Does a Hydrogen Economy Make Sense?

Electricity obtained from hydrogen fuel cells appears to be four times as expensive as electricity drawn from the electrical transmission grid.

By Ulf Bossel

ABSTRACT | 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, not one of politics. It must be based on proven technology and existing engineering experience. The transition process will take many years and should start soon. Unfortunately, politics seems to listen to the advice of visionaries and lobby groups. Many of their qualitative arguments are not based on facts and physics. A secure sustainable energy future cannot be based on hype and activism, but has to be built on solid grounds of established science and engineering. In this paper the energy needs of a hydrogen economy are quantified. Only 20%–25% of the source energy needed to synthesized hydrogen from natural compounds can be recovered for end use by efficient fuel cells. Because of the high energy losses within a hydrogen economy the synthetic energy carrier cannot compete with electricity. As the fundamental laws of physics cannot be chanced by research, politics or investments, a hydrogen economy will never make sense.

KEYWORDS | Electrolysis; electron economy; energy; energy efficiency; heating values; heat of formation; hydrogen; hydrogen compression; hydrogen economy; hydrogen liquefaction; hydrogen pipelines; hydrogen storage; hydrogen transfer; hydrogen transport; metal hydrides; onsite hydrogen generation; reforming

I. INTRODUCTION

The technology needed to establish a hydrogen economy is available or can be developed. Two comprehensive 2004 studies by the U.S. National Research Council [1] and the American Physical Society [2] summarize technical options and identify needs for further improvements. They are concerned with the cost of hydrogen obtained from various sources, but fail to address the key question of the overall energy balance of a hydrogen economy. Energy is needed to synthesize hydrogen and to deliver it to the user, and energy is lost when the gas is converted back to electricity by fuel cells. How much energy is needed to liberate hydrogen from water by electrolysis or high-temperature thermodynamics or by chemistry? Where does the energy come from and in which form is it harvested? Do we have enough clean water for electrolysis and steam reforming? How and where do we safely deposit the enormous amounts of carbon dioxide if hydrogen is derived from coal?

This paper extends a previous analysis of the parasitic energy needs of a hydrogen economy [3]. It argues that the energy problem cannot be solved in a sustainable way by introducing hydrogen as an energy carrier. Instead, energy from renewable sources and high energy efficiency between source and service will become the key points of a sustainable solution. The establishment of an efficient "electron economy" appears to be more appropriate than the creation of a much less efficient "hydrogen economy."

II. THE CHALLENGE

The following examples illustrate the nature of the challenge involved in creating a hydrogen economy.

It takes about 1 kg of hydrogen to replace 1 U.S. gal of gasoline. About 200 MJ (55 kWh) of dc electricity are needed to liberate 1 kg of hydrogen from 9 kg of water by electrolysis. Steam reforming of methane (natural gas) requires only 4.5 kg of water for each kilogram of hydrogen, but 5.5 kg of CO_2 emerge from the process. One kilogram of hydrogen can also be obtained from 3 kg of coal and 9 kg of water, but 11 kg of CO_2 are released and need to be sequestered. Even with most efficient fuel cell systems, at most 50% of the hydrogen HHV energy can be converted back to electricity.

The full dimensions of the challenge become apparent when these numbers are translated to a specific case. The following case study may serve to illustrate the point. About 50 jumbo jets leave Frankfurt Airport every day, each loaded with 130 tons of kerosene. If replaced on a 1 : 1 energy base by 50 tons of liquid hydrogen, the daily needs would be 2500 tons or 36 000 m³ of the cryogenic liquid, enough to fill 18 Olympic-size swimming pools. Every day 22 500 tons of water would have to be electrolyzed. The continuous output of eight 1-GW power plants would be required for electrolysis, liquefaction, and transport of hydrogen. If all 550 planes leaving the airport were converted to hydrogen, the entire water consumption of Frankfurt (650 000 inhabitants) and the output of 25 full-size power plants would be needed to meet the hydrogen demand of air planes leaving just one airport in Germany.

For hydrogen derived from fossil hydrocarbons, the availability of water and the safe sequestration of CO_2 may pose serious problems, not because of inadequate technology, but with respect to logistics, infrastructure, costs, safety, and energy consumption. To fuel the 50 jumbo jets with hydrogen, about 7500 tons of coal and 11 250 tons of water are needed daily and 27 500 tons of carbon dioxide must be liquefied for transport, shipped to a suitable disposal site (perhaps in the deep waters of the mid-Atlantic) and safely deposited. The significant energy needs for hydrogen liquefaction and transport are the same for any source of hydrogen. Fueling the 50 jumbo jets at Frankfurt airport is only an insignificant part of a hydrogen economy. Has the magnitude of the task been recognized?

Questions of this nature need to be addressed before resources are invested in a hydrogen infrastructure. The mission should not be the development of technology and the introduction of new energy carriers, but the establishment of a sustainable energy future. There are other options to be considered before we make major commitments to a hydrogen future.

III. SUSTAINABLE ENERGY FUTURE

In this paper, fossil and nuclear energy are defined as unsustainable because the resources are finite and the waste cannot be absorbed by nature. If one accepts this definition, renewable energy harvested in a sustainable way becomes the key to a sustainable energy future.

With the exception of biomass, all renewable energy is of a physical nature: heat (solar, geothermal), solar radiation (photovoltaic) and mechanical energy (wind, hydro, waves, etc.). Heat obtained from solar collectors, geothermal sources, and waste incineration may also be converted to electricity. Thus, in one vision of a sustainable future, electricity from renewable sources will become the dominant primary energy carrier replacing chemical carriers of today's economy.

Physical energy provided by nature is best distributed as physical energy without intermediate chemical carriers, because, excepting food, people need physical energy for transport, space conditioning, fabrication processes, cooking, lighting, and communication. Hydrogen would make sense only if its production, distribution, and use are superior to the distribution of electricity by wires.

For centuries hydrogen has fascinated people. Hydrogen can be derived from water and other chemical compounds. The conversion of hydrogen to heat or power is often simplified by the popular equation "hydrogen plus air yields electricity and drinking water." Also, hydrogen, the most common chemical element on the planet, is hailed as an everlasting energy source [5]. But nature does not provide hydrogen in its elemental form. High-grade energy (electricity or heat) is needed to liberate hydrogen from its chemical source.

Economy means trade. A hydrogen economy involves all economic stages between hydrogen production and hydrogen use, i.e., between renewable electricity received to electrolyzers and useful electricity drawn from fuel cells. Between the two ends of the economic chain hydrogen has to be packaged by compression or liquefaction to become a commodity. In the transportation, hydrogen has to be produced, packaged, transported, stored, transferred to cars, then stored and transported again before it is finally admitted to fuel cells.

All these processes require energy. Compared to natural gas (methane) or liquid fuels much more energy is required for the marketing of hydrogen. This is directly related to the physical properties of hydrogen (density 0.09 kg/m³, boiling point 20.3 K [6], [7]). Compared to methane, the volumetric energy density of hydrogen is less than one third. Even in the liquid state, the density of hydrogen (70 kg/m³) is not much above the density of heavy duty styrofoam. Gasoline and even wood pellets carry 3.5 or 1.2 times more energy per volume than liquefied hydrogen. One cubic meter of the cold liquid holds 70 kg, the same volume of gasoline 128 kg of hydrogen. The best way to store hydrogen is in chemical combination with carbon. The volumetric higher heating values (HHV) of common energy carriers are shown in Fig. 1

IV. ENERGY NEEDS OF A HYDROGEN ECONOMY

The energy needed to produce, compress, liquefy, transport, transfer, and store hydrogen and the energy lost for its conversion back to electricity with fuel cells can never be recovered [3]. The heat of formation or HHV has been used throughout to base the analysis on true energy contents in agreement with the law of energy conservation.

In contrast, the lower heating value (LHV), a man-created accounting convention, is appropriate only when energetic processes are compared for identical fuels. In
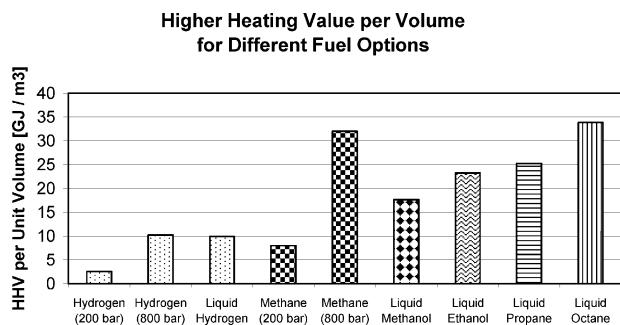
Higher Heating Value per Volume for Different Fuel Options

Fig. 1. *Volumetric HHV energy density of different fuels.*

many "well-to-wheel" studies [8], [9], hydrogen solutions are embellished by 10% as a result of an LHV accounting. When hydrogen is made by whatever process at least the heat of formation HHV of the synthetic energy carrier has to be invested in form of electricity, heat, or HHV energy content of precursor materials. For a correct accounting the output of a fuel cell should also be related to the HHV, not the LHV energy content of the hydrogen gas. Also, LHV accounting may turn conventional energy equipment into perpetual motion machines with efficiencies exceeding 100%. The use of the higher heating value HHV is appropriate for all serious energy analyses [10].

Although cost of energy is an important issue, this study is only concerned with energy balances. Energy is needed for solving the energy problem and energy waste has to be minimized. However, a quick visit to the market is helpful. According to [11], every GJ of hydrogen energy will cost around $5.60 when produced from natural gas, $10.30 from coal, and $20.10 from electrolysis of water. Before taxes, gasoline costs about $3.00 per GJ.

A. Production of Hydrogen by Electrolysis

Making hydrogen from water by electrolysis is an energy-intensive process. However, in a sustainable energy future, this is the direct route from renewable electricity to a chemical energy carrier. The standard potential for the water formation is 1.48 V, corresponding to the heat of formation or the higher heating value HHV of hydrogen. For advanced solid polymer or alkaline electrolyzers about 0.1 V is lost by polarization, while $0.2 \, \Omega-cm^2$ is typical for the area-specific resistance. For an atmospheric low-temperature electrolyzer, the characteristic shown in Fig. 2 is representative.

Under optimized conditions the electrolyzer is operated at 2.00 V and a current density of about 2.00 A/cm^2. Compared to 1.48 V, about 1.35 times higher voltage has to be applied for an rate-optimized hydrogen production resulting in an electric process efficiency of about 75%.

The electrolysis is frequently performed under pressure. In that case, part of the electrical energy input is used

for an isothermal compression. Pressure is not obtained for free, but by this meaningful procedure compression losses and equipment costs are reduced. Pressure electrolysis offers energetic and commercial advantages over atmospheric electrolyzers.

Electrolysis may be the only practical link between renewable energy and hydrogen. Although solar or nuclear heat can also be used for high-temperature cyclic processes, it is unlikely that a recognizable fraction of the global energy demand can be served with hydrogen from solar concentrators or high-temperature reactors. Local wind farms may deliver energy at lower costs than distant solar or nuclear installations.

B. Hydrogen From Biomass

Hydrogen from biomass is another option with uncertain future. Biomass has to be converted to biomethane by aerobic fermentation or gasification before hydrogen can be made. However, biomethane of natural gas quality (above 96% CH$_4$) is already a perfect fuel for transport and stationary applications. Why reform it to hydrogen? In many European countries, biomethane from sewage digesters is already sold at fueling stations to a growing number of satisfied drivers.

In a sustainable future, hydrogen could also be obtained by reforming of alcohols or wood. This is not likely to happen, because the listed biofuels are much better energy carriers than hydrogen. The inherent value of these substances is the natural bond of hydrogen and carbon atoms. By chemical rearrangement (e.g., Fischer Tropsch) it is possible to synthesize liquid hydrocarbons for long distance transport by air, ship, rail, or road. Hydrogen production from biomass shall not be considered in this context.

Using autothermal processes the conversion can be very efficient. The process heat obtained by burning some of the biomass is transferred to the hydrogen stream. Industrial natural gas reformers generate hydrogen with energetic HHV efficiencies of 90%. Today, this is the most economical method to obtain hydrogen. As stated earlier,
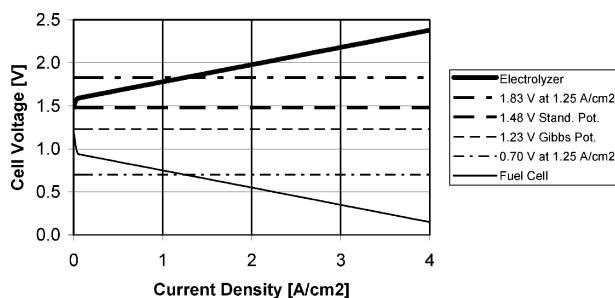

Fig. 2. *Voltage–current characteristics of hydrogen electrolyzer and fuel cell.*

hydrogen production from fossil hydrocarbons is not here considered sustainable.

C. Packaging of Hydrogen by Compression

Compressing gas requires energy. The compression work depends on the thermodynamic process. Ideal isothermal compression, which is impossible in practice, follows the simple equation

$$W = p_0 V_0 \ln(p_1/p_0).$$

For ideal gases, and real gases far above their boiling temperature, the actual thermodynamic process is more closely described by the adiabatic compression equation [12]

$$W = [\gamma/(\gamma - 1)]p_0 V_o \left[(p_1/p_0)^{(\gamma-1)/\gamma} - 1 \right] \quad (1)$$

where

|	
W [J/kg]	specific compression work;
p_0 [Pa]	initial pressure;
p_1 [Pa]	final pressure;
V_0 [m³/kg]	initial specific volume;
γ [−]	ratio of specific heats, adiabatic coefficient.

In both isothermal and adiabatic compression, the compression work is the difference between the final and the initial energy states of the gas. At identical final pressures, the different compression processes yield different temperatures of the compressed medium. In the ideal isothermal case, the temperature would remain constant, while it rises considerably under adiabatic conditions. Moreover, the compression work depends on the nature of the gas.

For example, for hydrogen and methane, the adiabatic coefficients and initial specific volumes are

$$\begin{aligned} \text{H}_2 \quad & \gamma = 1.41 \quad V_0 = 11.11 \text{ m}^3/\text{kg} \\ \text{CH}_4 \quad & \gamma = 1.31 \quad V_0 = 1.39 \text{ m}^3/\text{kg}. \end{aligned}$$

For adiabatic compression of diatomic hydrogen and five-atomic methane from atmospheric conditions to higher pressures, the energy consumed is shown in Fig. 3. Compared to methane, about nine times more energy per kg is required to compress hydrogen, and 15 times more (ratio of molecular masses) than for air. The energy consumption for compression of hydrogen is substantial and has to be considered.

Multistage compressors with intercoolers operate somewhere between the isothermal and adiabatic limits. Compared with methane, hydrogen passes the compression heat faster to the cooler walls thus bringing the process closer to isothermal. Data provided by a leading
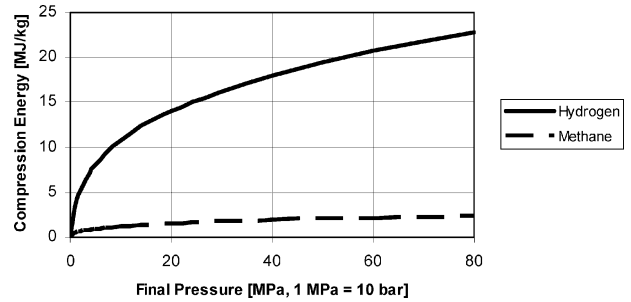

Fig. 3. *Adiabatic compression work versus final pressure for hydrogen and methane.*

manufacturer of hydrogen compressors [13] show that the energy required for a five-stage compression of 1000 kg of hydrogen per hour from ambient pressure to 20 MPa is about 7.2% of its HHV. Adiabatic, isothermal, and a multistage compression of hydrogen are compared in Fig. 4.

For multistage compression to a final pressure of 20 MPa, about 8% of the HHV energy content of hydrogen is required. This analysis does not include any losses in the electrical power supply system. At least 1.08 units of energy must be invested in compression to obtain 1 unit of hydrogen HHV at 20 MPa. The number becomes 1.12 for compression to 80 MPa for hydrogen transfer to the proposed 70 MPa standard vehicle tanks of automobiles. If mechanical and electrical losses are also considered, the total electricity needs for compression may reach 20% of the HHV hydrogen energy leaving the process.

D. Packaging of Hydrogen by Liquefaction

Even more energy is needed to compact hydrogen by liquefaction. Theoretically, only about 14.2 MJ/kgLH$_2$ have to be removed to cool hydrogen gas from 298 K (25 °C) to 20.3 K and to condense the gas at 20.3 K and atmospheric pressure [14]. However, at such low
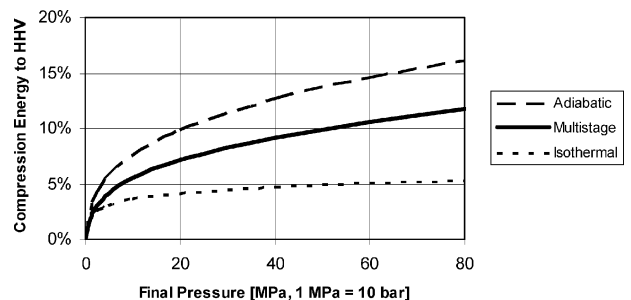
Fig. 4. *Energy required for the compression of hydrogen compared to its higher heating value.*

temperatures, no heat sinks exist for cooling and condensing hydrogen. Generally, a three-stage propane refrigeration system is used for cooling hydrogen gas from ambient temperature to about 170 K, followed by multistage nitrogen expansion to obtain 77 K, and a multistage helium compression–expansion to complete the liquefaction of hydrogen at 20.3 K and atmospheric pressure [15]. The energy consumed by these three stages is much higher than the exergetic limit mentioned above. Therefore, published data of representative hydrogen liquefaction plants are used for reference.

The medium size liquefaction plant of Linde Gas AG at Ingolstadt in Germany produces 182 kg/h of LH_2 [16] at a specific energy consumption of about 54 MJ/$kgLH_2$ [14]. Advanced larger plants in the United States require 36 MJ/$kgLH_2$ to liquefy hydrogen [14]. In a Japanese feasibility study [17] of a hydrogen liquefaction plant of 300 metric tons LH_2 per day or 12 500 $kgLH_2$/h, the best case power consumption is given at 105.2 MW. This corresponds to 30.3 MJ/$kgLH_2$ for a plant about six times larger than any existing facility. The use a helium–neon mixture for the low-temperature cycle has been suggested to reduce the energy consumption to, perhaps, 25.2 MJ/$kgLH_2$($= 7$ kWh/$kgLH_2$) for a plant producing 7200 $kgLH_2$ per hour, or 173 metric tons LH_2 per day [14]. However, experimental results are not yet available.

The real-world requirements are much higher. Twenty-five hundred metric tons of liquid hydrogen would be required daily to fuel 50 jumbo jets departing from Frankfurt Airport. For this, 22 500 m^3 of clean water must be split by electrolysis. Hydrogen production and liquefaction consumes the continuous output of eight 1-GW power plants. The numbers may be multiplied by five if Frankfurt airport were totally converted to hydrogen.

Large liquefaction plants are more efficient than small facilities. The variation of energy consumption with capacity for existing hydrogen liquefaction plants [18] is reflected in Fig. 5. More electrical energy is consumed for the liquefaction of hydrogen in small plants than in large facilities.

For very small liquefaction plants (> 5 $kgLH_2$/h), the energy needed to liquefy hydrogen may exceed the HHV

Fig. 5. *Liquefaction energy relative to the HHV of hydrogen versus plant capacity.*

energy. Even 10 000 $kgLH_2$/h plants (perhaps four times larger than any existing liquefaction facility) would consume about 25% of the HHV energy of the liquefied hydrogen. For the available technology, 40% would be a reasonable number. On other words, 1.4 units of energy would have to be supplied to the liquefier as hydrogen and electricity to obtain 1 HHV unit of liquid hydrogen. However, no liquefaction plants of comparable performance have yet been built.

Moreover, liquid hydrogen storage systems lose some hydrogen gas by boiloff. This is due to unavoidable heat leakage, and must be permitted for safety reasons. The loss rate is dependent on the size of the store, but would be significant for those used in vehicles, and may amount to 3%–4% a day [19]. Boiloff hydrogen has to be vented from parked vehicles. For example, when a car is left at an airport for two weeks, 50% of the original hydrogen may be lost by evaporation.
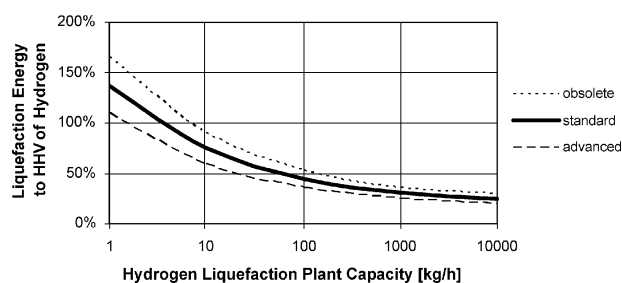
E. Physical Metal Hydrides

Hydrogen may be stored physically, e.g., by adsorption in spongy matrices of special alloys of metal hydrides. The hydrogen forms a very close physical, but not a perfect chemical bond with alloys like $LaNi_5$ or $ZrCr_2$.

The energy balance shall be described in general terms. Again, energy is needed to produce and compress hydrogen. Some of this energy is lost. Also, heat is released and normally lost when metal hydride storage containers are filled with hydrogen. Conversely, heat must be added to liberate the stored hydrogen from the hydrides. The energy needed to store hydrogen in physical metal hydrides and to liberate it later is significantly more than the energy needed to compress the gas to 3 MPa, the typical filling pressure of hydride storage containers [20].

However, according to [21], metal hydrides store only around 55–60 kg of hydrogen per m^3 of storage volume. For comparison, liquid hydrogen has a volumetric density of 70 kg/m^3. Moreover, metal hydride cartridges are heavy. A small metal hydride container holding less than 2 g of hydrogen has a weight of 230 g. Hence, around 50 kg of hydrides are required to store 1 kg of hydrogen, the equivalent of about 4 L or 1 U.S. gal of gasoline. Hydride storage of hydrogen is not practical for automotive application, unless the volumetric and gravimetric energy density of the storage medium can be raised. Today, the specific energy density of metal hydride storage devices is comparable to that of advanced Li–Ion batteries.

F. Chemical Metal Hydrides

Hydrogen may also be stored chemically in alkali metal hydrides. Alkali metal hydrides have high energy densities with gravimetric energy content comparable to firewood. The weight of alkali hydride materials poses no problems. One kg of CaH_2 or LiH reacting with water yields 13.6 or 36.1 MJ of HHV hydrogen energy,

respectively. However, the energy needed to produce the alkali metal hydrides would discourage their commercial use on a larger scale.

There are many options in the alkali group like LiH, NaH, KH, and 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 [22]. None of these compounds can be found in nature. All have to be synthesized from pure metals and hydrogen.

Let us consider the case of calcium hydride CaH_2. The compound is produced by combining calcium metal with hydrogen at 480 °C. Energy is needed to extract calcium from calcium carbonate (limestone) and hydrogen from water by electrolysis according to the following endothermic processes:
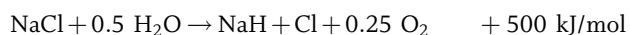
$$CaCO_3 \rightarrow Ca + CO_2 + 1/2 \ O_2 \qquad + 808 \ kJ/mol$$
$$H_2O \rightarrow H_2 + 1/2 \ O_2 \qquad + 286 \ kJ/mol.$$
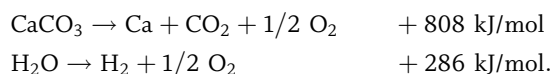
Some of the energy is recovered when the two elements are combined at 480 °C by an exothermic process

$$Ca + H_2 \rightarrow CaH_2 \qquad - 192 \ kJ/mol.$$
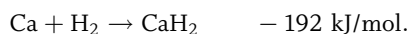
The three equations combine to the virtual net reaction

$$CaCO_3 + H_2O \rightarrow CaH_2 + CO_2 + O_2 \qquad + 902 \ kJ/mol.$$

Similarly, for the production of NaH and LiH from NaCl or LiCl, one obtains

$$NaCl + 0.5 \ H_2O \rightarrow NaH + Cl + 0.25 \ O_2 \qquad + 500 \ kJ/mol$$

and

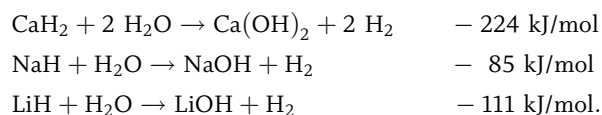$$LiCl + 0.5 \ H_2O \rightarrow LiH + Cl + 0.25 \ O_2 \qquad + 460 \ kJ/mol.$$
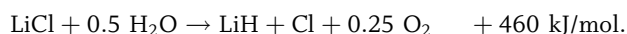
The material is then cooled to room temperature under hydrogen, granulated, and packaged in airtight containers.

In use, the hydrides react vigorously with water, and release heat and hydrogen

$$CaH_2 + 2 \ H_2O \rightarrow Ca(OH)_2 + 2 \ H_2 \qquad - 224 \ kJ/mol$$
$$NaH + H_2O \rightarrow NaOH + H_2 \qquad - 85 \ kJ/mol$$
$$LiH + H_2O \rightarrow LiOH + H_2 \qquad - 111 \ kJ/mol.$$

In fact, the reaction of hydrides with water produces twice the hydrogen contained in the hydride compound itself, because the water is reduced in the process while the hydrides are oxidized to hydroxides. Normally, the generated heat is lost by cooling. For three common hydrides, the energy balances are shown in Table 1.

For hydrogen storage in hydrides, at least 1.6 times more high-grade energy has to be invested to produce 1 HHV energy unit of hydrogen, resulting in a stage efficiency of less than 60%.

G. Road Delivery of Hydrogen

Although pipeline transport is preferred for gases, hydrogen transport by trucks will play a role in a hydrogen economy. Because of the low density of the gaseous energy carrier, transport of pressurized or liquid hydrogen is extremely inefficient. Forty-ton trucks can carry only 350 kg of hydrogen at 200 bar in the gaseous, or 3500 kg in the liquid state. The bulk weight is steel for pressure tanks and cryogenic vessels. It takes about 22 hydrogen tube trailers to deliver the same amount of energy as a single gasoline tanker.

The energy analysis is based on information obtained from some of the leading providers of industrial gases in Germany and Switzerland: Messer-Griesheim [23], Esso (Schweiz) AG [24], Jani GmbH [25], and Hoyer [26]. The following assumptions are made. Hydrogen gas (at 20 MPa = 200 bar), liquid hydrogen, methanol, ethanol, propane, and octane (representing gasoline) are trucked from the refinery or hydrogen plant to the consumer. Trucks with a gross weight of 40 metric tons are fitted with suitable containers. Fuel consumption is 40 kg of diesel fuel per 100 km and metric ton. The engine efficiency does not depend on the vehicle weight.

Table 1 Energy Input of Alkali Metal Hydride Production

		Ca-Hydride	Na-Hydride	Li-Hydride
Hydride production from		$CaCO_3$	NaCl	LiCl
Energy to make hydride	kJ/mol	902	500	460
H_2 liberated from hydride	mol/mol	2	1	1
Production of H_2	g/mol	4	2	2
Energy input / H_2	MJ/kg	225	250	230
HHV of H_2	MJ/kg	142	142	142
Energy input / HHV of H_2	-	1.59	1.76	1.62

The 40-metric-ton tanker trucks are designed to carry a maximum of fuel. For liquids like gasoline, ethanol, and methanol, the payload is about 26 metric tons. One hundred percent of the liquid fuels are delivered to the customer. In contrast, only 80% of the compressed gases are transferred by blow-down. The remaining 20% of the gas load is returned to the gas plant. Such pressure cascades are standard practice today. As a consequence, the payload of pressurized gas carriers is 80% of the load. However, in anticipation of technical developments, this analysis assumes that in future, trucks will be able to carry 4000 kg methane or 500 kg of hydrogen, of which 80% (3200 kg or 400 kg, respectively) are delivered to the consumer.

The transport of liquid hydrogen is limited by volume, not by weight. A large trailer-truck may have a useful box volume of 2.4-m width, 2.5-m height, and 10-m length, i.e., 60 m^3. As the density of 70 kg/m^3, only 4200 kg of liquid hydrogen could possibly be loaded. But space is needed for the cryogenic container, thermal insulation, safety equipment, etc. In fact, a large truck has room for about 2100 kg of the cryogenic liquid. However, trucking liquid hydrogen is more energy efficient than delivering the pressurized gas.

For common energy carriers, Fig. 6 shows the ratio of energy consumed for delivery compared to the energy delivered to the customer. The energy needed to transport any of the liquid hydrocarbon fuels is reasonably small. For a one-way delivery distance of 100 km, the diesel fuel consumption remains below 0.5% of the HHV energy content of the delivered liquid fuels. However, for delivering pressurized hydrogen, the parasitic energy consumption is significant. About 7% of the delivered energy is consumed for delivery, about 13 times more than for gasoline. For liquid hydrogen the ratio is about 3.5.

H. Pipeline Delivery of Hydrogen

Hydrogen pipelines exist to transport the chemical commodity "hydrogen" from sources to production sites.

The energy required to deliver the gas is part of the production process and energy costs are absorbed in the final price of the product. People do not mind paying for hydrogen in aspirin, plastic materials, or steel. However, energy is the currency in pipeline transport of hydrogen. Parasitic energy losses reduce the amount of energy available for useful purposes. Hydrogen transport by pipelines has to compete with electricity transport by wires.

The assessment of the energy required to pump hydrogen through pipelines is derived from natural gas pipeline operating experience. It is assumed that the same amount of energy is delivered through identical pipelines. In reality, existing pipelines must be modified for hydrogen, because of diffusion losses (mainly in sealing areas), brittleness of materials and seals, compressor lubrication, and other technical issues. Also, as the volumetric HHV energy content of hydrogen is about 3.5 times less than that of natural gas, pipes of larger diameters are needed to accommodate similar energy flow rates. Natural gas is diluted by adding hydrogen, not upgraded.

In our analysis, the symbols have the following meaning:

V_o volumetric flow rate $[m^3/s]$;
A cross section of pipe $[m^2]$;
v flow velocity of the gas [m/s];
Δp pressure drop [Pa];
D pipeline diameter [m];
L pipeline length [m];
ρ density of the gas $[kg/m^3]$;
HHV   higher heating value of the transported gas [MJ/kg];
Re   Reynolds number;
η dynamic viscosity [kg/(m s)];
ζ resistance coefficient.

The energy flow through the pipeline $Q[W]$

$$Q = V_o \rho HHV = A v \rho HHV. \tag{2}$$

At a pressure of 1 MPa ($= 10$ bar), the densities of methane and hydrogen are 7.2 and 0.9 kg/m^3, respectively. According to (2), for the same energy flow through a pipeline of the same diameter, the velocity of hydrogen has to be 3.13 times that of methane.

The Reynolds number is given by

$$Re = \rho v D / \eta. \tag{3}$$

At a pressure of 1 MPa, the dynamic viscosities of methane and hydrogen are 11.0×10^{-6} and 8.92×10^{-6} kg/(s m), respectively [27]. Hence, according to (3) and for a pipe diameter of 1 m, the Reynolds numbers of methane and hydrogen are 6.55×10^6 and

Fig. 6. *Energy needed for the road delivery of fuels relative to their HHV energy content.*

3.16×10^6, respectively. Since both values greatly exceed 2000, the flow regime is turbulent in both cases.

For turbulent flow the theoretical pumping power N [W] requirement is given by

$$N = V_o \Delta p = A v \Delta p = p/4 \; D^2 v \Delta p$$
$$= p/4 \; D^2 v \; L/D \; 1/2 \; \rho v^2 \zeta. \qquad (4)$$

From (4), the ratio of the theoretical pumping powers N_{H2} for hydrogen and N_{CH4} for methane, is

$$N_{H2}/N_{CH4} = (\rho_{H2}/\rho_{CH4})(v_{H2}/v_{CH4})^3. \qquad (5)$$

Hence, for the same energy flow hydrogen requires about 3.85 times more energy than for natural gas.

Typically, a compressor is installed every 150 km for natural gas transport through pipelines at 10 m/s. The compressor motors are fueled from the gas taken from the stream, each compressor consuming about 0.3% of the local energy flow [28]. Applying this model to the transport of hydrogen through the same pipeline, (5), each compressor would require 3.85 more energy or 1.16% of the local energy flow. The remaining mass flow is decreasing with pipeline length. This crude model needs to be refined by pipeline experts. It does not consider the higher energy needs for hydrogen compression discussed above.

For a pipeline length of 3000 km (e.g., for gas from Russian fields to Germany), the mass fraction consumed for transporting natural gas is about 20%, while transporting hydrogen gas over the same distance would require about 35% of the original mass flow. This result was obtained for pipes of equal diameter.

In Fig. 7, the energy consumed for transport is related to the HHV of the delivered gases. For a transport distance of 3000 km, at least 1.5 kg of hydrogen must be fed into the line for the delivery of 1 kg to the customer. Moving hydrogen over long distances by pipeline is not a good option. However, hydrogen pipelines have been suggested for the transport of solar energy from northern Africa or the Middle East to central Europe.
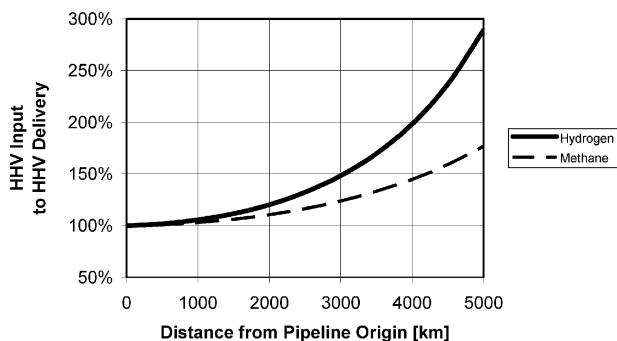
I. On-Site Generation of Hydrogen

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 and compress hydrogen by this scheme is compared to the HHV energy content of the hydrogen transferred to cars. Natural gas reforming is not a sustainable solution and thus not considered for the reasons stated earlier.

Consider a filling station now pumping 60 000 L of fuel (gasoline or diesel) into 1000 cars, trucks, or buses per day. This number is typical for service areas along European freeways. In most parts of the United States, many smaller filling stations are located roadside at freeway exits. On a 1 : 1 energy base, 60 000 L of fuel corresponds to about 17 000 kg of hydrogen. However, hydrogen vehicles are assumed to have a 1.5 times higher tank-to-wheel efficiency than IC engine cars [29]. The frequently cited number of 2.5 cannot be justified any longer in light of the high efficiency of diesel or hybrid vehicles. In fact, the well-to-wheel studies of 2002 [8], [9] are based on lower heating values, optimistic assumptions of fuel cells, and disregard of the efficiency potentials of diesel engines and hybrid systems. The shortcoming of LHV analyses is discussed in [30]. Furthermore, more recent well-to-wheel studies appropriately based on the higher heating values [10] do not identify hydrogen-fuel-cell cars as the best transportation option. In fact, the efficiency of all-electric cars is three times better than for hydrogen-fuel-cell vehicles [31].

Under the favorable assumption of a 1.5 advantage of hydrogen versus gasoline, 60 000 liters of fuel will be replaced by 12 000 kg of hydrogen per day. The electrolyzer efficiency may be 75%. Also, losses occur in the ac–dc power conversion. Making 12 000 kg of hydrogen per day by electrolysis requires 25 MW of continuous power and 108 000 liters of water must be pumped and demineralized. Compression power is needed for storing the hydrogen to 10 MPa and for transfer at 40 MPa to vehicle tanks at 35 MPa. In all, to generate and store 12 000 kg of hydrogen per day, the filling station must be supplied with continuous electric power of about 28 MW. There are many sites in arid regions where neither the electricity nor the water is available for hydrogen production.

The final results of this analysis are shown in Fig. 8. For 12 000 kg of hydrogen per day (this corresponds to 1000 conventional vehicles per day), about 1.65 units of energy must be invested to obtain 1 unit of hydrogen HHV, giving a stage efficiency of 60%.

Fig. 7. *HHV hydrogen energy fed into the pipeline inlet compared to HHV hydrogen energy delivered at the pipeline outlet.*
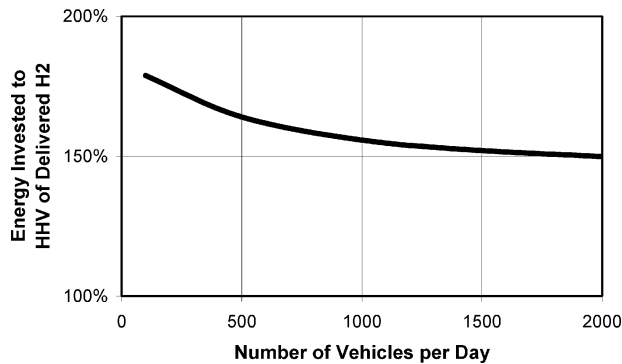
Fig. 8. *Energy needed for on-site generation of hydrogen by electrolysis stored at 10 MPa and subsequent compression to 40 MPa for rapid transfer to 35 MPa vehicle tanks relative to the HHV energy content the hydrogen.*

Assuming continuous operation, a 1-GW electric power plant must be available for every 20–30 hydrogen filling stations on European freeways. Today, about one fifth of the total energy consumption is electricity. The national electric power generating capacity must be significantly increased to power the transition from fossil fuels to hydrogen. It may be difficult to derive the needed electrical energy from "renewable sources" as suggested by hydrogen promoters. One would certainly use off-peak power from wind and solar sources for hydrogen production. However, electrolyzers, pumps, and storage tanks must be sized for peak demand during rush hours and vacation traffic. Not only must the electric peak power demand be considered, but also the storage of substantial amounts of hydrogen to meet the daily and seasonal demands at filling stations.

J. Transfer of Hydrogen

Liquids can be drained from a full tank into an empty container by gravity. No additional energy is required, unless the transfer is from a lower to a higher level, or at accelerated flow rates.

However, energy is needed to transfer hydrogen from a voluminous low-pressure storage container into the small high-pressure tank of a fuel cell vehicle. This adds to the parasitic energy consumption of a hydrogen economy. The amount of energy required for gas transfer by pumping is given by the difference of the work needed to compress the gas to final pressure p_2 (e.g., 40 MPa) and work needed to reach the intermediate pressure p_1 of the large volume store (e.g., 10 MPa).

Consider the following typical case. For multistage compressors, the compression work is about twice the ideal isothermal compression

$$W \approx 2 p_0 V_0 \left[\ln(p_2/p_0) - \ln(p_1/p_0) \right] \qquad (6)$$

where
W [J/kg]   specific compression work;
p_0 [Pa]   initial pressure;
p_1 [Pa]   intermediate pressure;
p_2 [Pa]   final pressure;
V_0 [m³/kg]   initial specific volume.
For the example case

$$\begin{aligned} p_0 &= 10 \text{ MPa} \quad (= 1 \text{ bar}) \\ p_1 &= 10 \text{ MPa} \quad (= 100 \text{ bar}) \\ p_2 &= 40 \text{ MPa} \quad (= 400 \text{ bar}) \\ V_0 &= 11.11 \text{ m}^3/\text{kg} \\ p_0 V_0 &= 1.111 \text{ MJ/kg}. \end{aligned}$$

To transfer the remaining hydrogen from the supply tank into the receiving tank by a multistage compression, the energy required is

$$W = 1.54 \text{ MJ/kg}.$$

This is about 1.1% of the HHV energy content of the compressed hydrogen. Including mechanical and electrical losses of the small compressors installed at the filling stations, this number may be closer to 3%. Moreover, to transfer hydrogen from a large storage tank at 10 MPa into a small vehicle tank at 35 MPa would require at least 4.32 MJ/kg or, including other losses, at least 3% of the HHV energy content of the transferred hydrogen. Hence, to transfer one unit of HHV hydrogen energy from a 10-MPa storage tank to a 35-MPa vehicle tank requires at least 1.08 units of (electrical) energy for the transfer against pressure.

At least 1.08 electrical energy units must be invested to transfer 1 HHV hydrogen energy unit from a 10-MPa storage vessel to the 70-MPa gas tank of a hydrogen vehicle.

V. ENERGY EFFICIENCY OF A HYDROGEN ECONOMY

When the original report [3] was published in 2003, the parasitic energy needs of a hydrogen economy had not even been considered by promoters of a hydrogen economy. The intent of the original study was to create an awareness of the fundamental energetic weaknesses of using hydrogen as an energy vector. Since then equations and results for producing, packaging, distributing, storing, and transferring hydrogen have been checked by others and found correct.

For selected hydrogen strategies, the accumulated parasitic energy needs of all important stages can be determined by multiplication or addition of the losses of
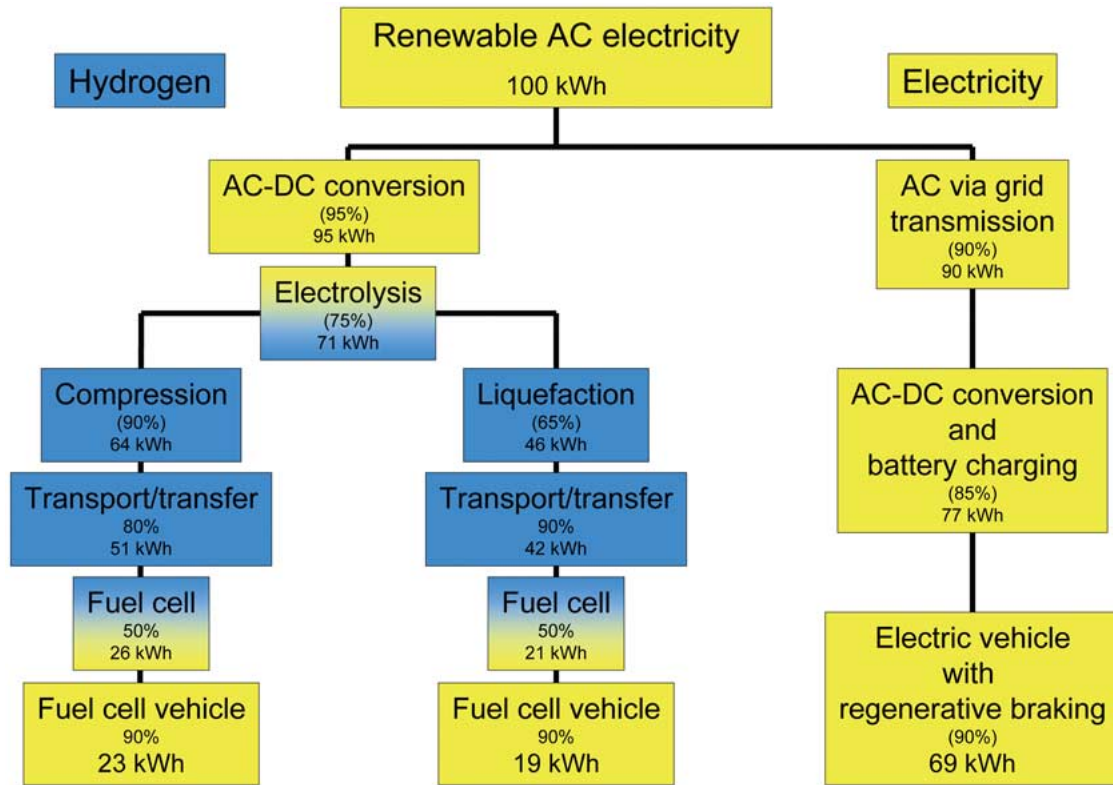
Fig. 9. *Useful transport energy derived from renewable electricity.*

the stages involved. Four cases may serve to illustrate the point [3].

- 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.
  Energy input to hydrogen energy delivered: 1.59
- B) Hydrogen is produced by electrolysis, liquefied, and distributed by road to filling stations, then transferred to vehicles.
  Energy input to hydrogen energy delivered: 2.02
- C) Hydrogen is produced by electrolysis on-site at filling stations or consumers, stored at 10 MPa, and subsequently compressed to 40 MPa for rapid transfer to vehicles at 35 MPa.
  Energy input to hydrogen energy delivered: 1.59
- D) Hydrogen is produced by electrolysis and used to make alkali metal hydrides. Hydrogen is then released by reaction of the hydride with water.
  Energy input to hydrogen energy delivered: 1.90

The analysis reveals that between 1.6 and 2.0 electrical energy units must be harvested from renewable sources for every energy unit of hydrogen gas sold to the user. The high energy losses may be tolerated for some niche markets, but it is unlikely that hydrogen will ever become an important energy carrier in a sustainable energy economy built on renewable sources and efficiency.

Moreover, the delivered hydrogen must be converted to motion for all transport applications. IC engines convert hydrogen within 45% efficiency directly into mechanical motion, while equally efficient fuel cells systems produce dc electricity for traction motors. Further losses may occur in transmissions, etc. All in all, hardly 50% of the hydrogen energy contained in a vehicle tank is converted to motion of a car. The overall efficiency between electricity from renewable sources and wheel motion is only 20 to 25%. In comparison, over 60% of the original electricity can be used for transportation, if the energy is not converted to hydrogen, but directly used in electric vehicles [30]. Fig. 9 illustrates the energy flow for transportation systems based on hydrogen or electricity. The energy advantages of battery-electric cars over hydrogen-fuel-cell-electric vehicles are obvious. However, further work is needed in the area of electricity storage, converters, drive systems, and electricity transfer.

VI. HYDROGEN ECONOMY OR ELECTRON ECONOMY

The foregoing analysis of the parasitic energy losses within a hydrogen economy shows that a hydrogen economy is an

extremely inefficient proposition for the distribution of electricity from renewable sources to useful electricity from fuel cells. Only about 25% of the power generated from wind, water, or sun is converted to practical use. If the original electricity had been directly supplied by wires, as much as 90% could have been put to service. This has two serious consequences to be considered in future energy strategies.

A) About four renewable power plants have to be erected to deliver the output of one plant to stationary or mobile consumers via hydrogen and fuel cells. Three of these plants generate energy to cover the parasitic losses of the hydrogen economy while only one of them is producing useful energy. Can we base our energy future on such wasteful schemes?

B) As energy losses will be charged to the customer, electricity from hydrogen fuel cells will be at least four times more expensive than electricity from the grid. Who wants to use fuel cells? Who wants to drive a hydrogen-fuel-cell car?

Fundamental laws of physics expose the weakness of a hydrogen economy. Hydrogen, the artificial energy carrier, can never compete with its own energy source, electricity, in a sustainable future.

The discussion about a hydrogen economy is adding irritation to the energy debate. We need to focus our attention on sustainable energy solutions. It seems that the establishment of an efficient electron economy should become the common goal. There are many topics to be addressed, like electricity storage and automatic electricity transfer to vehicles, yet electric cars equipped with Li–Ion-batteries already have a driving range of 250 km [32]. In 2010, Mitsubishi will commercialize an electric car with 260 hp on four wheels and a driving range of 500 km (300 mi). It seems that by focusing attention on hydrogen we are missing the chance to meet the challenges of a sustainable energy future.

The title question "Does a hydrogen economy make sense?" must be answered with a definite "Never." However, niche applications for the use of hydrogen energy are abundant and should be addressed. ∎

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    After two years as Assistant Professor at Syracuse University, he returned to Germany to lead the free molecular flow research group at the DLR in Göttingen. He left the field for solar energy in 1976, was founder and first president of the German Solar Energy Society, and started his own R&D consulting firm for renewable energy technologies in 1979. In 1986, Brown Boveri asked him to join their new technology group in Switzerland. He became involved in fuel cells in 1987 and later (after BBC's merger with Asea to ABB) director of the company's fuel cell development efforts worldwide. After ABB decided to concentrate its resources on the development of conventional energy technologies, he established himself as a freelance fuel cell consultant, with clients in Europe, Japan, and the United States. He has created and is still in charge of the annual fuel cell conference series of the European Fuel Cell Forum in Lucerne, Switzerland.