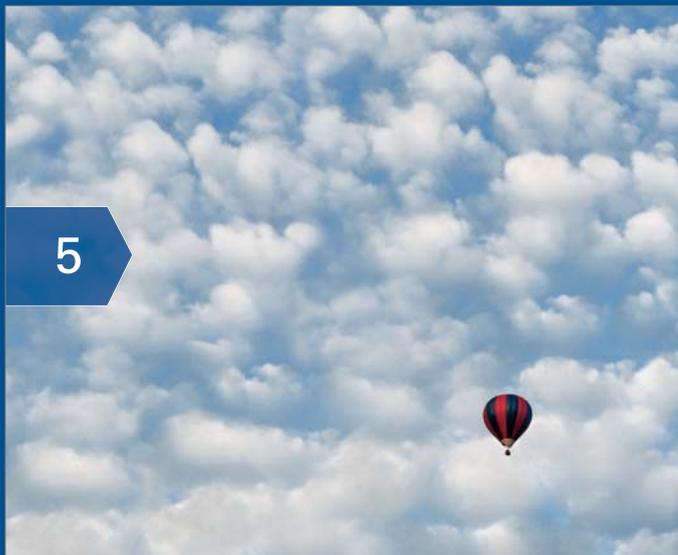
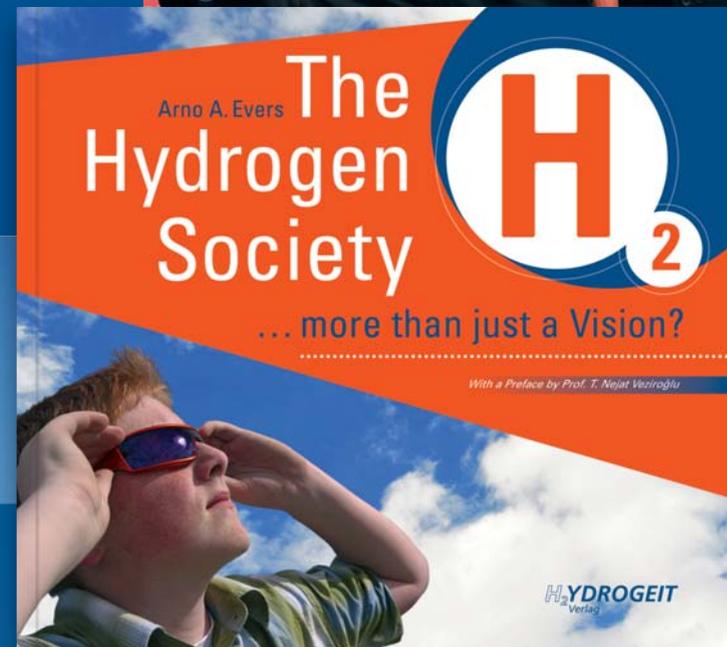


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5

Up, Up and Away: The Making of Hydrogen

On the threshold of the twentieth century, aviation conquered the laws of gravity. As this new century unfolds, we venture out to another quest: the production and use of hydrogen on Earth. Gaseous hydrogen with a density of 0.0837 kg/m³ can hardly be found on our planet. With just seven percent the density of air, it easily escapes from the Earth's gravitational attraction. However, hydrogen does occur on Earth virtually limitlessly: bonded with oxygen in water, and in organic matter such as biomass, coal and natural gas. The hydrogen we use today is extracted from these naturally occurring compounds in a variety of generation processes. But how feasible and affordable is it to produce the hydrogen?

Impressions

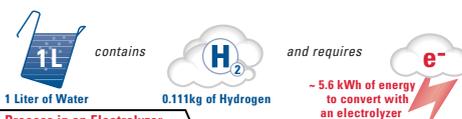
Hydrogen and the Laws of Physics

Hydrogen's atomic structure, consisting of a single proton and a single electron, makes it the lightest and simplest of all chemical elements. It is a colorless, odorless, tasteless gas that has, after helium, the second lowest boiling point, -252.9°C (-423.2°F), and the second lowest freezing point, -259.3°C (-434.7°F), of all elements.

Hydrogen is an energy carrier like electricity, and not a primary source. It must therefore be produced from some other form of energy. These conversion processes are not 100 percent efficient, because some of the energy is always converted into thermal energy which is dissipated to the atmosphere and can no longer be used to perform work. Heat, electricity, or chemical energy can be employed to extract hydrogen from various compounds. But only if renewable energy is used for this purpose, will the resulting hydrogen be

a truly clean and green energy carrier. Electrolysis, which uses direct current electricity to separate hydrogen from water, could be a possible technology used to produce hydrogen entirely renewably and without pollution, but it requires the input of large amounts of electrical energy as shown in Figure 5.1. In an ideal system, 3.9 kWh of electricity and 1 liter of pure water are required to produce 0.111 kg of hydrogen. But typical commercial electrolyzer system efficiencies vary between 56 and 73 percent which corresponds to 70.1 to 53.4 kWh/kg or roughly 5.6 kWh for extracting 0.111 kg of hydrogen from 1 liter of water. In these calculations the energy lost to generate the electricity (and to convert it from AC to DC) is not included.

Splitting water into hydrogen and oxygen is reversible, therefore, it is possible to let both gases react and combine to form water using a fuel cell, releasing



Process in an Electrolyzer

electrical power, and producing only water and heat as a by-product. But there is a catch: 0.111 kg of hydrogen contains only 3.7 kWh of energy which becomes 1.8 kWh of electricity through a fuel cell (which is roughly 50 percent efficient). It is clear that using electrolysis to split water to form hydrogen and oxygen and then to combine them again to generate electricity seems to be a quite straightforward process. But you cannot break even. The energy required to create hydrogen is always higher compared to the energy you would get

when using it. Moreover, if the electricity for the electrolyzer is derived from fossil fuels then there is no advantage over using fossil fuels directly. You still get all the pollution, in addition to a considerable loss of energy inevitably resulting from the laws of thermodynamics. Electrolysis currently supplies roughly 4 percent of the world's hydrogen. But there are other processes that may or may not use electricity as an intermediate form of energy. What about their efficiencies and environmental impacts? Let's have a look!

Process in a Fuel Cell System



Data Source: Daryl Wilson, Hydrogenics Corporation, Mississauga, Ontario, Canada

Figure 5.1 Hydrogen and the Laws of Physics

Hydrogen Production from Renewable Energies without Electricity

Although a renewable energy source in conjunction with electrolysis would eliminate the dependence on fossil fuels, it still requires the production of electricity in the first place. The overall efficiencies of these processes are thereby reduced. Alternative methods without the need for electrical power include:

Photoelectrochemical (PEC) hydrogen
 PEC systems use sunlight directly to generate sufficient energy to split water into hydrogen and oxygen. The advantage over conventional electrolysis using photovoltaic is the elimination of an electrical current network and the associated current transmission losses.

Biological Photolytic Hydrogen
 Another way to directly tap solar energy for hydrogen production is to take advantage of certain microalgae and photosynthetic bacteria that sometimes use photo-

synthesis to make hydrogen instead of sugar and oxygen. However, the algal enzymes that trigger hydrogen production are inhibited by oxygen, so bioengineering of enzymes or a whole new organism would be required to make this process even remotely practical.

Conversion of Biomass and Wastes
 Hydrogen can be produced via pyrolysis (thermochemical conversion) or anaerobic digestion (fermentation) of biomass resources such as agricultural residues, wastes including plastics and waste grease; or biomass specifically grown for energy uses. Specific research areas include reforming of pyrolysis streams and development and testing of fluidizable catalysts.

Scientists are also working on "dark fermentation" reactions which do not require light energy at all. Here, a variety of bacteria ferment sugars and produce hydrogen using multi-enzyme systems. Sugars are relatively

Hydrogen from Biomass

In research laboratories around the world, scientists are working on various options to produce hydrogen from biomass. One is the National Renewable Energy Laboratory (NREL), a national laboratory of the U.S. Department of Energy (DOE), based in Golden, Colorado, which visited in August 2004. NREL possesses immense knowledge as well as practical insights when it comes to examining issues related to renewable energy sources and hydrogen production. At the time of my visit, NREL was developing, among other things, a pilot scale project focusing on hydrogen production by biomass gasification in a fluidized bed reactor.

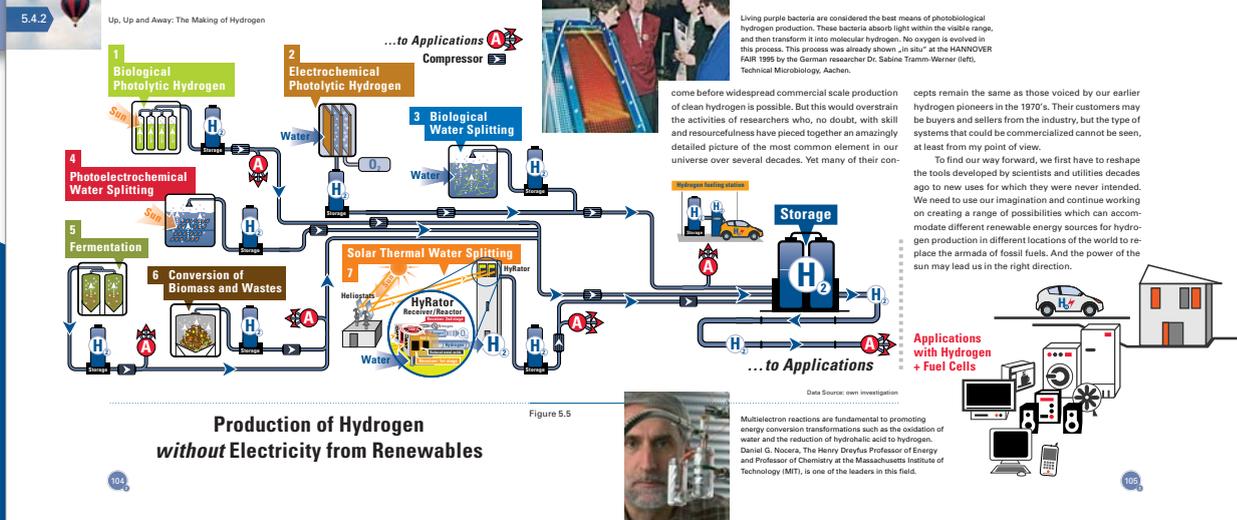
They gave me a realistic picture about the complex numbers of biomass-to-hydrogen conversion processes and challenges from the standpoint of a research institution. Seen from my perspective, the technology has always been, and is still in an early stage of development with major potential for optimization. Each generation process will represent a huge investment.

expensive substrates so engineering pretreatment technologies to convert lignocelluloses biomass into sugar-rich feedstock including hemicelluloses and cellulose that can be fermented directly to produce hydrogen, ethanol, and other high-value chemicals will be needed.

Solar Thermal Water Splitting
 Water usually decomposes at temperatures of more than 2,500°C into hydrogen and oxygen. Researchers have demonstrated that highly concentrated sunlight can be used to generate these temperatures. However, catalysts based on metals or inorganic sulfur compounds can lower the heat needed to the more moderate range of 800 to 1,200°C. Such high-temperature, high-flux solar driven thermo-chemical processes offer a novel approach for the environmentally benign production of hydrogen, and thus shall be explored in more detail in chapter 5.5 Here Comes the Sun.

All the above mentioned methods are still in experimental phases and capable of supplying only small amounts of hydrogen. It seems that many technical, economical, and even mental hurdles need to be over-

from his book



Production of Hydrogen without Electricity from Renewables

Figure 5.5

Living purple bacteria are considered the best means of photobiological hydrogen production. These bacteria absorb light within the visible range, and then transform it into molecular hydrogen. No oxygen is evolved in this process. This process was already shown, 'in situ' at the HANNOVER FAIR 1995 by the German researcher Dr. Sabine Tramm-Werner (left), Technical Microbiology, Aachen.

come before widespread commercial scale production of clean hydrogen is possible. But this would overstrain the activities of researchers who, no doubt, with skill and resourcefulness have pieced together an amazingly detailed picture of the most common element in our universe over several decades. Yet many of their concepts remain the same as those voiced by our earlier hydrogen pioneers in the 1970's. Their customers may be buyers and sellers from the industry, but the type of systems that could be commercialized cannot be seen, at least from my point of view.

To find our way forward, we first have to reshape the tools developed by scientists and utilities decades ago to new uses for which they were never intended. We need to use our imagination and continue working on creating a range of possibilities which can accommodate different renewable energy sources for hydrogen production in different locations of the world to replace the armada of fossil fuels. And the power of the sun may lead us in the right direction.

Multi-electron reactions are fundamental to promoting energy conversion transformations such as the oxidation of water and the reduction of hydrohalic acid to hydrogen. Daniel G. Nocera, The Henry Dreyfus Professor of Energy and Professor of Chemistry at the Massachusetts Institute of Technology (MIT), is one of the leaders in this field.

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