The losses inevitably associated with the use of hydrogen as a carrier of energy to users makes the idea of a 'hydrogen economy' a non-starter, argues Ulf Bossel, himself an enthusiastic supporter of sustainable energy and founder of the European Fuel Cell Forum. Instead, a sustainable energy future will be characterized by the intelligent use of precious renewables-based electricity, reduced demand and biomass-fuelled cogeneration.

The hydrogen 'illusion'

why electrons are a better energy carrier

Hydrogen is the topic of the day. The 'Hydrogen Initiative' of US President Bush has led politicians from many countries and the European Union to follow suit without questioning the promises of the hydrogen enthusiasts. Hydrogen is presented as the ultimate solution to all energy problems. The equation: 'hydrogen + air = electricity + drinking water' is certainly fascinating. Representatives from industry or the public are seen on television drinking the drip-off from tail pipes of hydrogen fuel cell vehicles. Indeed, the conversion of hydrogen back to its natural state (water) is clean, but how benign is the fabrication and distribution of this synthetic energy carrier?

Certainly, hydrogen is the most abundant element in the biosphere. Unfortunately, it appears only in chemical compounds such as hydrogen oxide, commonly known as water. More energy is needed to split water than can ever be retrieved from the generated hydrogen. How much energy is really consumed to make, package, distribute and transfer hydrogen? Where does the energy come from? How efficient is the distribution of the lightest, thus most impractical of all energy gases? How much energy is needed to run a hydrogen economy? Can we afford such a wasteful hydrogen economy at all?

These questions need to be answered before investments are made in a hydrogen future. It will cost trillions of dollars to convert the entire energy system to hydrogen. Thus, it is simply due diligence to question the optimistic claims of the hydrogen promoters before tax money is spent on research, development and hardware. Any new energy technology must be based on a sound platform of physics, engineering and economics.

Unfortunately, hydrogen is not a new source of energy, but merely another energy carrier. Like electricity, it provides a link between an energy source and energy consumers. The energy source may be a chemical energy carrier such as natural gas, coal and oil, or electricity. With few exceptions, the conversion of fossil fuels into hydrogen, i.e. the transfer of chemical energy from one substance to another, cannot improve overall efficiency or reduce the emission of greenhouse gases. Carbon dioxide is released into the atmosphere when natural gas is reformed to hydrogen or when natural gas is burnt in furnaces.

Hydrogen is clean only if it is made from renewable electricity. However, electricity from any source, conventional or renewable, can be transmitted to the consumer by power lines,

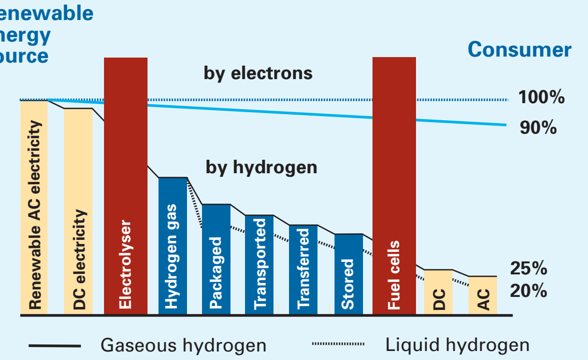

Figure 1. Energy cascade for energy transport by electrons and hydrogen

pollution-free and with a relatively high efficiency. So why use electricity to split water by electrolysis, spend more electricity to package hydrogen by compression or liquefaction to make it marketable, use energy to distribute it to the consumer and convert it back, with considerable losses, to electricity in stationary or mobile fuel cells? In a sustainable future, cheaper power will come from the grid.

Also, renewable electricity will soon replace fossil fuels which are now used for stationary power generation or space conditioning. The replaced oil will probably be sold at fuelling stations to power vehicles. For many years this substitution process will dominate the transition within the energy market from stationary to mobile applications of fuels. The most important source of petroleum fuel will be the improvement of building thermal standards. For years to come, hydrogen has to compete with replaced fossil fuels. But will hydrogen be a promising option after the depletion of oil wells, when renewable energy has become abundant?

ENERGY EFFICIENCY AND SUSTAINABILITY

In the future, renewable electricity will be the main source of energy. Like electricity from decentralized cogeneration, renewable electricity will be generated near consumers' sites to minimize transmission losses. Excess power generated will be supplied to the grid. Electrolysis and fuel cells may be used for temporary energy storage with hydrogen, but, for overall efficiency, renewable electricity will be transmitted directly by electrons and not by synthetic chemical energy carriers. Today, around 10% of electrical energy is lost by optimized power transmission between power plant and consumer, although power grids, in particular in the US, have not yet reached this standard. This figure is lower for shorter transmission distances.

However, if renewable electricity is converted to hydrogen, and hydrogen is subsequently reconverted to electricity, then significantly more energy is needed to drive the process. In fact, only about 25% of the original electrical energy may be recovered by the consumer in stationary and mobile applications.

At first glance, this may sound unbelievable, but the high losses are directly related to the two electrochemical conversion processes and the difficulty of distributing the light energy carrier. Compared to natural gas, packaging and distribution of hydrogen requires much more energy. We have analysed the energy consumption associated with all significant stages of a hydrogen economy, with results that surprised the hydrogen community worldwide.

Table 1 lists the energy consumed at all the significant stages of a hydrogen economy. In most cases electricity is consumed. Energy losses are calculated using the true energy content of hydrogen, i.e. its higher heating value (HHV) of 142 MJ/kg.

A hydrogen economy will be based on one or many optimized mixes of these stages. Hydrogen may be compressed to 100 bar for distribution to filling stations in pipelines, and then compressed further to 850 bar for rapid transfer into pressure tanks of automobiles. Liquefaction of hydrogen may be preferred to compression to save transportation energy, or on-site production of hydrogen with less efficient electrolysers may offer economic advantages over hydrogen production in large

Table 1. Energy consumed at stages of a hydrogen economy; HHV = higher heating value of hydrogen

Stage	Details	% of HHV	Energy consumed
AC–DC conversion	–	5	Electricity
Electrolysis	–	35	Electricity
Compression	200 bar	8	Electricity
	800 bar	13	Electricity
Liquefaction	Small plants	50	Electricity
	Large plants	30	Electricity
Chemical hydrides	CaH_2, LiH, etc.	60	Electricity
Road transport	200 km, 200 bar	13	Diesel fuel
	200 km, liquid	3	Diesel fuel
Pipeline	2000 km	20	Hydrogen
On-site generation	100 bar	50	Electricity
Transfer	100 to 850 bar	5	Electricity
Re-conversion	Fuel cell, 50%	50	Hydrogen
DC–AC conversion	–	5	Electricity

centralized plants and distribution by pipelines. There are no general solutions. Figure 1 illustrates the energy cascade of a representative hydrogen option and compares it with energy transport 'by electrons'.

Whichever scheme is selected, a hydrogen economy will be extremely wasteful compared to today's energy system and to a sustainable energy future based on the efficient use of renewable energy, i.e. the direct use of electricity and liquid fuels from biomass.

THE NEED FOR RENEWABLE ELECTRICITY AND A NEW INFRASTRUCTURE

Let us symbolize renewable electricity by wind turbines – see Figure 2. Assume that the power output of one wind turbines is supplied to a certain number of consumers by electrons, i.e. by conventional electric power lines. If hydrogen is used as the energy carrier, four wind turbines must be installed to provide these consumers with the same amount of energy. Essentially, only one of these wind turbines produces consumer benefits, while the remaining three are needed to compensate the energy losses arising from the hydrogen luxury.

Electrical power can be transmitted by a modestly upgraded

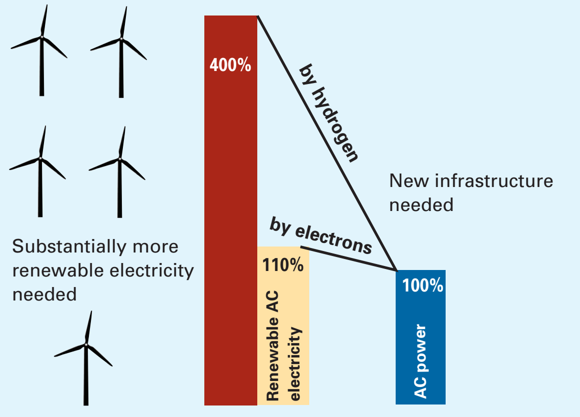

Figure 2. Renewable electricity generators needed for energy transport by electrons and by hydrogen

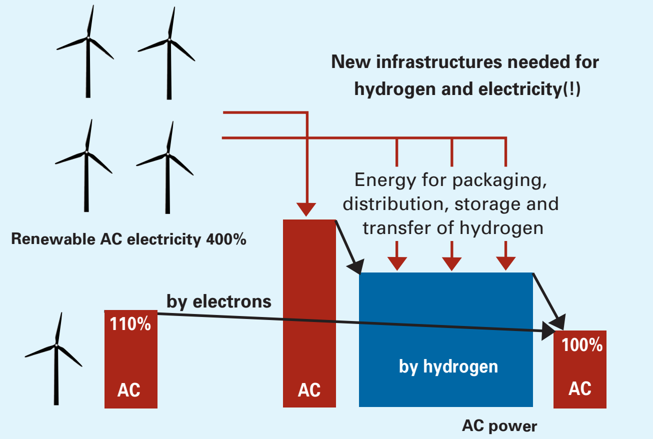

Figure 3. A hydrogen economy requires a hydrogen infrastructure and an extension of the electric power grid

version of the existing power distribution system. For energy transport by hydrogen, a new infrastructure must be established and, in addition, the electricity grid must be extended to deliver power to all the active elements of the hydrogen infrastructure such as pumps and compressors, hydrogen liquefiers, and on-site hydrogen generators. Figure 3 illustrates this point.

ENERGY MIX IN A SUSTAINABLE ENERGY FUTURE

A sustainable energy future will be based on renewable energy from various sources. With the exception of biomass, renewable energy is harvested as electricity, with solar, wind, hydro or ocean power plants. In addition, solar thermal and geothermal power plants will also produce AC power. One may assume that 80% of the renewable energy becomes available as electricity while only 20% is derived from biomass or used directly for heating. This picture is a complete reversal of today's scenario, which is characterized by 80% of energy being fossil-derived and only 20% coming from physical sources.

Renewable energy will be precious and therefore should be distributed and used intelligently. Wasteful electrochemical conversion processes such as electrolysis and fuel cells will be avoided whenever possible. Distribution losses will be minimized by local or regional energy solutions. Global energy exchange comparable to transporting oil around the world will not be practiced, because the transport of hydrogen requires too much energy compared to the low energy content of the transported commodity. This is true for the transport of compressed or liquefied hydrogen by pipelines, land vehicles and ships.

In a sustainable future, energy demand and supply will be matched by strict energy conservation in buildings, by reduced energy consumption in the transportation sector and by the use of electricity wherever and whenever possible.

COST OF ENERGY

Put at its simplest, one can say that a customer receives only 50% of the original renewable electricity energy with hydrogen gas, and that losses rise to 75% or higher when this hydrogen is converted back to electricity. Needless to say, the conversion is done by very efficient fuel cells.

Today, natural gas prices serve as reference for the cost of electricity. Based on its energy content, grid power is about four times more expensive than natural gas. In a sustainable energy future electricity will be the price-setter. It will cost more than it does today, but it will be the cheapest form of energy in the commercial market. Because of the energy losses associated with the hydrogen economy, the following energy price relations may be expected for electricity-derived hydrogen:

- at filling stations, hydrogen will cost at least twice as much as electrical energy from the grid
- electricity from hydrogen fuel cells will cost about four times as much as electricity from the grid.

Consequently, for stationary applications such as space heating, natural gas will hardly ever be replaced by hydrogen, but small electric heaters and heat pumps will be used to condition well insulated buildings.

Similarly, electric cars may become the choice for short-distance commuting, because electric power from an outlet in the garage will cost only half as much as hydrogen at the fuel station. Furthermore, the 'battery-to-wheel' efficiency of electric cars is about 80%, while the 'tank-to-wheel' efficiency of fuel cell cars can barely reach 40%, based on the higher heating value of hydrogen. The daily drive to work in a hydrogen fuel cell car will cost four times more than in an electric or hybrid vehicle. The economic optimization clearly favours electric solutions.

WHERE DOES THE ELECTRICITY COME FROM?

A hydrogen economy will be characterized by a massive increase of electric power needs. It is unlikely that this demand can be satisfied from renewable sources alone. Coal-fired and nuclear power plants will continue to be in use with all the known consequences for the environment and for safety. Therefore, before a hydrogen economy is established, the source of electrical energy has to be identified and developed.

The installation of wind energy converters, solar power plants and tidal power generators is essential for a sustainable energy future. Together with the rational use of energy, renewable sources may be sufficient to match the reduced energy demand worldwide. However, it is unlikely that renewable generation capacity can be stretched threefold to cover the losses of the hydrogen luxury. The conversion of electrical energy into hydrogen is not wise at this time, nor will it ever be.

HYDROGEN AND COGENERATION

Presently, hydrogen is made from fossil fuels, i.e. from energy carriers also used in most cogeneration applications. There is no indication that the hydrogen detour offers benefits over the direct use of hydrocarbons with respect to overall efficiency and greenhouse gas emissions. Recent 'well-to-wheel' studies based on the true energy content of chemical fuels, i.e. on HHV, conclude that hydrogen is not a promising energy carrier.

For years to come, hydrogen will not be able to beat natural gas with respect to overall efficiency, the environment and economy. Advanced hydrogen technologies such as fuel cells cannot compensate for the losses and energy consumption associated with hydrogen production and distribution. Polymer fuel cell cogenerators in the 200 kW class have hardly ever provided line power at lower heating value (LHV) efficiency above 32%. Modern diesel engines, even microturbines, show better yields.

But molten carbonate or solid oxide fuel cells may soon become a viable cogeneration technology. With modest fuel conditioning, these cells convert fossil fuels directly with up to 50% LHV electrical efficiency. They will compete with conventional cogeneration equipment in a natural gas economy. Although still too expensive, high-temperature fuel cells are clean converters of hydrocarbons into electricity. Also, high-temperature waste heat can be recovered easily for many uses. Time will show the potential of cogeneration with high-temperature fuel cells.

In a distant sustainable energy future, with most renewable energy being harvested as electricity, the role of cogeneration must be redefined. Because of its energy efficiency, cogeneration will remain important for biomass-derived chemical energy. This may include the conversion of digester gas, biogas, etc. into power and heat. It may also include thermal energy obtained by combustion of wood waste, residues and farmed biomass in steam power plants. Again, it is unlikely that hydrogen will be produced from biomass or by electrolysis, to be subsequently converted to electricity in cogeneration facilities.

Because of its inherent energy efficiency, cogeneration will continue to be one of the key power generation technologies in a sustainable energy economy. Whenever electricity is produced by Carnot processes, the unavoidable waste heat will be utilized for space conditioning, hot water or industrial processes. Cogeneration technology will be further developed and adapted to a variety of sustainable fuels from biomass.

CONCLUSIONS

The rush into a hydrogen economy is neither supported by energy efficiency arguments nor justified with respect to economy or ecology. In fact, it appears that hydrogen will not play an important role in a sustainable energy economy because the synthetic energy carrier cannot be more efficient than the energy from which it is made. Renewable electricity is better distributed by electrons than by hydrogen.

Consequently, the hasty introduction of hydrogen as an energy carrier cannot be a stepping stone into a sustainable energy future. The opposite may be true. Because of the wastefulness of a hydrogen economy, the promotion of hydrogen may counteract all reasonable measures of energy conservation. Even worse, the forced transition to a hydrogen economy may prevent the establishment of a sustainable energy economy based on an intelligent use of precious renewable resources.

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