

Hydrogen: The energy carrier of the future?

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I. Background

Over the past decade there has been a growing interest in Hydrogen as a future energy carrier. A number of national and international high level political-expert gatherings over the past couple of years; in Washington, Tokyo, and Brussels, decisively has placed hydrogen on the political agenda. President Romano Prodi of the European Commission, at the European Union Conference on Hydrogen economy in Brussels June16-17, 2003, stated that [1] “It is our declared goal of achieving a step-by-step shift towards a fully integrated hydrogen economy, based on renewable energy sources by the middle of the century”. The European Commission has since followed up this vision by establishing, in January 2004, a Hydrogen/Fuel Cell Technology Platform [2]. The US government has recently launched similar, even more ambitious programs, with clear objectives and milestones, according to US Secretary of Energy, Spencer Abraham [3]. And there are large national Hydrogen/ Fuel cell initiatives in Japan, Germany, France, Great Britain, Italy, and other countries.

Hydrogen clearly has many attractions as energy carrier. It is environmentally friendly, with no harmful emissions, just water. Produced locally based on solar or renewable energy sources, it could be widely available around the world, as opposed to oil or natural gas. It has a high energy density, which, applied as fuel for cars, allows powerful “engines” and long range. Hydrogen would in many respects be complementary to electricity, which is also expected to play an increasing role in our future energy mix. In fact, most predictions indicate a continued strong global growth in electricity demand, perhaps a doubling over the next two decades [4], which is significantly higher than energy increase in general. Electricity is exceptionally well suited for a wide range of stationary applications, whereas hydrogen in theory would be ideal to replace gasoline as fuel in the transport sector.

There are, however, still barriers of a technical-economical nature, against a rapid development towards increased use of hydrogen, not to mention a global hydrogen economy. First of all, hydrogen is a gas, not available in free form of any quantity in nature. It has to be produced from some basic energy source, which is energy inefficient, costly, and possibly even environmentally harmful. Secondly, increased use of hydrogen is limited by the main “engine” for this, fuel cells, being too expensive. Finally, entirely new large-scale hydrogen distribution systems and infrastructures must be established.

Nevertheless, there is an emerging consensus among politicians and experts that a future emission free energy system based on electricity and hydrogen as main energy carriers is a realistic scenario. A relevant question at this point is whether this consensus is based on realistic assumptions and foresights or wishful thinking. What does it mean and what will it take to create a global hydrogen economy in the near future? Evidently, this is an extremely complex undertaking, with very demanding infrastructural and socio-economic challenges. Success will require clear, factually based strategies, substantial political support and public-private initiatives on a global scale. These issues will not be further discussed in this paper, which is primarily concerned with technological challenges and foresight.

II. Technological challenges

Assessing the prospects of hydrogen as a future energy carrier, it is essential to consider the entire hydrogen cycle, i. e. the production, conversion and application chain. The complexity is indicated in figure 1, taken from the EU High Level Group (HLG) report [2]. There are basically three main types of technological barriers to a rapid, economic, widespread deployment and use of hydrogen:

1. Energy efficiency of the complete hydrogen cycle (production, distribution and use),
2. Fuel cell costs, operational reliability, and lifetimes,
3. Efficiency, safety and reliability of hydrogen storage media for mobile systems; in that order of importance.

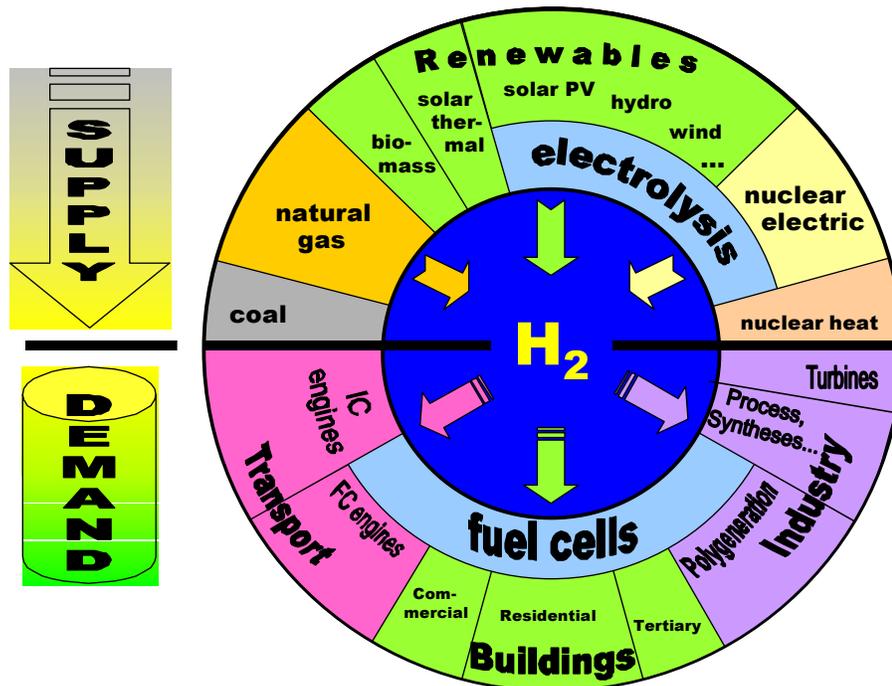


Figure 1. Primary energy sources, energy converters and applications of hydrogen (EU HLG report [2])

1. Energy efficiency of the complete Hydrogen cycle

Global hydrogen production has steadily increased over the past century, to an estimated 45 million tons (500 billion Sm³) per year [5]. Hydrogen is currently not used as energy carrier, but mainly as feedstock in chemical production, petroleum refining and certain industrial applications. If used as fuel, however, hydrogen could cover about 1% of global energy demand. Current annual European production of hydrogen is about 8 million tons. If used as fuel, this would be equivalent to some 30 billion liters of gasoline, enough to fuel about 20 million cars. Bringing half of Europe's car fleet (about 90 million cars) over to hydrogen would consequently require roughly 5 times current European Hydrogen production.

1.1 Hydrogen production

About 96% of current hydrogen is produced from fossil sources and 4% by electrolysis [5], as shown in figure 2. Production efficiencies depend on process and source type, whether based on electrolysis from electricity, or direct production from solar, biomass, natural gas, coal or nuclear energy. Current energy efficiencies of electrolysis methods are typically 70-75% [5, 11].

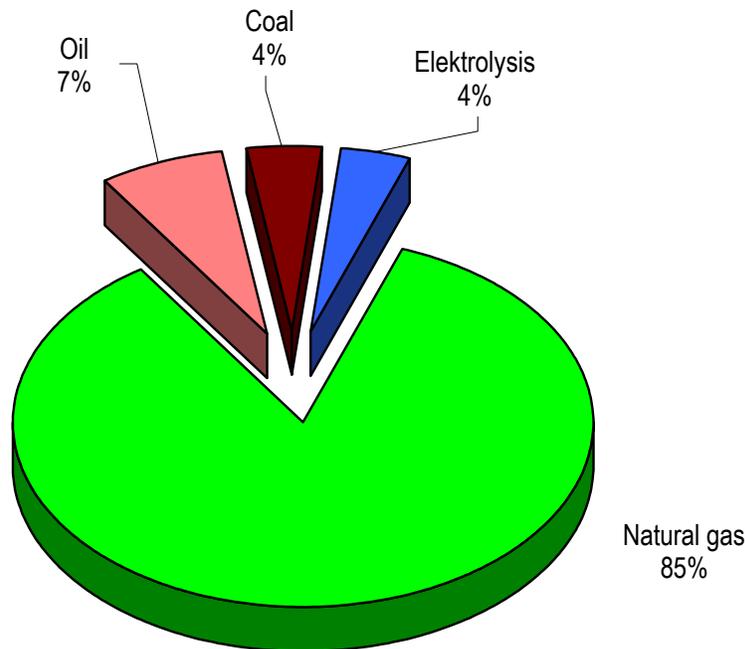


Figure 2: Sources of global hydrogen production (IEA; International Gas Union, 2001)

In addition there are significant efficiency losses in producing the required electricity. The efficiency of direct conversion methods based on reforming natural gas or coal; splitting hydrocarbon fuels with hot steam (SMR), critically depends on system size. Large-scale units are commercial and widespread based on natural gas, with high efficiencies, of the order 80-85%. Small scale SMRs are not yet commercial, but efficiencies are of the order of 50-60%.

There is an extra energy penalty for all fossil based hydrogen production systems, including electrolysis, making hydrogen *in principle* more inefficient for most stationary applications than using the electricity directly. Gas or coal-fired power plants may be well suited for CO₂-sequestration, but current concepts result in an extra 15-20% relative efficiency loss, and consequently very low total efficiencies, down to 30% for the entire hydrogen production process. This is not necessarily the case for mobile applications, where the efficiency of the hydrogen chain must be compared with the entire gasoline or diesel chain, which is also very low (15-20%).

Gasification methods based on splitting heavy hydrocarbons or biomass into hydrogen and hydrocarbons are well understood for heavy hydrocarbon large-scale systems, but not yet commercially demonstrated for biomass. There are, however, demo plants in operation, e.g. Güssing, Austria. Reliable efficiencies are difficult to estimate, but are significantly lower than for reforming.

In conclusion, current production efficiencies are low, at least for hydrocarbon-based sources. Low efficiencies may, however, be acceptable for renewable sources, as these may not always have alternative use. For instance, in periods without alternative electricity demand such systems could provide added value by producing hydrogen.

Current production methods are evidently inadequate to initiate a forceful transition to a hydrogen economy in the near future. More innovative methods include thermo-chemical or -physical production based on high temperature heat from nuclear or possibly focused solar energy sources, as proposed by Prof. Carlo Rubbia [6]. Thermo-physical production of hydrogen is based on a catalytic process, splitting water molecules into ions and electrons at reasonable temperatures (1000°C), applying ceramic membranes, conducting both electrons and protons, recombining into hydrogen atoms at the other side. According to Rubbia, the method is simple, with high conversion efficiency and reasonable economy, representing a major break-through that should “be vigorously pursued” [6]. Direct thermo-chemical production requires very high temperatures, of the order 3000°C, necessitating a chain of intermediate catalytic reactions. The method has a rather high efficiency (50%) and was developed in the 1980ies based on nuclear heat. Both these methods could provide large-scale hydrogen production at relatively low cost, without greenhouse gas emissions. Again according to Rubbia [6], a 36 by 36 km² solar concentrators plant in Sahara, could fuel Europe’s fleet of approximately 175 mill cars at a cost of 2,5-3,5cents-€/kWh, requiring less area per car (13m²) than a regular parking space! This would be comparable with gasoline prices, but there are, unfortunately, no such systems available. Typical hydrogen production costs based on large scale SMRs are of the order 0,7US\$/kg, or 2,5cents€/kWh on site [5], which is of the same order.

Finally, direct photobiological hydrogen production from bacteria or algae may eventually provide a large, but inefficient source. These methods are still at the research stage.

1.2 Hydrogen distribution systems and use

The overall efficiency of hydrogen distribution and storage systems is currently difficult to estimate. Regarding end use, fuel cells are theoretically very efficient, of the order 70-90%, whereas the energy efficiencies of hydrogen fuelled internal combustion engines, Stirling engines and turbines are more speculative, so far. To ensure a gradual increase in overall energy efficiency, it is essential to further optimise system designs, reducing losses in all parts of the hydrogen production – application chain. This requires advanced modelling capabilities to optimise hydrogen distribution, storage and retrieval systems, covering a variety of functions and components, including refuelling efficiency, safety and regulatory requirements.

2. Fuel cell costs, operational reliability and lifetimes

Fuel cells convert fuel and air to electricity, heat and water through an electrochemical process, at temperatures ranging from room temperature to 1000 C. Contrary to current beliefs, fuel cells are a relatively old invention, dating back to the 1830ies, when William Grove applied porous platinum electrodes and a sulphuric acid as electrolyte bath. Later, William W. Jacques coined the term “fuel cells”. Practical application was slow, however, but accelerated through the 1960s with NASA’s use of alkaline fuel cells as electric power source for spacecrafts.

Fuel cells are very efficient, with a high ratio of electricity to heat, providing high quality electric (DC) power. They are emission-free and silent, but expensive. Fuel cells are increasingly applied in niche markets where quality, stability or low noise requirements are important, for instance in local office power back-up systems, and portable devices such as mobile phones and PCs. Fuel cells may not yet be regarded as commercial as car “engines”; high costs and short life-times are critical problems that must be overcome to achieve a significant market.

Fuel cells are, however, a game change technology. A technological breakthrough leading to increased use of fuel cells over a wider range of applications could accelerate the transition from hydrocarbon to hydrogen based energy carriers. An example of new innovative concepts, demonstrating the potential of fuel cell technologies, is the IFE/PROTOTEC/CMR Zero Emission Gas Energy Station [7]. A full-scale 15 MW unit may look as indicated in figure 3. It produces electricity from natural gas in a high temperature fuel cell, simultaneously producing hydrogen in an adjacent reactor, using the fuel cell waste heat. It may achieve very high El-efficiencies of 70-80%, hydrogen production at a yield of 95% (compared with typically 70-75% for SMRs) and a cost of half of current

small-scale SMRs. Pure CO₂ is separated out in the process, practically free of costs. This is, however, still a research project with many uncertainties, high risks and a time horizon

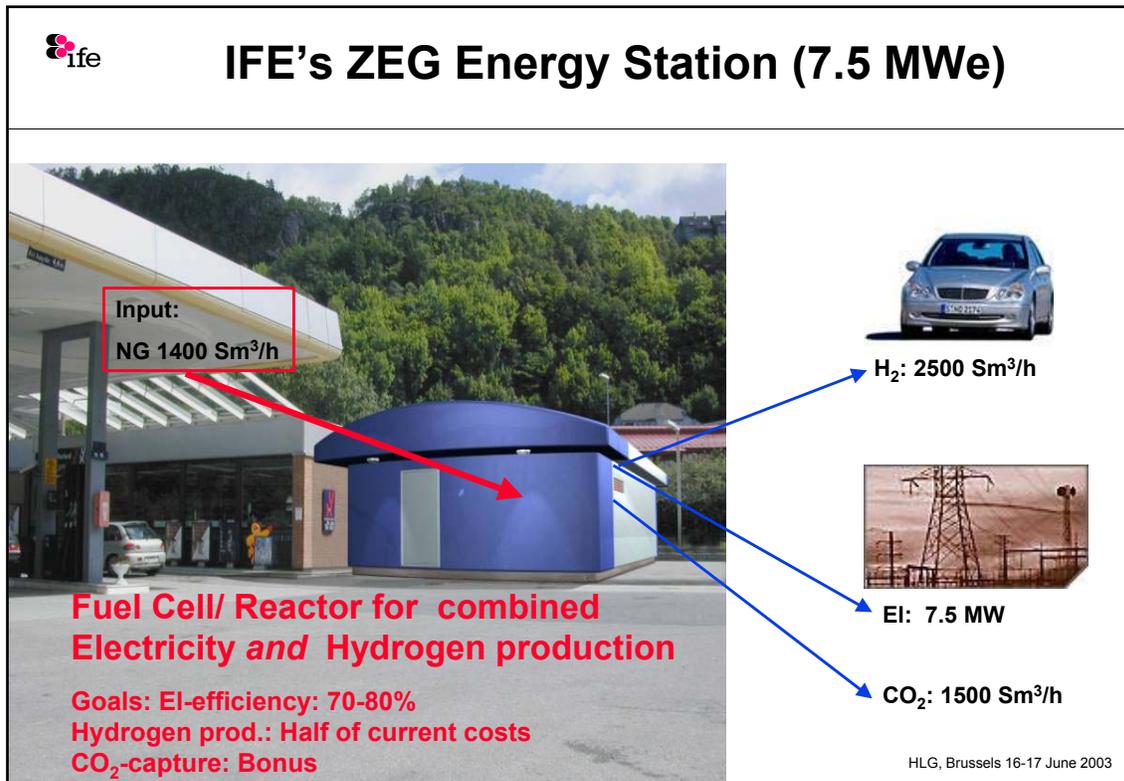


Figure 3: IFE/Prototec/CMR Zero Emission Gas Energy station [7].

of 5-10 years. Similar systems may also be developed based on gasified coal, and there are, in fact, such initiatives in the US [8].

3. Hydrogen storage systems

The challenge is to develop safe, efficient and cost effective hydrogen storage systems. Several different storage technologies are investigated, both for stationary and mobile applications, including compressed hydrogen gas containers, liquefied hydrogen units, metal hydrides, and possibly different carbon structures.

Compressed gas cylinders are available up to pressures of 400 bar, containers for higher pressures are under development. Higher pressures yield proportionally higher energy densities stored, but they are, even at 700 bar, lower than for gasoline. Liquid hydrogen storage requires low temperatures, high quality insulation, and is costly.

Metal hydrides have been studied as potential hydrogen storage media for decades, and some progress has been made [9, 10]. Promising storage densities have been obtained locally in small regions in heavy metal hydrides, as reported by IFE [9]. Hydrogen atom separation distances significantly less than previously assumed, were achieved, of the order 1,6 Ångström, yielding a local hydrogen density of 7,8 with respect to liquid hydrogen, as indicated in figure 4. However, obtaining commercially viable products will

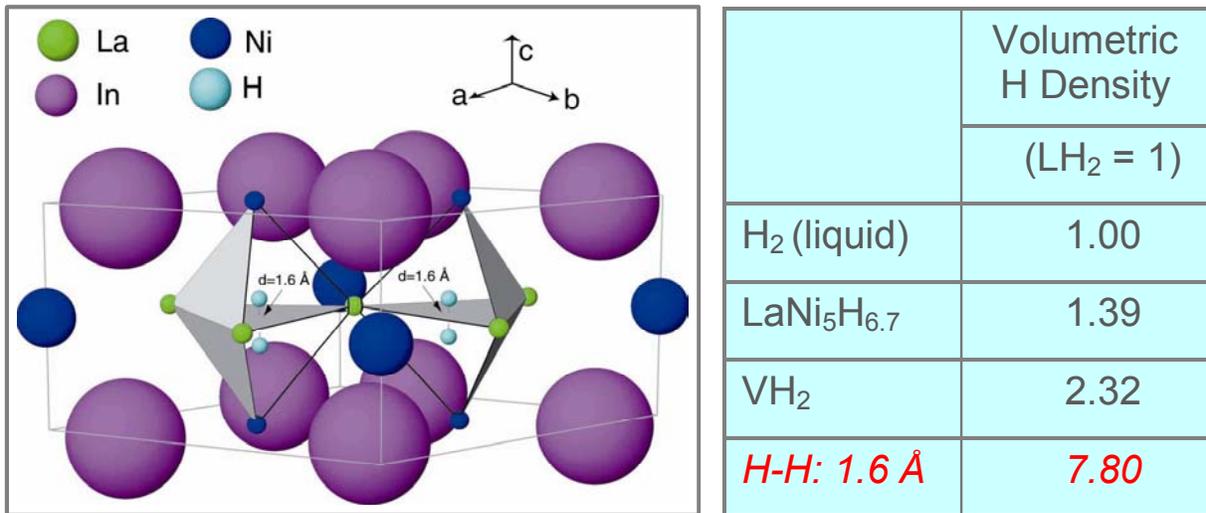


Figure 4: Example of heavy La-Ni-In metal hydride with extremely large local hydrogen density (IFE world record, 2001 [9]).

require a technological breakthrough for lighter hydrides. The IEA has recently set a target for economic, on-board metal hydride storage units of 5wt% retrievable hydrogen, with desorption at 80°C [11]. The US DoE has announced an even stricter requirement, of 6.5wt%. Examples of current metal hydride storage units and an illustration of relative volume requirements are shown in figures 5-6.

More innovative concepts, for instance based on Carbon nanomaterials (tubes and cones), are promising and potentially very attractive due to their low weight. But these concepts are still at the research stage, poorly understood, long-term, with no verified performances.

III. Technological foresights

Replacing or even supplementing our global hydrocarbon based energy supply systems with hydrogen is an enormous, long-term challenge. Main drivers for this transition are certainly not all favourable. The development of hydrogen-based economies depends on several individual but interdependent factors, with quite different expected growth rates and time horizons. A strong short-term driver is expected to be an emerging, potentially large market for fuel cells; in electronic devices, PCs and mobile phones, stationary high quality power back-up systems, military and space applications, in addition to the car industry. Environmental requirements and limitations regarding local city pollution and climate constitute another type of technology driver. Finally, there is a limited but emerging market for stand-alone RE/H₂ power systems, as illustrated in figure 7. This applies both to fuel cells, storage technologies and hydrogen distribution systems.

1. Hydrogen production systems

Hydrogen produced from renewable energy sources causes no emissions of greenhouse gases and represents a climatically favourable alternative. Hydrogen production from other sources, fossil or nuclear, would be necessary in a transition period, however. Fossil based production could in fact be a driver for new CO₂-sequestration technologies for reducing emissions from fossil fuels.

2. Deployment rate of hydrogen distribution systems

Establishing an efficient, widespread and reliable hydrogen infrastructure is an enormous, very costly long-term challenge. According to the European Commission High Level Group (HLG), this will require investments of the order of some hundred billions of euros [2], just for Europe. A step-wise approach, based on current hydrogen pipeline networks, co-transport with natural gas networks, truck transport of liquid hydrogen and local production systems, seems to be a preferred introductory policy. In the transport sector, a reasonable first step is to establish city bus fleets with centralised refuelling stations, as has already been done, e.g. in Madrid, Stuttgart and Reykjavik. If followed by networks of regional demo- or pilot-projects, including cars, the infrastructure could then be gradually expanded, both in terms of geographical regions and vehicle types.

Infrastructures will develop over decades, and there will certainly be a transition period where intermediate, non-optimal solutions must be applied and repeated in very many places to get started and create a viable hydrogen market. In this transition period, hydrogen fuel would co-exist and compete with gasoline and other fuels in the market. Use of natural gas in parallel with hydrogen could speed up the transition and form a bridge from the fossil-based economy of today to the Hydrogen economy of the future.

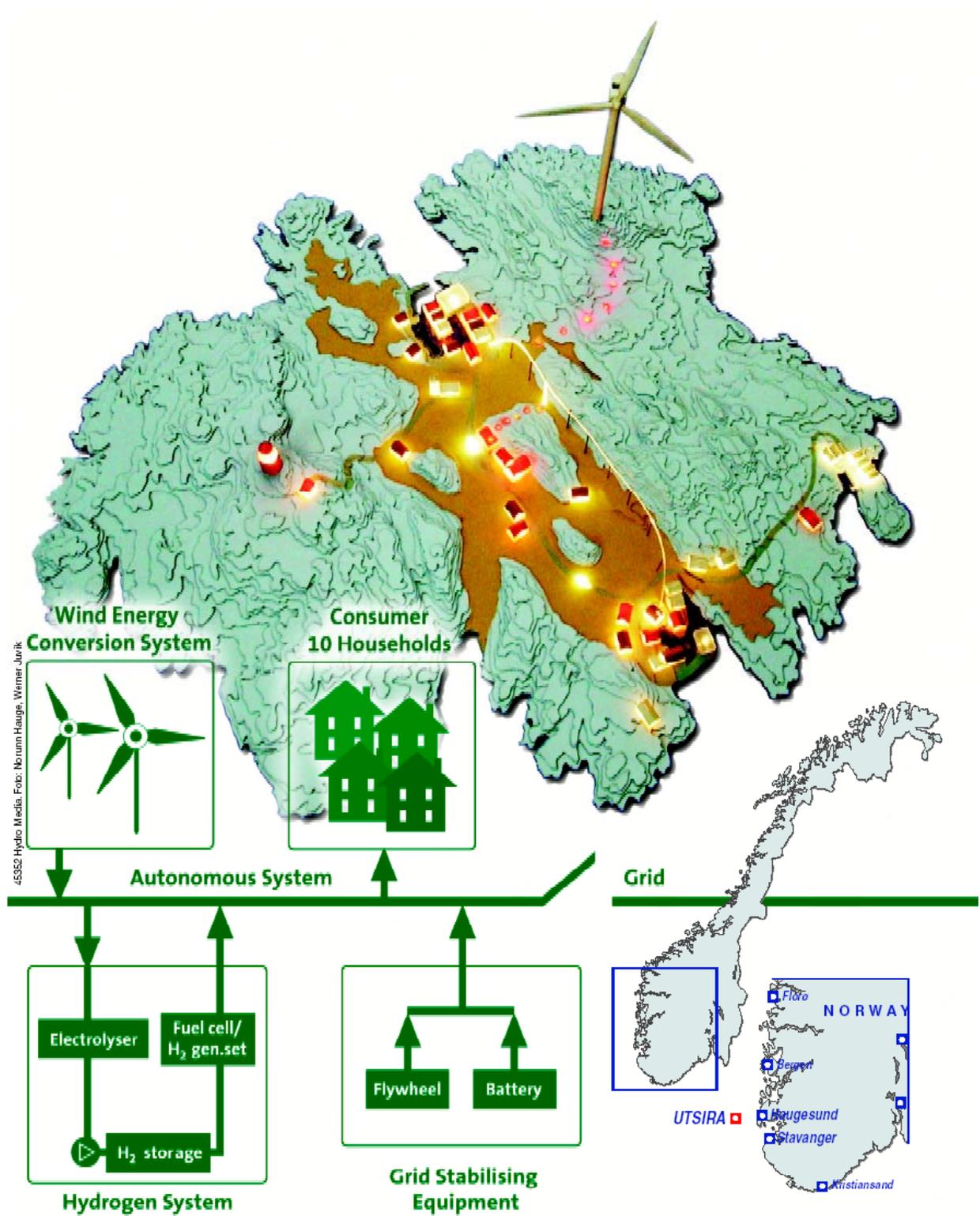


Figure 7: The Utsira stand-alone RE/H2 project (Norsk Hydro)

3. Expected Fuel cell market growth

Fuel cells constitute a potential game change technology. A technological breakthrough leading to fuel cells being used in new applications could significantly accelerate the demand for hydrogen and create a large H₂-market. In the transport sector alone, the Japanese have recently announced targets of 50000 fuel cell cars by 2010, and 5 million by 2020. This would mean an increase in installed capacity to some 2100MW by 2010, and corresponding ambitious targets for hydrogen production and infrastructure growth. European objectives are, according to the HLG, considerably more vague and specified in general terms, only [2]. But, President Prodi, in his June 16, 2003 address [1], announced three specific targets for European energy policy;

- To increase the 6 R&D Framework Program budget for sustainable development and renewable energies to 2.1 billion euro,
- To generate 22% of Europe's electricity from renewable sources by 2010, and
- To achieve a step-by-step shift towards a fully integrated hydrogen economy based on renewable energy sources, by the middle of the century.

It is difficult to assess the realism of these objectives. In view of the recent IEA World Energy Outlook [4], the second target is certainly questionable, and the first one may not be sufficiently ambitious. The US has taken a more cautious political approach, for instance in keeping different options open for producing hydrogen. In addition to renewables, new nuclear and "clean coal" with carbon sequestration [3-4] is being considered. The level of US public funding in this area, however, still far exceeds that of the EU. The US government recently launched several relevant public-private R&D initiatives; a \$1,3bn program on energy efficiency and renewable energy, a clean coal and carbon sequestration programme, a \$1bn Future Gen public-private initiative to realise the worlds first coal-fired emission free plant to produce both electricity and hydrogen, and finally, the \$1,7bn US Freedom Car and Hydrogen Fuel initiative [3, 5].

There are other large national initiatives in Japan, Germany, France, Great Britain, Italy, and many other countries. And there is a growing international coordination of efforts through inter-national agencies, notably the IEA, and the G-8 group Action Plan on Science and Technology.

IV. Conclusions

Hydrogen clearly has many attractions as energy carrier. It is environmentally friendly, with no harmful emissions. Produced locally based on renewable energy sources, it could be made widely available around the world, as opposed to oil or natural gas. Hydrogen would in many respects be complementary to electricity, which is also expected to play an increasing role in our future energy mix. Electricity is exceptionally well suited for a wide range of stationary applications, whereas hydrogen in theory would be ideal to replace gasoline as fuel in the transport sector.

But, it is clearly too early to conclude on the future of hydrogen. The development depends on technological barriers being overcome, but even more so on the future global

energy–climate situation. The seriousness of greenhouse gas emissions, and if they have to be significantly reduced, will be scientifically clarified beyond doubt over the next decade. This will have critical impact on the role of coal, oil, gasoline, and thus hydrogen; wishful thinking will not. What *is* clear, however, is that hydrogen and electricity would be a perfect energy carrier mix.

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