The Hydrogen Society

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1 The concept

Before the industrial revolution in the late 18th century and early 19th century, energy was used in a sustainable way. World population was under 1 billion. Wood and small quantities of coal and oil were the main energy sources used for heating and transportation. After the beginning of the industrial revolution, energy demand grew exponentially. Larger and larger quantities of coal, oil and natural gas were used to power the technology and transportation networks. Due to the large quantities of greenhouse gases released in the atmosphere, the Earth's average near-surface atmospheric temperature rose 0.6 ± 0.2 degrees Celsius in the 20th century. Besides global warming, the smog present in all major settlements became a health hazard.

It has been estimated that the total quantity of crude oil existent on Earth was between 2050 and 2400 gigabarrels. Depending on the study, 45% to 70% have been used so far. Estimates of undiscovered reserved range between 275 to 1469 gigabarrels. It is estimated that by 2050 the world population will increase to 9 billion and energy demands will at least double. Even without consideration for the environment, the oil reserves are considered to become depleted or economically unrecoverable in about 50 years. It is obvious that sooner or later the use of different sources of energy will become compulsory. Because of the increasing environmental damage caused by pollution, this shift from fossil fuels has to be done sooner rather than later.

Energy literally falls from the sky. Every form of energy present on Earth was generated in some way from solar radiation. On one extreme we have fossil fuels, where the energy has been accumulating and concentrating over a long period of time. At the other extreme there the photovoltaics, which capture the energy as it comes. In order to be usable in most applications, like powering an automobile or heating a house, energy has to be captured and stored. It also has to be available on demand. Fossil fuels are a very efficient form of energy storage. Unfortunately, they are limited and environmentally harmful. Besides, fossil fuel reserves are not evenly distributed on the the planet, but highly concentrated in strategically insecure places. Sustainable and clean energy sources like solar panels or wind generators are omnipresent but have the disadvantage of being dependent on the presence of sunlight or wind. Some kind of "buffer" to store this energy when available and release it when needed is necessary. The best such buffer proves to be the hydrogen.

Hydrogen is most abundant element in the universe. It it evenly distributed and accessible in any location. Hydrogen is not a source of energy but an energy carrier, therefore it must be obtained in the first place. Ways of doing this will be described in the following section. It suffices to say that hydrogen can by cleanly obtained. By combining with oxygen in an explosive reaction inside internal combustion engines (ICE) or quietly inside fuel cells (FC), hydrogen releases a large amount of energy (four times that of an equivalent amount of gasoline) with little (some NOx in the case of ICEs) or no (in the case of FCs) emissions. The only by-product of the reaction will be water.

The **Hydrogen Society** represents a futuristic society where hydrogen is used as an energy carrier. Energy is stored from various renewable sources in the form of hydrogen, which is then used for heating, transportation, and so on. Almost no green-house gases are emitted and the level of CO_2 begins to drop. Smog and sound pollution due to noisy automobiles gradually disappears. Energy becomes cheap and abundant. Global warming effects begin to attenuate. However, the transition will not be easy.

Hydrogen stores a high amount of energy but is also the lightest element. Storing hydrogen in a dense form proves to be quite a challenge. Currently, the cheapest way of producing hydrogen is from fossil fuels; shifting to renewables is not an easy task. Also, the whole distribution infrastructure has to be created from scratch. The public acceptance is also of importance as people often associate hydrogen with the Hindenburg accident rather than with the automate solution for the energy problem.

2 Hydrogen production

One of strong points of hydrogen is that it can be produced in any place, using a wide range of methods. Basically, one can tap into almost any energy source and store the energy as hydrogen.

2.1 From fossil fuels

Currently, the cheapest way of producing hydrogen is by extracting it from fossil fuels. Although this contradicts the idea of clean energy and sustainability, it seems a necessary step until further technological breakthroughs or a high increase in the cost of fossil fuels make cleaner alternatives economically viable. It is also hoped that *sequestration*, the process by which CO_2 is captured and stored at great depths or in some way that prevents it to reach the atmosphere, will partially solve the emission problems.

2.1.1 From natural gas

Steam reforming of natural gas, also called *steam methane reforming* is the most widely used method for producing hydrogen on an industrial scale. It is also the cheapest. At temperatures of around 700 - 1000 degrees Celsius, stem reacts with methane in the presence of a metal based catalyst. The result of this reaction is hydrogen and carbon monoxide.

Besides the centralized production, steam methane reforming can be done on site. Hydrogen stations and other systems like household co-generation installations take advantage of the existing gas infrastructure and produce in this way hydrogen on site.

Various methods to make this method of production cleaner, like carbon sequestration, are being researched. *Partial oxidation with autothermal reforming* [5] or *advanced membrane separation* [13] are some of the most promising ones.

2.1.2 From coal

Close to the process of steam methane reforming, *coal gasification* converts the coal into *syngas* (composed mainly from hydrogen and carbon monoxide) from which hydrogen is extracted in a similar way. This method can be applied in countries like China where large amounts of cheap coal can be found.

Like steam methane reforming, coal gasification can also be combined with carbon sequestration or advanced membrane separation.

2.1.3 From other hydrocarbons

A similar process of gasification can be applied to other hydrocarbons as well. In particular, the on-site gasification of methanol inside a fuel cell vehicle can be a viable method, since the presence of a hydrogen fuel tank becomes unnecessary.

2.2 Biomass gasification

When biomass is heated in the presence of little or no oxygen, it gasifies to a mixture of hydrogen and carbon monoxide. This process is known as *biomass gasification*. The process is considered carbon neutral, since the released CO_2 is compensated by the amount consumed during the plant's lifetime. The process can be applied in undeveloped countries, where agriculture plays a major role in the economy. A very large amount of land is required to grow the feedstock, making this method generally infeasible.

2.3 Electrolysis

Electrolysis is the process by which in the presence of an electric current, water splits into oxygen and hydrogen. Supplied with electricity from renewable sources (wind and hydro generators, solar panels, (arguably) nuclear plants), it is the most promising hydrogen production method. Currently, hydrogen produced by this method is limited to areas where very pure hydrogen is required. Generally speaking, it is still too expensive to be economically competitive.

2.4 Nuclear

Electrolysis is more efficient at a higher temperature, therefore a very efficient and (arguably) renewable method is by using the electricity and heat generated inside a fusion of fission reactor.

2.5 Photocatalysis

Photocatalysis is the process by which, in the presence of a special catalyst, water is directly split into hydrogen and oxygen without the need for electrolysis. This process is still experimental.

2.6 Bio-hydrogen

Hydrogen can also be produced directly by microorganisms, usually via reactions catalyzed by enzymes. The process hasn't left the laboratory yet.

3 Hydrogen transportation and storage

Transportation of hydrogen is similar to the one of natural gas, but requires some modifications. Hydrogen can be transported in gaseous form using pipes or trucks or by using trucks, trains and plains if liquefied. Gaseous hydrogen is 2.7 times lighter than natural gas therefore a higher pressure is necessary to provide to distribute the same amount. Thus, steel pipes have to be used instead the regular plastic gas pipes. When liquefied, hydrogen requires better insulation.

If hydrogen is to become the future energy carrier, storage is one of the key factors. This comes to a great premium especially when dealing with portable appliances, like hydrogen vehicles. While the energy content compared to is the weight is very high, hydrogen has a rather low energy content compared to its volume. This poses great storage challenges as compared to gasoline. There are basically three storage alternatives:

- store in compressed form in a high pressure tank
- store in liquid form in a very well insulated tank
- store inside some solid compound

Storage in compressed gaseous form is currently the best storage alternative. Great progress has been made regarding both the weight of the tank and the pressure at which hydrogen can be stored. Still, a high pressure tank poses some safety problems.

Storage in liquid form is usually employed in the case of planes or spacecraft. Usage in a regular vehicle is not so efficient because part of the hydrogen has to be used in order to cool the tank, therefore the fuel will be consumer even if not used.

Storing the hydrogen inside a “spongeous” metallic compound is the safest alternative, since hydrogen is always trapped and cannot ignite. Unfortunately, the wight of the compound compared to the one of the hydrogen it can store is prohibitively high.

4 Hydrogen usage

Hydrogen can be used both as an energy carrier and as raw material (e.g. for the production of ammonia, used in explosives or fertilizers). As an energy carrier, hydrogen can be either burned like gasoline inside an internal combustion engine or, much more efficiently, used inside a fuel cell. Fuel cells are clean and mechanically speaking extremely reliable (no moving parts).

4.1 The fuel cell

A fuel cell takes as input hydrogen and oxygen and produces electric current. It is the opposite of electrolysis. Due to their high efficiency and zero emissions, fuel cells are the way to go for the Hydrogen Society. The mechanism of a fuel cell is presented in Fig. 1.

Currently, there are various types of fuel cells. The best known is the PEMFC (Proton Exchange Membrane) fuel cell, used in most mobile applications due to its low operating temperature. It can output a power of 100-500kW, suitable for powering vehicles. Another widely used fuel cell is the DMFC (Direct Methanol) fuel cell, which can work directly with methanol (does not need reformer). DMFCs are limited in the power they can provide and are not very efficient but since methanol stores a high amount of energy, it can generate a small current for a long period of time. This makes it suitable for a wide range of electronic devices, like laptops, CD players, and so on. For large scale fixed systems, which have to provide a lot of power (in the range of MW) and size or operating heat is not that important, MCFC (Molten Carbonate) fuel cells are generally used. This type of fuel cell is able to provide up to 100MW of power, therefore suitable for powering buildings or industrial installations.

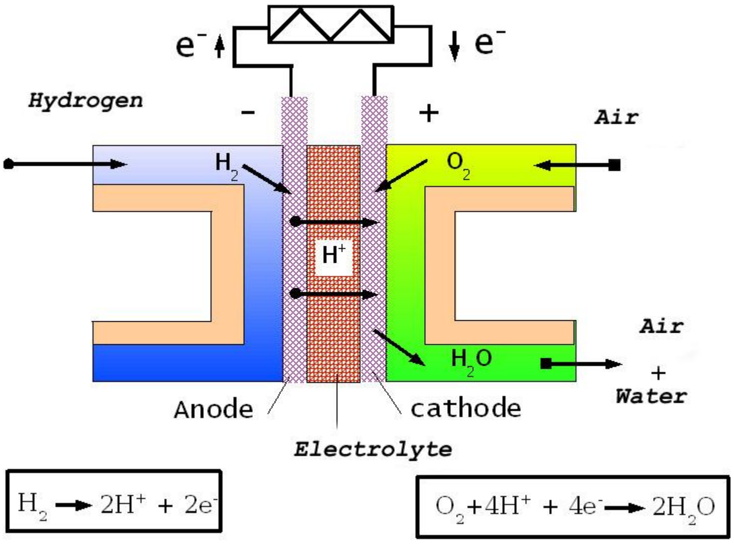

Figure 1: Proton Exchange Membrane fuel cell. Hydrogen enters the anode. While the proton can traverse the electrolyte membrane, the electron must take a longer, exterior route. This creates an electric current. When the proton meets the electron, in the presence of oxygen, water is formed.

4.2 Hydrogen vehicles

The most important technology towards a Hydrogen Society is certainly the hydrogen-powered vehicle. Although a hydrogen combustion engine is more efficient and much cleaner than a gasoline one, the fuel cell vehicle (FCV) holds the greatest hopes. Zero emissions and no noise are just some of its advantages. Besides vehicles, there is a great potential for fuel cell powered scooters.

4.3 Distributed generation and co-generation

Production of electricity from hydrogen via fuel cells opens the possibility of distributed power generation. Small generators that power a neighborhood or just one house can be very easily implemented. Fuel cells are used even now as backup power generators or as primary generators in remote locations where connecting to the power grid was difficult.

Co-generation is the process by which not only the power but also the heat generated by the fuel cell is used. This can be employed both in industrial applications or in a household, where usually power is bought for the grid while gas is used for heating. When the generated power exceeds the needed amount, it can be sold back to the grid. It is considered that using co-generations decreases overall costs by about 25% and carbon emissions by up to 40%.

4.4 Consumer electronics

Fuel cells (the DMFC especially) can be used to power a wide range of consumer electronics, from laptops to media players.

5 The past

Studying hydrogen energy and the Hydrogen Society seems like looking into the future, but in fact this not at all a new idea. The first hydrogen-powered car has been created 200 years ago and first small scale Hydrogen Society project is more than 70 years old. It seemed appropriate to investigate this history and see what conclusions can be drawn from here. In the following, some of the most important events regarding hydrogen energy will be presented in chronological order.

- 1766 - the British scientist Henry Cavendish discovers hydrogen
- 1800 - electrolysis is discoveded
- 1807 - the first car powered by a hydrogen combustion engine is created by François Isaac de Rivaz, though the design proves to be unsuccessful
- 1838 - the Swiss chemist Christian Friedrich Schoenbein discovers the fuel cell effect
- 1889 - the first fuel cell is built
- 1920 - the German engineer Rudolf Erren converts internal combustion engines to hydrogen obtaining great efficiency
- 1934 - in Canada, Andrew T. Steward observes that while Canada imports almost all energy, the usage of the hydro generators on Niagara falls is below 40%. He builds an electrolyzer to convert the unused power to hydrogen used mainly for fertilizers. He also plans to transform the local community into an experimental hydrogen economy but, because cheap natural gas is discovered, all is abandoned.
- 1959 - the first hydrogen-air fuel cell is built and put to use inside a fuel-cell powered tractor
- 1970 - the notion of Hydrogen Economy begins to take shape
- 1988 - the first hydrogen plane is built
- 1994 - NECAR I, the first commercial fuel cell vehicle is presented
- 1998 - Iceland announces the prospect of a Hydrogen Society by 2030

Seeing this history of hydrogen energy, one can draw the conclusion that economics has in fact greater weight than technology. Although it was clear from that time that hydrogen is clean and more efficient, availability of cheap oil and natural gas made ecology uninteresting. This will probably continue until oil will get scarce and expensive and using hydrogen will become the profitable thing to do. Considering the fact that there is a chicken-and-egg problem related to the hydrogen infrastructure (no users $\rightarrow$ not economical to make an infrastructure $\rightarrow$ no infrastructure $\rightarrow$ not economical to use hydrogen $\rightarrow$ no users), left on its own, this technology will probably not be available in the very near future. Thinking of the disastrous environmental impact fossil fuels have, by then it may be too late. This implies that the problem should be addressed more from an economical point of view than from a technological one. Taxes on pollution and subsidies for green technologies should be studied and implemented. Minimal governmental investments in infrastructure should also be considered. Fortunately, governments are becoming aware of this facts and have began detailed studies in this direction.

6 The present

Progress towards a hydrogen economy has been made, but still a lot is to be done. In this section we review the current status of the technology involved in making this transition possible.

6.1 Fuel

The currently cheapest way of producing hydrogen is from fossil fuels. In this case, the current price is roughly 2 times more than the price of the amount of gasoline which would give the same amount of energy. Hydrogen generated from renewable sources by electrolysis is about 4 times more expensive. Almost all of the hydrogen production is currently using SMR, without sequestration.

6.2 Infrastructure

A very limited number of hydrogen pipes exist at this time, most of the transport being done using trucks. A number of around 120 hydrogen fuel stations exist around the world, 12 of them in Japan. Most of the hydrogen stations either bring hydrogen by truck or produce it by on-site methane reforming.

6.3 Fuel cell vehicles

The current price tag of a fuel cell vehicle is around 1 million dollars. Most of this money represent the cost of the fuel cell. Every major car manufacturer experimented with different prototypes (around 200 models were built so far) and around 100-300 vehicles are currently on the road, in experimental programs. As characteristics, the acceleration and top speed are lower than that of gasoline vehicles, but the efficiency is much better. The range for a full tank is about 300-400km, lower than in the case of gasoline vehicles.

6.4 Power generation

Fuel cells are currently used as backup or primary power source in a number of buildings. Commercial household co-generation systems are beginning to penetrate the market. As an example, in Japan a 1kW reformer + fuel cell co-generation system designed by Ballard-Ebara is commercially available for around 1 million yen. It is supposed to save up to 26% in overall expenses and reduce emissions with up to 40%. It is currently installed in around 600 households.

7 The future

Progress seems to continue in the right direction, at a faster rate than before. Here, we show predictions and future trends concerning the key aspects of the Hydrogen Society.

7.1 Fuel

Currently, the cheapest hydrogen is made using SMR. This is going to change, as electrolysis from renewables (using photovoltaics) will gradually become cheaper while the price of fossil fuels will constantly grow (Fig. 2). Predictions show that electrolysis will become cheaper than SMR somewhere between year 2020 and 2025. Electrolysis from renewables seems to be only method whose price is going down, which is a very good sign.

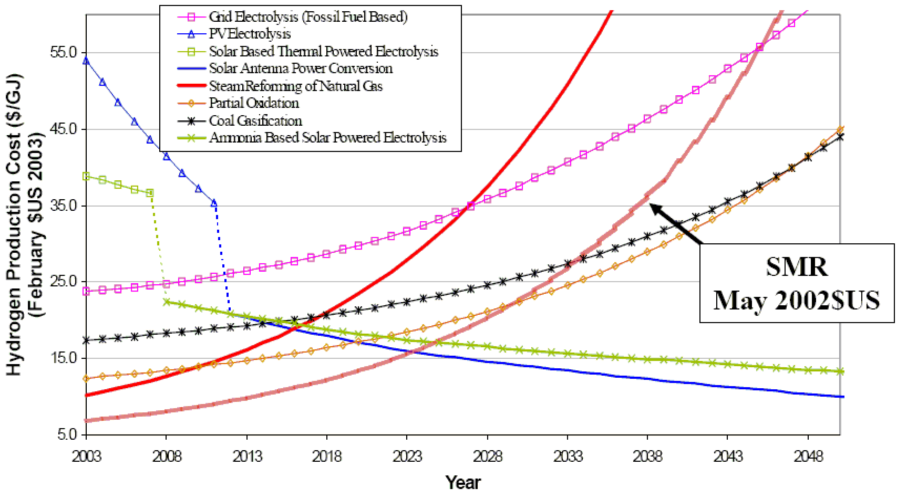

Figure 2: Forecast for the price of hydrogen, depending on the production method (according to [2])

7.2 Infrastructure

The growth of the infrastructure is one of the major unknowns. It is usually agreed that the current infrastructure is most insufficient, and that the growth will be rather slow and in proportion to the demand. It is also expected that the government will contribute with substantial investments in infrastructure.

The infrastructure growth models can be roughly divided into two categories. In the first category, projections for the increase in market share of hydrogen vehicles and power generating systems are used to estimate the evolution of the hydrogen requirements followed by the computation of the infrastructure required to satisfied those needs ([6, 12]). Ways in which these investments could be made in an economical way is usually not considered here. In the second category, a more co-evolutionary approach between demand is supply, therefore addressing the chicken-and-egg problem, is taken. Some consider the process is initiated by the manufacturers, and then the infrastructure will follow as the demand increases ([10, 11]). Others assume that it will start with fleets of buses and cabs ([4, 8]).

At the beginning, with only a limited number of hydrogen consumers present, industrial hydrogen, hydrogen produced from off-peak power and refinery excess hydrogen seems to be enough ([8, 9]). Hydrogen will probably be transported by highway trucks and by pipes in places close to production facilities ([8, 12]). As time passes and hydrogen vehicles grow in share, more and more pipes will be build, as this proves to be the cheapest alternative.

7.3 Fuel cell vehicles

Most manufacturers situate the mass commercialization date for FCVs between 2015-2020. With mass production, a substantial decrease in price for fuel cells and hence for the whole vehicle is expected. Forecasts for retail price in 2020 range from 1.3 to 2 times the cost of a similar gasoline vehicle.

There are a wide range of scenarios regarding the introduction of FCVs, ranging from 2-3% penetration by 2050 in the most pessimistic ([3]) and 40-50% in 2030 for the most optimistic ([7]).

7.4 Power generation

Household co-generation systems will increase in market share. For instance, Japan predicts an increase from the current 600 installations to more than 10000 in 2010.

8 Barriers

As previously described, the major barriers towards a hydrogen powered economy are the high hydrogen and fuel cell production costs and the lack of an infrastructure. Beside these, barriers related to the presence of competitors and public acceptance are also present.

FCVs have strong competition from cheap and improved gasoline and diesel vehicles and efficient hybrid cars. Compared to hybrids, at least in the first 10 years from introduction, FCVs will cost more, have about 30% of the range and limited refueling options. Not surprisingly, various studies (including our own) show that the market for fuel-efficient vehicles is at first almost saturated by hybrids (Fig. 3).

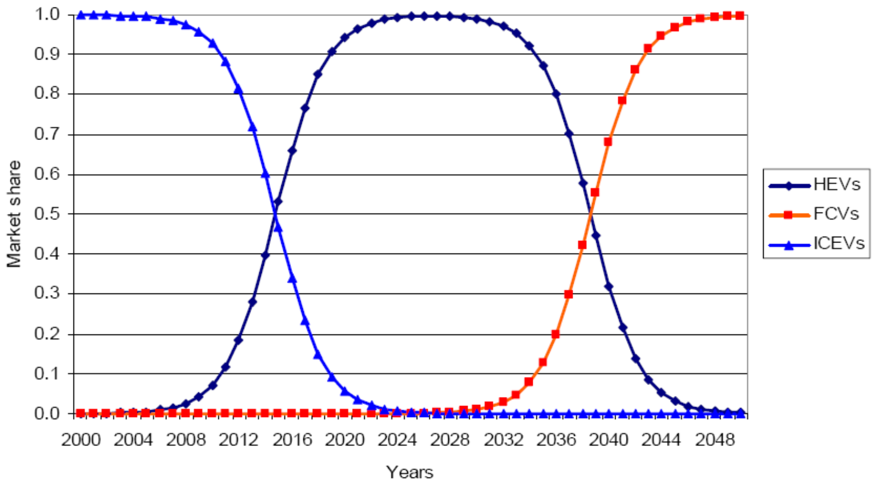

Figure 3: Market share divided between hybrids (HEVs), fuel cell vehicles (FCVs) and internal combustion engine vehicles (ICEs) from [1]. While the maximum market share value and the time when each vehicle hype reaches it varies from study to study, the general trend is the the same: gasoline vehicles are being replaced by hybrids which are then being replaced by fuel cell vehicles.

Regarding public acceptance, people still associate hydrogen with the hydrogen bomb and the Hindenburg disaster. As with any new technology, concerns regarding safety and fiability are an issue.

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