (dimethylether) will compete with hydrogen. They are ideal for most transportation applications. The future in the mobile sector may not be pure hydrogen, but hydrogen packaged in synthetic liquid hydrocarbons.

A Synthetic Liquid Hydrocarbon Economy

The hydrogen-only perspective is obscuring the search for a clean energy solution, an energy economy in which synthetic liquid hydrocarbons play an important role. For all transportation applications the ideal energy carrier would be a liquid with a boiling point above 80°C and a freezing point below -40°C. Such energy carriers would remain liquid under normal climate conditions and at high altitudes. Gasoline, diesel fuel (= heating oil) are excellent examples. They are in common use not only because they can be derived from crude oil and natural gas, but mainly because their physical and energetic properties make them ideal for transportation applications. During the early days of oil, they emerged as the best solutions with respect to handling, storage, transport and energy content. Even if oil had never been discovered, the world would not use synthetic hydrogen, but one or more synthetic hydrocarbons for road transport.

As illustrated in Figure 6, a Synthetic Liquid Hydrocarbon Economy could be based on the two natural cycles of water and carbon dioxide, and provide consumer-friendly energy carriers produced entirely from renewable sources. Water is the source of hydrogen while carbon can be taken from the biosphere ("bio-carbon"), i.e. from biomass, organic waste and CO_2 captured from flue gases. Both natural cycles are energized by direct or indirect action of the sun. In addition, renewable energy harvested with technical installations would supply additional energy to the process. The sum of natural and harvested renewable energy would be available to meet society's energy needs. Synthetic liquid hydrocarbons could become the taxis for transporting solar energy to the user.

Typically, biomass has a hydrogen-to-carbon ratio of two. In methanol synthesis, two additional hydrogen atoms are attached to every bio-carbon. Instead of converting biomass into hydrogen, hydrogen from renewable sources or even plain water could be added to biomass by efficient chemical processes to form methanol, ethanol or DME. In a Synthetic Liquid Hydrocarbon Economy, carbon atoms will stay bound in an energy carrier until its final use. They are then returned to the atmosphere and captured by plants and converted to biomass, or they may be directly recycled by CO_2-recovery from flue gases. Due to the lesser upstream energy required, especially for packaging, delivery, storage, and transfer, such Synthetic Liquid Hydrocarbons are environmentally superior to pure hydrogen itself.

Synthetic-Liquid-Hydrocarbon Economy

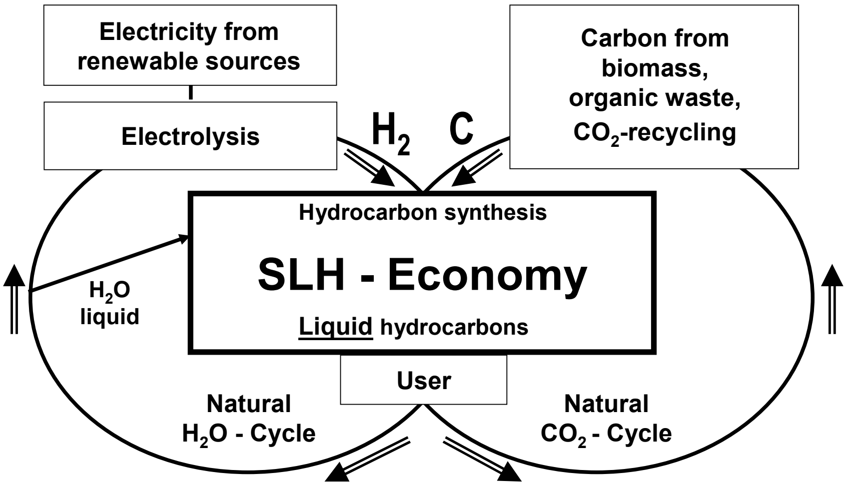

Figure 6 A Synthetic Liquid Hydrocarbon Economy may be based on the two natural cycles of water and carbon dioxide. Natural and synthetic liquid hydrocarbons are provided to the user

Liquid Hydrocarbons

Methanol, ethanol and dimethylether (DME) are favored as gasoline substitutes. The first two can be directly derived from biomass. With respect to density all three substances compare well with gasoline, but their HHV energy content is somewhat less than that of today's favorite fuel. The Higher Heating Values are 22.7, 29.7 or 31.7 MJ/kg for methanol, ethanol and DME, respectively, while gasoline contains about 45 MJ per kg. The three liquids carry between two and almost four times more energy per unit volume than liquid or 80 MPa (800 bar) gaseous Hydrogen.

Also, all of the three substances contain substantially more hydrogen per unit volume than liquid hydrogen. The best way to distribute hydrogen is to combine it with carbon to a liquid fuel. The chemical process technology has been in use for many years.

Methanol can be directly converted to electricity by conventional means or by Direct Methanol Fuel Cells (DMFC), Molten Carbonate Fuel Cells (MCFC) and Solid Oxide Fuel Cells (SOFC). It can also be reformed easily to hydrogen for use in Polymer Electrolyte Fuel Cells (PEFC or PEM) and Alkaline Fuel Cells (AFC). Methanol could become a universal fuel for fuel cells and many other applications.

Ethanol is non-poisonous (in moderation), and may be derived directly from biomass by fermentation, as well as synthesized from bio-carbon and water. Having a relatively high volumetric energy density, it is particularly suitable for use in vehicles. In fact, "Direct Ethanol Fuel Cells" are currently under development.

Hence methanol, ethanol and DME could become the preferred hydrogen carriers in a future energy economy based on renewable energy sources and the recycling of carbon dioxide.

Conclusions

The analysis shows that a "Hydrogen Economy" for road transport would have a low power-plant-to-tank efficiency and hence a low environmental quality. In particular, if the electrical energy were generated in coal-fired power plants, the "mine-to-tank" efficiency might fall below 20%. Even if the hydrogen were used in fuel cells, the overall "mine-to-wheel" efficiency would become comparable to that of the steam engine era in the late part of the 19th century.

The time has come to shift the focus of energy strategy planning, research and development from a visionary “Hydrogen Economy” to a realistic "Sustainable Energy Economy. This will certainly include pure hydrogen as well as synthetic liquid hydrocarbons. But it will be based on energy conservation and physical energy carriers like electricity and district heat rather than the replacement of these proven, efficient and clean energy carriers by an equally clean, but inefficient and unproven hydrogen infrastructure. The limited human, material, and financial resources should be applied to build a sustainable energy future and not to experiment with hydrogen visions, the physical base of which are shaky and often not supported by the laws of nature.

Mankind needs fuel cells not as stepping stones for a Hydrogen Economy, but because of their high efficiency, their environmentally benign behavior and their potentials for small-scale power generation. Mankind needs fuel cells for hydrocarbon fuels, be it with external reformer, or with internal reforming. What mankind does not need is the intellectual alliance between fuel cells and a Hydrogen Economy. The fuel cell industry is threatened by the promotion of hydrogen by individuals who are neither linked to the hydrogen market nor involved in the development of fuel cells, and whose claims are based on visions rather than on hard fact of science and engineering.