# The Future of the Hydrogen Economy: Bright or Bleak?

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## Introduction

Hydrogen is a fascinating carrier of energy. Its conversion to heat or power is simple and clean. When combusted with oxygen hydrogen forms water. No pollutants are generated or emitted. The water is returned to nature where it originally came from. But hydrogen, the most common chemical element on the planet, does not exist in nature in its pure form. It has to be generated or "produced" by separating it from chemical compounds. Hydrogen can be produced from water by electrolysis, from hydrocarbon fuels by reforming or thermal cracking, or from other hydrogen carriers by chemical processes. But clean energies such as electricity from solar, wind and hydro must be applied to produce clean hydrogen, i.e. without greenhouse gases or nuclear waste being generated in the production process. Hydrogen may actually be the only meaningful link between renewable energy and chemical energy carriers.

Hydrogen has fascinated generations of people with good intentions. Promoters of hydrogen claim that a "Hydrogen Economy" will be the ultimate solution to all problems of energy and environment. Hydrogen societies have been formed for the promotion of this goal by publications, meetings and exhibitions. But has the physics also been properly considered?

With this article we intent to take a closer look at some of the energy aspects related to the use of hydrogen as energy carrier. The "Hydrogen Economy" involves not only production and use of hydrogen, but also all other ingredients of an energy market like packaging, storage, delivery and transfer. This market can flourish if the energy consumed within the market itself is small compared to the energy delivered to the customer. Today, the energy lost in power transmission, oil refineries or sea and land transport of fuels usually amounts to less than 10% of the energy traded. Therefore, we would like to present rough estimates of the energy required to operate a "Hydrogen Economy".

One important reason for the renewed interest in the hydrogen economy is the problem of global warming. Eighty percent of all commercial energy on earth is provided by fossil fuels. It is almost certain that the use of fossil hydrocarbons and the resulting emission of greenhouse gases such as carbon dioxide cause global warming. It has never been more urgent to find energy resources that do not cause any emissions of green house gases. Renewable energy from the sun, wind, water and biomass are such energy sources, but they have to be converted to chemical energy for the general energy market. Hydrogen may provide that link. Another possible path is to continue using fossil fuels for producing hydrogen but to capture and sequester $CO_2$, before it is emitted into the atmosphere.

Without question, technical solutions exist or can be developed for a hydrogen economy. In fact, enormous amounts of hydrogen are generated, handled, transported and used in the chemical industry today. But this hydrogen is a chemical substance, not an energy commodity. Hydrogen production and transportation costs are absorbed in the price of the synthesized chemicals. The cost of hydrogen remains irrelevant as long as the final products find markets. Today, the use of hydrogen is governed by economic arguments and not by energetic considerations.

But if hydrogen is used as an energy carrier, energetic argument must also be considered. How much high-grade energy is used to make, to package, to handle, to store or to transport hydrogen? The global energy problem cannot be solved in a renewable energy environment, if the energy consumed to make and deliver hydrogen becomes comparable to the energy content of the delivered fuel. It is important to assess and compare the energy balances of different energy path options. Are they as efficient as possible? Will there be only the hydrogen path in future? In the following presentation we show that the future hydrogen economy is unlikely to be based on pure hydrogen only. It will certainly be based on hydrogen, but most likely, the synthetic fuel gas will be chemically packed in consumer-friendly hydrocarbons.

In the following article we present preliminary results of a detailed study by the authors [1]. The study will be published in its entirety later this year.

## Properties of Hydrogen

The physical properties of hydrogen are well known [2, 3]. It is the smallest of all atoms. Consequently, hydrogen is the lightest gas, about 8 times lighter than methane (representing natural gas). Hydrogen has a gravimetric heating value (we consider only the higher heating value HHV in this study) of [9]:

| | | | |
|---|---|---|---|
| Hydrogen: | HHV | 142 MJ/kg | (Higher Heating Value "HHV") |
| | LHV | 120 MJ/kg | (Lower Heating Value "LHV") |
| compared to methane: | HHV | 55.5 MJ/kg | |
| | LHV | 50.0 MJ/kg | |

The volumetric heating values are (1 bar, 25°C):

| | |
|---|---|
| HHV $H_2$: | 11.7 kJ/liter |
| LHV $H_2$: | 9.9 kJ/liter |
| HHV $CH_4$: | 36.5 kJ/liter |
| LHV $CH_4$: | 32.9 kJ/liter |

The gravimetric heating value has little relevance for the hydrogen trade. The volume available for fuel tanks is always limited, not only in automotive applications. The diameter of pipelines cannot be increased at will. Therefore, for all practical assessments it is more meaningful to use the volumetric rather than the gravimetric energy density. Hydrogen has to be compacted by compression or liquefaction for storage, transport or transfer. In today's energy economy the handling of natural gas and liquid fuels does not pose major problems. But is this also true for hydrogen?

Figure 1 shows the volumetric HHV energy densities of different energy carrier options. At any pressure, hydrogen gas clearly carries less energy per volume than methane (representing natural gas), methanol, propane or octane (representing gasoline). At 800 bar pressure gaseous hydrogen reaches the volumetric energy density of liquid hydrogen. But the volumetric energy density of methane at 800 bar is higher by factor 3.2. The common liquid energy carriers methanol, propane and octane (representing gasoline) surpass liquid hydrogen by factors 1.7 to 3.4, respectively. But at 800 bar or in the liquid state hydrogen must be contained in hi-tech pressure tanks or in cryogenic containers, while the liquid fuels are kept under atmospheric conditions in unsophisticated containers.

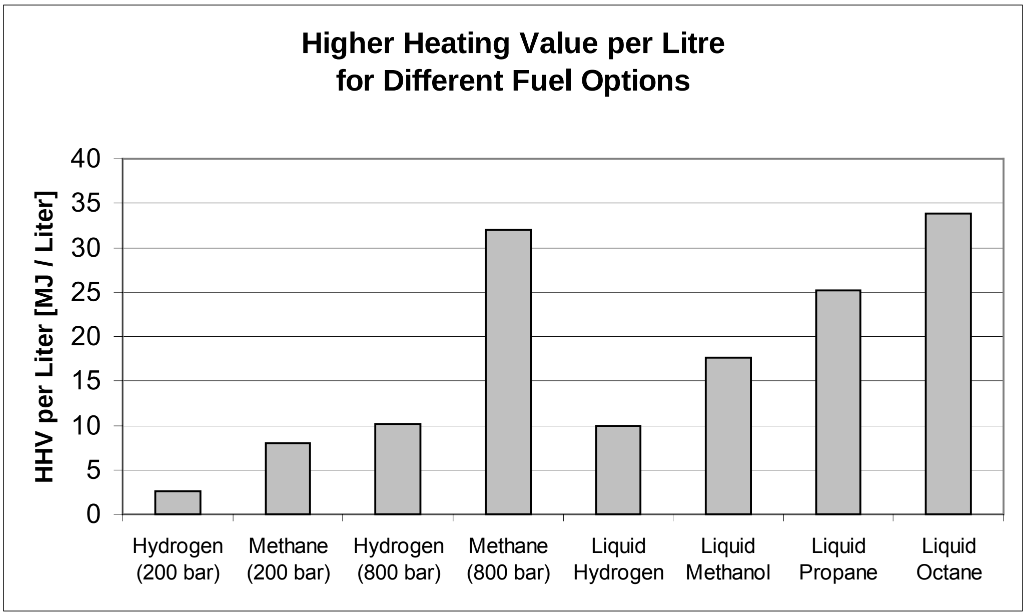


Figure 1 Volumetric HHV energy density for different fuels

# Energy Cost of Energy in a Hydrogen Economy

Hydrogen is a synthetic energy carrier. High-grade energy must be invested to produce, compress, liquefy, transport, transfer or store hydrogen. In most cases this energy could also be distributed directly to the end user. Also, instead of gaseous hydrogen, other liquid hydrocarbons such as methanol could serve as the general energy carrier of the future. Carbon from biomass or $CO_2$ captured from flue gases could become the essential chemical carrier molecule for hydrogen generated with energy derived from renewable or nuclear sources.

We want to emphasize that not only the monetary cost of hydrogen is important and should be as low as possible, but also the energy cost of synthesizing hydrogen and bringing it to the end user. As stated before, the hydrogen economy will be meaningful, only if the energy consumed to produce, package, store and distribute hydrogen should be as low as possible compared to the energy content of the delivered fuel gas. So far, this aspect has not been properly recognized. But because of the physical properties of the light gas, the hydrogen economy differs significantly from the natural gas economy. The energy invested to extract and clean natural gas is small compared to its energy content. Not so for hydrogen! The transition to a new energy economy will affect the entire energy supply and distribution system. Therefore, we should discuss the prominent options before investing in a hydrogen gas economy.

Some of the more important energetic aspects of a hydrogen economy are analyzed in the following. The aim of this study [1] is to provide a first rough assessment of the amount of energy invested to make, compress, liquefy, transport, transfer or store hydrogen as compared to the amount of energy contained in the delivered fuel and to compare the results with similar analyses for established energy carriers. Throughout the study only representative technical solutions will be considered.

# Production of Hydrogen

## Energy Needed to Produce Hydrogen

Hydrogen does not exist in nature in its pure state, but has to be produced from sources like water and natural gas. The synthesis of hydrogen requires energy. This process is always associated with energy losses. Hydrogen production by both, electrolysis or chemical reforming is a process of energy transformation. Electrical energy or chemical energy of hydrocarbons is transferred to chemical energy of hydrogen.

Making hydrogen from water by electrolysis is the most energy-intensive way to produce the fuel. But it is a clean process as long as the electricity comes from a clean source. Less energy is needed to convert a hydrogen-rich energy carrier like methane ($CH_4$) or methanol ($CH_3OH$) into hydrogen by steam reforming, but the energy invested always exceeds the energy contained in the hydrogen. Thermal losses limit the efficiency of hydrogen production by reforming to about 90%. Consequently, more $CO_2$ is released by this "detour" process than by direct use of the hydrocarbon precursors. We assume efficiencies of 75% for electrolysis and 85% for reforming. About 1.2 to 1.4 energy units of valuable electricity, natural gas, gasoline etc. have to be invested to obtain one energy unit of hydrogen. But most of these source energies could be used directly by the consumer at comparable or even higher source-to-service efficiency and lower overall $CO_2$ emission.

Upgrading electricity or clean hydrocarbon fuels to hydrogen does not provide a universal solution to the energy future, although some sectors of the energy market may depend on hydrogen solutions. The transportation sector may be one of them. It should be mentioned that it is considerably more expensive to produce hydrogen with electricity from water than thermally from fossil fuels. According to [10] it costs around $5.6/GJ to produce hydrogen from natural gas, $10.3 /GJ to produce hydrogen from coal, but $20.1/GJ to produce hydrogen through electrolysis.

# Packaging of Hydrogen

## Energy Needed to Compress Hydrogen

Energy is needed to compress gases. The compression work depends on the thermodynamic compression process. The ideal isothermal compression cannot be realized. The adiabatic compression equation [2] is more closely describing the thermodynamic process for ideal gases.

$$W = [n/(n-1)]\, p_o V_o\, [(p_1/p_o)^{(n-1)/n} - 1] \qquad (1)$$

with

| | | |
|---|---|---|
| $W$ | specific compression work | J/kg |
| $p_o$ | initial pressure | Pa = N / m$^2$ |
| $p_1$ | final pressure | Pa = N / m$^2$ |
| $V_o$ | initial specific volume | m$^3$/kg |
| $n$ | adiabatic coefficient, ratio of specific heats | |

The compression work depends on the nature of the gas. This is illustrated by comparing hydrogen with helium and methane

| | | |
|---|---|---|
| $H_2$ | n = 1.41 | $V_o$ = 11.11 m$^3$/kg |
| He | n = 1.66 | $V_o$ = 5.56 m$^3$/kg |
| $CH_4$ | n = 1.31 | $V_o$ = 1.39 m$^3$/kg |

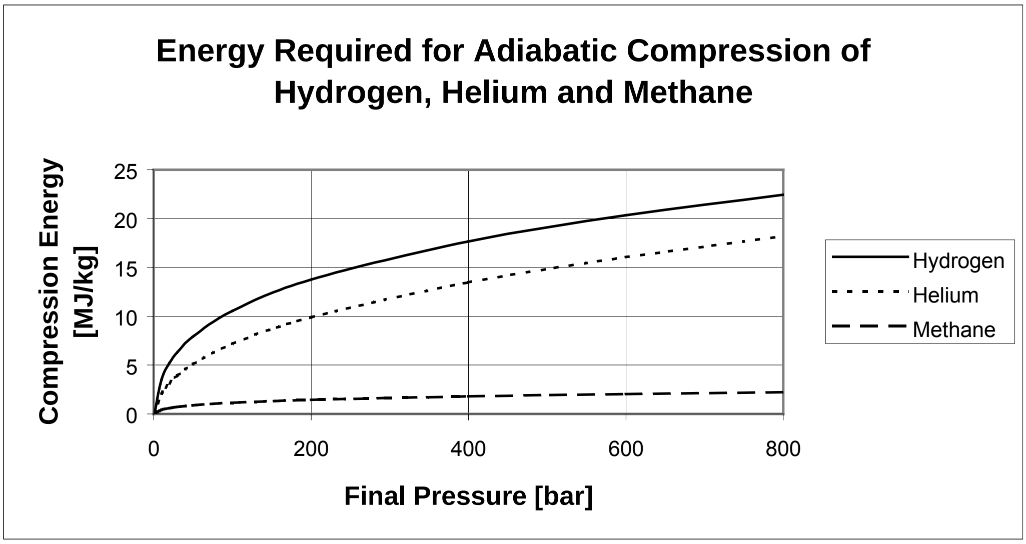


Figure 2 Adiabatic compression work for hydrogen, helium and methane

The energy invested in the adiabatic compression of ideal monatomic Helium, diatomic hydrogen and five-atomic methane from atmospheric conditions (1 bar = 100,000 Pa) to the final pressure is shown in Figure 2. Clearly, much more energy is required to compress hydrogen than methane.

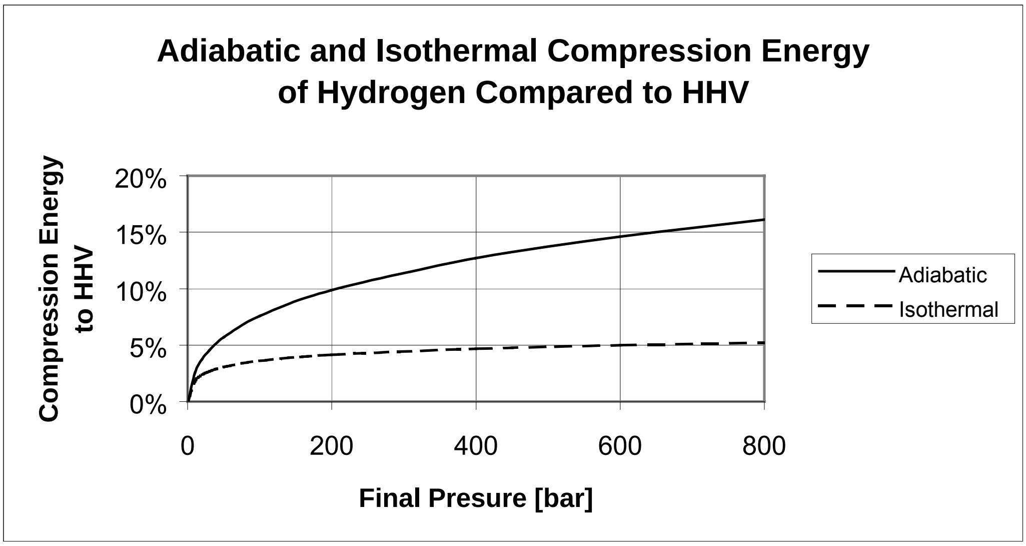


Figure 3 Energy required for adiabatic and isothermal ideal-gas compression of hydrogen compared to its higher heating value HHV.
The isothermal compression energy is determined by the simple equation: $W = p_o V_o \ln(p_1/p_o)$

Figure 3 illustrates the difference between adiabatic and isothermal ideal-gas compression of hydrogen. Multi-stage compressors with intercoolers operate between the two limits. Also, hydrogen readily passes compression heat to cooler walls, thereby approaching isothermal conditions. Numbers provided by a leading manufacturer [5a] of hydrogen compressors show that the energy invested in the compression of hydrogen is about 7.2% of its higher heating value (HHV). This number relates to a 5-stage compression of 1,000 kg of hydrogen per hour from 1 to 200 bar. For a final pressure of 800 bar 10% would perhaps be a realistic value. The analysis does not include losses in the electric motor.

## Energy Needed to Liquefy Hydrogen

Even more energy is needed to compact hydrogen by liquefaction. Theoretically only about 4MJ/kg have to be removed to cool hydrogen down to 20K (-253°C) and to condense the gas at atmospheric pressure. But the cooling process is extremely energy intensive with a Carnot efficiency of 7%. A theoretical analysis of the complicated, multi-stage liquefaction processes is difficult. We therefore use the actual energy requirements of existing hydrogen liquefaction plants as compiled by Linde Kryotechnik AG [5b]. The company is a well-known supplier of cryogenic equipment and cryogenic liquids.

The results of the compilation of the energy consumption of existing hydrogen liquefaction plants have been adapted to make them compatible with the current study. The liquefaction energy requirement depends on the process itself, the process optimization, the plant size, and on other parameters. Figure 4 shows the actual liquefaction energy consumption for plants having a capacity between 1 to 10,000 kg of liquid hydrogen per hour.

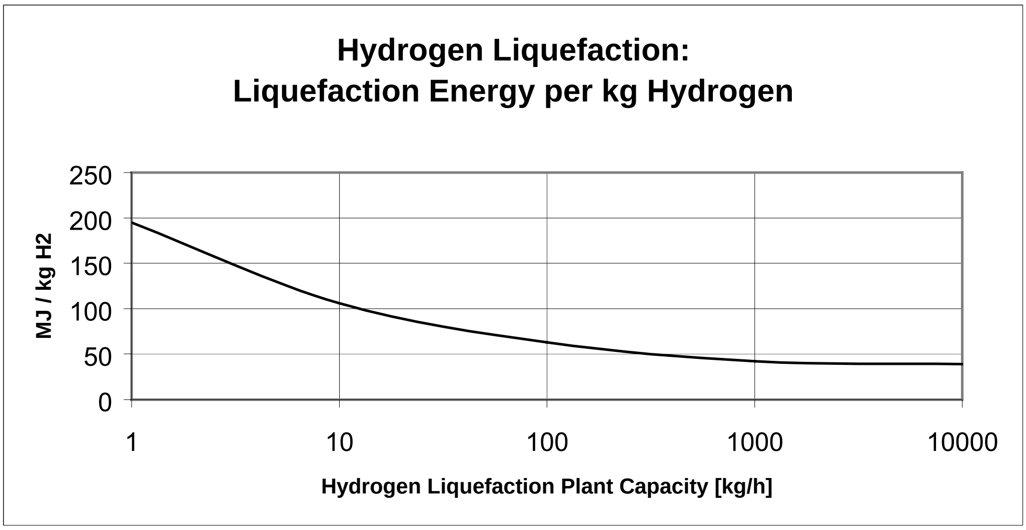


Figure 4 Typical energy requirements for the liquefaction of 1 kg hydrogen as a function of plant size and process optimization

The energy requirement for liquefaction is substantial. For a plant capacity of 100 kg liquid hydrogen per hour about 60 MJ of electrical energy is consumed to liquefy 1 kg of hydrogen. The specific energy input decreases with plant size, but a theoretical minimum of about 40 MJ per kg $H_2$ remains.

In Figure 5 the required energy input is compared to the higher heating value HHV of hydrogen.

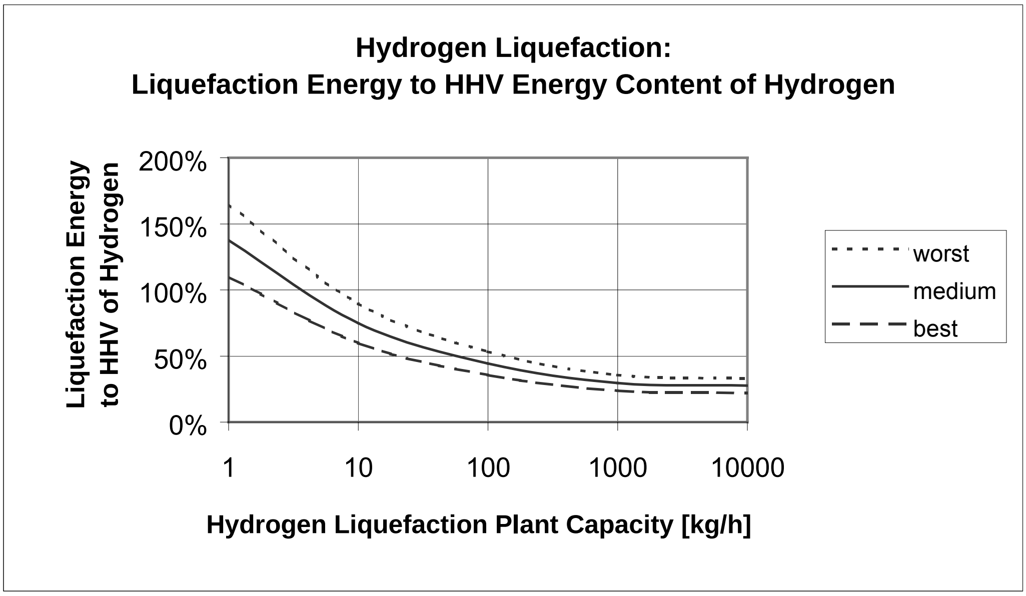


Figure 5 Typical energy requirements for the liquefaction of 1 kg hydrogen compared to HHV of Hydrogen

For small liquefaction plants the energy needed to liquefy hydrogen may exceed the HHV of the gas. But even with the largest plants (10,000 kg/h) about 30% of the HHV energy is needed for the liquefaction process.

## Energy Needed to Store Hydrogen in Hydrides

At this time only a generalized assessment can be presented for the physical (e.g. adsorption on metal hydrides) or chemical (e.g. formation of alkali metal hydrides) storage of hydrogen. There are many options for both types of hydrogen storage. This makes it difficult to present numbers. But a few cautious statements may be allowed.

The laws of nature certainly apply to this type of hydrogen storage as well. In the chemical case, a substantial amount of energy is needed to combine hydrogen with alkali metals. This energy is released when the hydrogen is liberated from the compound. The generated heat has to be removed by cooling and is normally lost.

For the physical hydride storage, the hydrogen gas must be pressurized. The energy required for compression has been assessed before. The compression energy is released as heat during the charging process. Also, external heating is needed to liberate the hydrogen from the hydride storage material. According to Ref. [11], p. 264 metal hydrides store only around 55-60 kg($H_2$)/$m^3$ compared to 71 kg($H_2$)/$m^3$ for liquid hydrogen. But 100 kg of hydrogen are contained in one cubic meter of methanol.

Hydride storage of hydrogen is by no means a low-energy process, but it may be compared to the compression of hydrogen. Generalized numbers cannot be presented today.

# Delivery of Hydrogen

## Energy Needed to Deliver Hydrogen by Road Transport

A hydrogen economy would certainly involve some hydrogen transport by trucks. There are other options for a hydrogen infrastructure, but road transport will always play a role, be it to serve remote locations or to provide back-up fuel to filling stations at times of peak demand.

The comparative analysis is based on information obtained from the fuel and gas transport companies Messer-Griesheim [6a], Esso (Schweiz) [6b], Jani GmbH [6c] and Hover [6d] some of the leading providers of industrial gases in Germany and Switzerland. The following assumptions are made: Hydrogen (at 200 bar), methane (at 200 bar), methanol, propane and octane (representing gasoline) are trucked from the refinery or hydrogen plant to the consumer. The delivery of liquid hydrogen is not considered at this time. In all cases, trucks with a gross weight of 40 tons are fitted with suitable tanks or pressure vessels. Also, at full load the trucks consume 40 kg of Diesel per 100 km. This is equivalent of 1 kg per ton per 100 km. The fuel consumption is reduced accordingly for the return run with emptied tanks. We assume the same engine efficiency for all transport vehicles.

Furthermore, the hydrogen and methane pressure tanks can be emptied only from 200 bar to about 42 bar to accommodate for the 40 bar pressure systems of the receiver. Such pressure cascades are standard praxis today. Otherwise compressors must be used to completely empty the content of the delivery tank into a higher-pressure storage vessel. This would not only make the gas transfer more difficult, but also require additional compression energy. Therefore, pressurized gas carriers deliver only 80% of their freight, while 20% of the load remains in the tanks and is returned to the gas plant.

Each 40-ton truck is designed to carry a maximum of fuel. For methanol and octane the tare load it is about 25 tons, for propane about 20 tons because of some degree of pressurization. At 200-bar pressure a 40-ton truck can deliver about 3.2 tons of methane, but only 320 kg of Hydrogen. This is a direct consequence of the low density of hydrogen, as well as the weight of the pressure vessels and safety armatures. In anticipation of technical developments, the analysis was performed for 500 kg of hydrogen, of which 80% or 400 kg are delivered to the consumer. With this assumption, 39.6 tons of dead weight have to be moved on the road to deliver 400 kg of hydrogen.

The results of this analysis are presented in Figure 6. The energy needed to transport any of the three liquid fuels is reasonably small. It remains below 5% of the HHV energy content of the delivered commodity for a delivery distance of

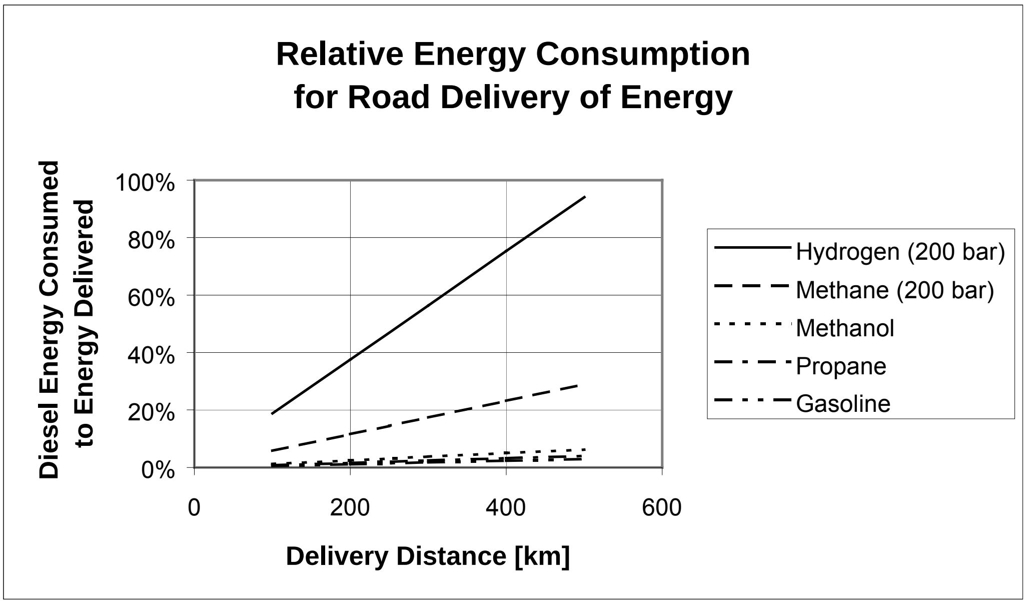


Figure 6 Energy needed for the road delivery of fuels compared to their HHV energy content

500 km. More energy is needed to truck methane. But the relative energy consumption becomes unacceptable for hydrogen at almost any distance.

The following note may serve to illustrate the consequences of the scenario. A mid-size filling station on any frequented freeway easily sells 25 tons of fuel each day. This fuel can be delivered by one 40-ton gasoline truck. But it would need 21 hydrogen trucks to deliver the same amount of energy to the station, i.e. to provide fuel for the same number of cars per day. Efficient fuel cell vehicles would change this number somewhat, but not considerably. The transfer of pressurized hydrogen from the truck to the filling station takes much more time than draining gasoline form the tanker into an underground storage tank. The filling station may have to close operations during some hours per day for safety reasons.

Today about one in 100 trucks is a gasoline or diesel tanker. For hydrogen distributed by road one may see 120 trucks on the road, 21 or 17% of them transport hydrogen. One out of six accidents involving trucks would involve a hydrogen truck. This scenario is unacceptable for political and social reasons.

## Energy Needed to Deliver Hydrogen through Pipelines

Hydrogen pipelines exist, but they are used to transport a chemical commodity from one to another production site. The energy required to move the gas is irrelevant in this context, because energy costs are part of the production costs. This is not so for energy transport through pipelines. Normally, pumps are installed at regular intervals to keep the natural gas moving. These pumps are energized by energy taken from the delivery stream. About 0.3% of the natural gas is used every 150 km to energize a compressor to keep the gas moving [7].

The assessment of the energy consumed to move hydrogen through pipelines must be based on a rough comparison with natural gas pipeline operating experience. The comparison is done for equal energy flows, i.e. the same amount of energy is delivered to the customer through the same pipeline either in the form of natural gas or hydrogen. But it is well established, though, that existing pipelines cannot be used for hydrogen, because of diffusion losses, brittleness of materials and seals, incompatibility of pump lubrication with hydrogen and other technical issue. The comparison further considers the different viscosities of hydrogen and methane.

The theoretical pumping power N [W] requirement is given by

$$N = V_o \, \Delta p = A \, v \, \Delta p = \pi/4 \, D^2 \, v \, \Delta p = \pi/4 \, D^2 \, v \, 1/2 \, \rho \, v^2 \, \zeta \quad (2)$$

with $\zeta = 0.31164 / Re^n$ (3)

and $Re = \rho \, v \, D / \eta$ (4)

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]
- $\Delta p$ pressure drop [Pa]
- $D$ pipeline diameter [m]
- $\rho$ density of the gas [$kg/m^3$]
- $\zeta$ resistance coefficient

| | |
|---|---|
| Re | Reynolds number |
| n | = 0.25 for turbulent pipe flow (Blasius equation) [8] |
| $\eta$ | dynamic viscosity [kg/(m s)] |

Furthermore, the flow of energy through the pipeline, Q [J/s] is given by

$$Q = V_o \rho \, HHV \qquad (5)$$

with HHV being the higher heating value of the transported gas.

Combining equations (2), (3), (4) and (5) one can asses the theoretical pumping power $N_{H2}$ for hydrogen and $N_{CH4}$ for methane and relate both to each other. One obtains

$$N_{H2} / N_{CH4} = (\eta_{H2} / \eta_{CH4})^n \; (\rho_{CH4}/ \rho_{H2})^2 \; (HHV_{CH4} / HHV_{H2})^{3-n} \qquad (6)$$

Since the pumps run continuously, the power ratio also represents the ratio of energy consumption.

Because of the low volumetric energy density of hydrogen, the flow velocity must be increased by over three times. Consequently, the flow resistance is increased, but the effect is partially compensated for by the viscosity difference. Still, about 4.6 times more energy is required to move hydrogen through the pipeline than is needed for the same natural gas energy transport.

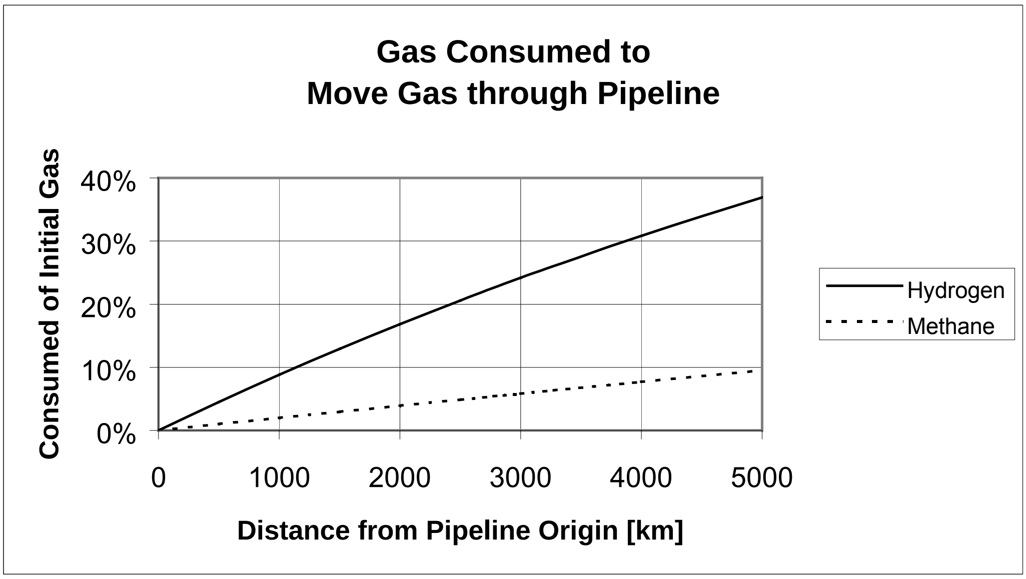


Figure 7 Energy needed to move hydrogen and methane through pipelines compared to the HHV energy content of the delivered gases.

Figure 7 shows the results of this approximate analysis. While the energy consumption for methane (representing natural gas) appears reasonable, the energy needed to move hydrogen through pipelines makes this type of hydrogen distributions difficult. Not 0.3% but almost 1.4% of the hydrogen flow is consumed every 150 km to energize the compressors. Only 60 to 70% of the hydrogen fed into a pipeline in Northern Africa would actually arrive in Europe

## Energy Needed to Generate Hydrogen at Filling Stations

One option for providing clean hydrogen at filling stations and dispersed depots would be to generate the gas on-site by electrolysis. Again, the energy needed to generate and compress hydrogen by this scheme is compared to the HHV energy content of the hydrogen delivered to local customers. Natural gas reforming is not considered for reasons stated earlier.

The analysis is done for hydrogen energy equivalent of conventional fuel necessary to serve 100 to 2,000 conventional road vehicles per day at a single gas station. On the average, each car or truck is assumed to accept 60 liters of gasoline or diesel. The hydrogen energy equivalent would be about 1,700 to 34,000 kg $H_2$ per day for 100 and 2000 vehicles per day, respectively.

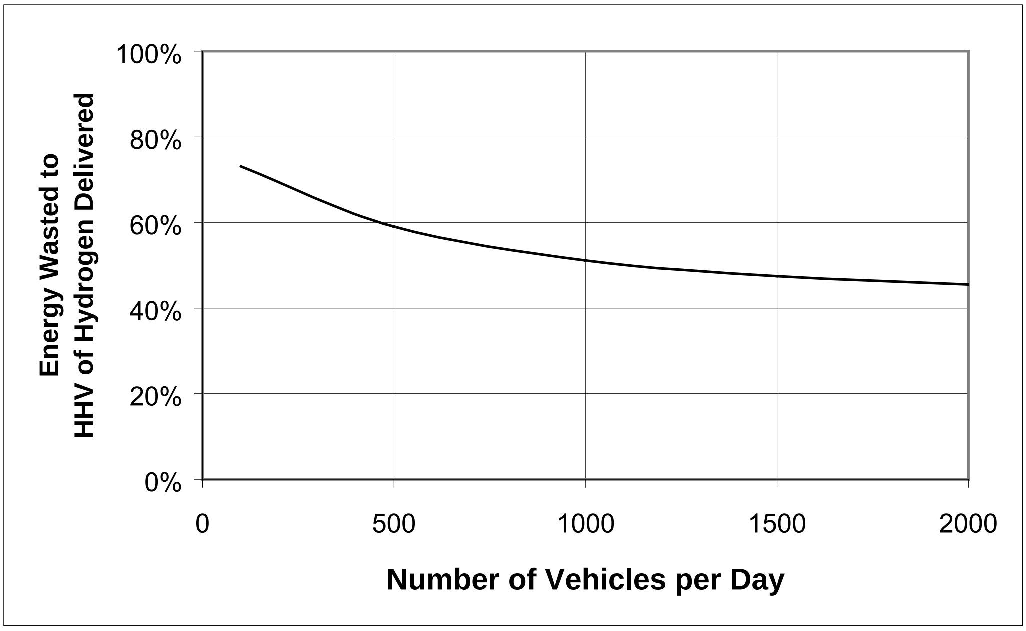


Figure 8 Energy wasted to generate hydrogen by electrolysis and to compress it to 200 bars at filling stations compared to the HHV energy content of the hydrogen delivered to road vehicles

The efficiency of the electrolysers varies from 70 to 85% for 100 and 2,000 vehicles per day, respectively. Also, losses occur in the AC-DC power conversion. Between 4 and 73 MW of power are needed for making hydrogen by electrolysis. Additional power is needed for the water make-up (0.1 to 2.2 MW) and for the compression of the hydrogen to 200 bar (0.4 to 6.MW). In all, between 5 and 81 MW of electric power must be supplied to the station to generate hydrogen for 100 to 2,000 vehicles per day.

It may be of interest that between 15 and 305 $m^3$ of water are consumed daily. The higher number corresponds to about 3.5 liters per second.

The results of this analysis are presented in Figure 8. The total energy needed to generate and compress hydrogen at filling stations exceeds the HHV energy of the delivered hydrogen by at least factor 1.5. The availability of electricity may certainly be questioned. Today, about one sixth of the energy for end-use is supplied by copper wires. The generation of hydrogen at filling stations would make a threefold increase of the electric power generating capacity necessary.

## The Limits of a Hydrogen Economy

The results of this analysis indicate the weakness of a "Pure-Hydrogen-Only-Economy". All problems are directly related to the nature of hydrogen. Most of the problems cannot be solved by additional research and development. We have to accept that hydrogen is the lightest of all gases and, as a consequence, that its physical properties are incompatible with the requirements of the energy market. Production, packaging, storage, transfer and delivery of the gas, in essence all key component of an economy, are so energy consuming that alternatives should be considered. Mankind cannot afford to waste energy for idealistic goals, but it will look for practical solutions and select the most energy-saving solutions. The Pure-Hydrogen-Only solution may never be acceptable.

But the degree of energy waste depends on the chosen path. Hydrogen generated from rooftop solar electricity and stored at low pressure in stationary tanks may be a viable solution for private buildings. On the other hand, hydrogen generated in the Sahara desert, transported to the Mediterranean Sea through pipelines, then liquefied for sea transport, docked in London and locally distributed by trucks may not provide an acceptable energy solution at all. Too much energy is lost in the process to justify the scheme. But there are solutions between these two extremes, niche applications, special cases or luxury installations. For instance, combusting the hydrogen at the same site where it is produced, as the Norwegian company Norsk Hydro suggested some years ago, is probably a workable solution. Simply because there is no transport and storage involved. Norsk Hydro proposed to separate natural gas on shore into hydrogen and carbon dioxide, sequester the carbon dioxide under the North Sea and burn the hydrogen in a power plant to make clean electricity.

As stated in the beginning, hydrogen may be the only link between physical energy from renewable sources and chemical energy. It is also the ideal fuel for modern clean energy conversion devices like fuel cells or even hydrogen engines. But hydrogen is not the ideal energy carrier between primary sources and distant end users. New solutions must be considered for the commercial bridge between the hydrogen electrolyser and the hydrogen consumer.

## Methanol Energy Economy

The ideal energy carrier would be a liquid with a boiling point of at least 60°C and a point of solidification below -40°C. Such energy carrier would stay liquid under normal weather conditions and at high altitudes. Gasoline, diesel and methanol are good examples of such fuels. They are in common use not only because oil companies distill them from crude oil or natural gas, but mainly, because they qualify for widespread use because of their physical properties. Even if oil had never been discovered, the world would not use synthetic hydrogen, but a synthetic hydrocarbon fuel. Gasoline, diesel, heating oil etc. have emerged as the best solutions with respect to handling, storage, transport and energetic use. With high certainty, such liquids will be synthesized from hydrogen and carbon in a distant energy future.

Methanol is certainly a serious candidate. It carries four hydrogen atoms per carbon atom. It is liquid under normal conditions. The infrastructure for liquid fuels exists. Also, methanol can either be directly converted to electricity 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). Methanol could become a universal fuel for fuel cells and many other applications.

But the synthesis of methanol requires hydrogen and carbon atoms. In a future sustainable energy world carbon could come from plant biomass, from organic waste and from captured $CO_2$. Typically, biomass has a hydrogen-to-carbon ratio of two. In the methanol synthesis two additional hydrogen atoms could be attached to every biomass carbon. Carbon from the biosphere may become the key element for in a sustainable energy future. Instead of converting biomass into hydrogen, hydrogen from renewable sources should be added to biomass to form methanol. Carbon atoms should stay bound in the energy chain as long as possible. They are returned to the atmosphere (or recycled) after the final use of energy. But synthetic methanol is one of a number of options to be seriously considered for the planning of a clean and sustainable energy future.

Time has come to shift the attention for a “Hydrogen Economy” to a “Methanol (or else) Economy” and to direct manpower and resources to find technical solutions for a sustainable energy future characterized by two closed natural cycles of water and $CO_2$ or hydrogen and carbon.

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# About the Authors

## Baldur Eliasson

Born1937 in Iceland, studied Electrical Engineering and Astronomy at the Swiss Federal Institute of Technology in Zurich, where he received his doctorate in 1966 on a theoretical study of microwave propagation. He then worked for three years as radio astronomer at the California Institute of Technology at Pasadena before joining the newly founded Brown Boveri (later ABB) Research Center in Switzerland in 1969. He is in charge of ABB's Energy and Global Change Program worldwide and reports directly to ABB's Chief Technology Officer. He represents ABB in a number of international programs. For instance he is Vice Chairman of the "R&D Program on Greenhouse Gas Mitigation Technologies" of the International Energy Agency. He has received many international awards for his contributions to environmental sustainability .

## Ulf Bossel

Born 1936 in Germany, studied Mechanical Engineering in Darmstadt (Germany) and the Swiss Federal Institute of Technology in Zurich, where he received his Diploma Degree (fluid mechanics, thermodynamics) in 1961. After a short work period at BBC, he continued his graduate education at the University of California at Berkeley. He received his Ph.D. degree in 1968 for experimental research in the area of space aerodynamics. 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 1986 BBC asked him to join their new technology group in Switzerland. He became involved in fuel cells in 1987 and later director of ABB's fuel cell development efforts worldwide. After ABB's decided to concentrate its resources on the development of more conventional energy technologies, he established himself as a free-lancing fuel cell consultant with clients in Europe, Japan and the US. He has created and is still in charge of the annual fuel cell conference series of the European Fuel Cell Forum in Lucerne.