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# Hydrogen Production & Distribution

## HIGHLIGHTS

■ **PROCESS AND TECHNOLOGY STATUS** – Hydrogen is currently used in a number of applications in chemical and refinery industry. It can be obtained from a variety of feedstock (i.e. water, chemicals, fossil and renewable fuels) based on a number of processes. Due to its high gravimetric energy density, hydrogen can also be used as a high-quality fuel or energy carrier, though the very low volumetric energy density poses significant storage and transportation issues. Costs and storage issues have hindered so far the use of hydrogen as a fuel. Main technologies for hydrogen production include: catalytic **steam reforming** (800-1000°C) and **partial oxidation** (600–900°C) of hydrocarbons (e.g. natural gas) or renewable fuels (e.g. bioethanol); coal or biomass **gasification**; **water electrolysis** (i.e. electrochemical split of water into hydrogen and oxygen); **thermo-chemical water splitting** at around 900°C; and **biological production**. It is worth noting that all processes based on fossil fuels need to be associated with a CO<sub>2</sub> capture and storage technology to produce carbon-free hydrogen. Hydrogen can be stored as a compressed gas (up to 700 bar), as a liquid at cryogenic temperature, as well as trapped (e.g. adsorbed) in solid materials. **Hydrogen storage** by compression and liquefaction are mature and energy-intensive processes, while solid storage is not yet a commercial option. Compressed hydrogen can be transported by either tube trailers (typically, up to 300 kg at 200 bar) and pipelines (typically, 10-20 bar, large quantities and distances), while liquid hydrogen is moved by tankers (typically, 400 to 4000 kg). The availability of cheap hydrogen could help the commercialization of **fuel-cell vehicles** as a possible clean alternative to internal combustion engines running on fossil fuels. However, further R&D is needed to reduce the fuel cell costs and solve on-board storage issues. Electrolytic hydrogen could also be used as an energy storage medium in combination with hydro, solar and wind energy. Though expensive, this is an option under consideration to exploit excess (e.g. overnight) electricity generation.

■ **PERFORMANCE AND COSTS** – Natural gas steam reforming is a mature technology with large-scale industrial plants in operation and a commercial efficiency ranging from 70 to 85% (even higher if steam is available from other sources). Coal gasification is a less used and less efficient (50-70%) process. Commercial alkaline electrolysis can meet hydrogen production demand from 1 to 1000 Nm<sup>3</sup>/h with an electricity-to-hydrogen efficiency of 62-82%. High-temperature or high-pressure variants can reduce the electrolysis energy use. As for hydrogen storage, compression energy amounts to 10-15% of the hydrogen energy content (up to 30% for very high pressure) while liquefaction absorbs between 30% and 40% of the energy content. Hydrogen production costs depend basically on process, feedstock and production capacity. Estimated ranges given as €/Nm<sup>3</sup> are 0.05–0.1 for natural gas steam reforming and coal gasification and 0.16–0.3 for electrolysis, which is very sensitive to the electricity cost. In general, production from fossil fuels offers competitive prices and large-scale potential but cannot be considered a viable option for large scale production in the absence of effective carbon capture and storage. In contrast, electrolysis is costly, but involves no or negligible emissions (apart from those from electricity generation) and produces high-purity hydrogen. Hydrogen compression cost is estimated to range between €0.9 and €1.75/kg. Transportation costs range from €0.13-0.15/kg for liquid tankers, 0.14-0.26/kg for pipeline and €0.5-0.6/kg for tube trailers (100 km).

■ **POTENTIAL AND BARRIERS** - Hydrogen is seen as an attractive, clean and versatile energy carrier (*hydrogen economy*). If produced from primary renewable energy, it materialises a 100% carbon-free fuel. However, several technology challenges need to be overcome for this to happen such as increasing production efficiency, reducing costs, and identifying viable options for storage and transportation. At present, hydrogen is almost entirely used as a basic feedstock in refining and chemical industry. Its use as an energy storage system in association with renewable electricity generation is under investigation. Hydrogen use as fuel for fuel-cell vehicles is currently challenged by electric vehicles. However, large-size batteries for electric vehicles also face their own technical and economic issues, and fuel cell cars continue to be an option under development. Hydrogen also needs a specific distribution infrastructure to be developed. It is currently unclear in which volumes and form (gaseous, liquid, etc.) hydrogen will be used, and system cost/benefit analyses have not been fully worked out. A key question is whether hydrogen is needed to achieve a sustainable low-carbon energy system. Continued R&D and demonstration as well as a regulatory framework are needed to introduce hydrogen in the world energy system.

### HYDROGEN PRODUCTION PROCESSES

Hydrogen is the most abundant element on the Earth. Because of its high chemical affinity, hydrogen is not available in nature as a pure gas, but is often combined with other elements. Hydrogen is used in a number of processes in chemical and refinery industry. It can be produced from a variety of feedstock (e.g. water, chemicals, fossil and renewable fuels) based on a number of processes using either renewable or non-renewable energy. Due to its high gravimetric energy density, hydrogen can be used as a fuel or as a high-quality energy carrier (e.g. space applications). However, compared with other gaseous fuels such as natural gas, hydrogen has a very low volumetric density, which poses specific storage issues. The considerable cost and energy consumption of hydrogen production and storage have hindered so far the use of hydrogen as a fuel for large-scale commercial applications.

Main technologies for hydrogen production include natural gas steam reforming, partial oxidation and auto-thermal reforming of hydrocarbons or renewable fuels (e.g. bioethanol) as well as coal and biomass gasification, water electrolysis, thermo-chemical water splitting, and biological production processes.

It is worth noting that in order to produce carbon-free hydrogen, all processes using fossil fuels as a primary feedstock need to be associated with an efficient technology to capture and store the resulting CO<sub>2</sub> emissions (CCS, see ETSAP E14). Similarly, steam, heat and electricity that are used in the process should also be generated from carbon-free energy sources, such as solar and wind energy or nuclear power.

■ **Steam Reforming** - In this process, a mix of steam and hydrocarbons (e.g. natural gas) or renewable fuels (e.g. bio-methane) is heated up to 800-1000°C in a catalytic reformer to produce a gas mixture (syngas) of mostly hydrogen and carbon monoxide, plus traces of other gases. The process is based on the *endothermic* reaction  $\text{CH}_4 + \text{H}_2\text{O} = 3\text{H}_2 + \text{CO}$  (206 kJ/mol). The gaseous mixture is then cooled down to around 400°C to enter a water-shift reactor, where CO reacts with steam to produce further hydrogen and CO<sub>2</sub> based on the *exothermic* reaction  $\text{CO} + \text{H}_2\text{O} = \text{H}_2 + \text{CO}_2$  (41.2 kJ/mol). Hydrogen is finally separated from other gases and purified.

Steam reforming of natural gas is a mature technology with a number of large-scale industrial plants (up to 250,000 Nm<sup>3</sup>/h) in operation worldwide. Advanced steam reformers incorporate technology improvements such as in *sorption-enhanced reformers* (i.e. in-situ CO<sub>2</sub> removal by sorption to shift the reaction equilibrium towards higher hydrogen production) or *hydrogen membrane reactors* (where hydrogen production is increased by selective permeation through a membrane). The overall efficiency of a steam reformer is well above 70% if steam

generation is accounted for in the energy balance. However, if the steam reformer is part of a large fertilizer or petrochemical plant that allows for steam import/export, then steam reforming efficiency may be much higher. Energy efficiency of steam reforming and other production technologies are given in Table 2 (Summary Table). Large-scale reformers are currently used in industrial processes while small-scale reformers have been developed for on-site, decentralised hydrogen production.

■ **Partial Oxidation** – Partial oxidation consists of mixing a hydrocarbon fuel with oxygen or air, to form a mixture of H<sub>2</sub> and CO (syngas), based on the *exothermic* reaction  $\text{CH}_4 + \frac{1}{2} \text{O}_2 = \text{CO} + 2\text{H}_2$  (38 kJ/mol). Partial oxidation can take place at high temperature (1100 to 1500°C) with no catalyst, or at a lower temperature (600–900°C) with a catalyst. If pure oxygen is used, the cost of the process is higher, because oxygen needs to be separated from air. In this case however, water-shift reaction and hydrogen purification are less demanding, thanks to the absence of significant amounts of nitrogen. Recent advances in partial oxidation process include the use of oxygen-permeable membranes to integrate the oxygen separation from air and the oxidation reaction, and the use of a metal oxide as an “oxygen carrier” for oxidation.

■ **Auto-thermal Reforming** - Auto-thermal reforming (ATR) is in fact a combination of the steam reforming and partial oxidation where the heat for the endothermic reforming is produced by partial oxidation of the basic feedstock. In the thermal section of the reactor, the feedstock generates heat by oxidation. The reformer is therefore more compact and its start-up time is shorter.

■ **Coal Gasification** - Coal gasification is driven by steam and oxygen and leads to the production of a gas mixture based on the following chemical reactions:  $\text{C} + \text{O}_2 = 2\text{CO}$ ;  $\text{C} + \text{H}_2\text{O} = \text{H}_2 + \text{CO}$ ;  $\text{C} + 2\text{H}_2 = \text{CH}_4$ ;  $\text{CO} + \text{H}_2\text{O} = \text{H}_2 + \text{CO}_2$ . In general, an air separation unit is used to obtain pure oxygen to be used in the reactions, and nitrogen for transportation of pulverized coal into the gasifier. If air is used instead of oxygen to avoid the separation cost, a significant amount of NO<sub>x</sub> is produced in the process. There are three types of gasifier, i.e. fixed bed, fluidized bed and entrained-bed (see ETSAP P05). The gas mixture can be used to produce liquid fuels (synthesis) or pure hydrogen. Typical efficiencies are between 35% and 50% (LHV). New developments concern the direct production of hydrogen from coal in a single-step reactor, with in-situ CO<sub>2</sub> absorption. With some modifications, the gasification process can also apply to solid biomass feedstock.

■ **Water Electrolysis** - In water electrolysis, electric current is used to electrochemically split water into hydrogen and oxygen. Today's most commercial electrolysis technology is the alkaline electrolysis, where

the current is transported from one electrode to another of the electrolytic cell by hydroxide ions. A less mature technology is the proton exchange membrane (PEM) electrolysis, where the electric current is transported by protons. Alkaline electrolyzers can meet hydrogen production capacity from 1 to 1000 Nm<sup>3</sup>/h, while PEM electrolyzers are generally limited to around 20 Nm<sup>3</sup>/h.

Electrolysis is an electricity-intensive process. The cost of electricity along with the capital cost of the electrolyser determine the cost of electrolytic hydrogen. To reduce the electricity consumption, part of the energy that is needed to split water into hydrogen and oxygen can be provided in form of heat (high-temperature electrolysis). This may increase the overall efficiency of the process depending on how heat is produced. Pressurised electrolysis is another option to increase the efficiency of the process and provide high-pressure hydrogen with no additional compression. Pressurised electrolysis at around 32 bar is a state-of-the-art process. Recently first units supplying hydrogen at 165 bar appeared in the market while higher pressures are being tested at laboratory scale. Electrolytic hydrogen is carbon free if renewable electricity is used.

Alkaline electrolyzers use an aqueous KOH solution as an electrolyte. They are best suited for stationary applications, with operating at pressure up to 25 bar. Usually, commercial alkaline electrolyzers consist of a number of electrolytic cells arranged in a stack. Main components are shown in Figure 1. A major challenge is to design and manufacture alkaline electrolyzers with lower costs, higher energy efficiency and lifetime.

Typical efficiencies of commercial alkaline electrolyzers are between 56% and 73%, corresponding to 70.1–53.4 kWh<sub>e</sub> per kg of hydrogen. The overall energy efficiency of commercial systems for electrolytic hydrogen production ranges from 62% to 82%, equivalent to 77 to 47 kWh<sub>e</sub>/kg (see the Summary Table, i.e. Table 2).

PEM electrolyzers use an organic polymer membrane-based electrolyte, in which protons that are generated at the anode move towards the cathode. PEM electrolyzers can potentially be designed for operating pressures up to several hundred bars, and are suited to either stationary and mobile applications. The major advantages of PEM over alkaline electrolyzers are the higher turndown ratio, the operation at partial load, the increased safety due to the absence of KOH, and a more compact design due to higher densities and operating pressure (with often no need for further hydrogen compression).

PEM electrolyzers are derived from PEM fuel cells (and vice versa). A typical PEM assembly includes the polymeric proton exchange membrane between two porous electro-catalytic layers (electrodes). The proton exchange membrane consists of perfluorosulfonic acid polymers, that are gas-tight electrical insulators, in which the ionic transport is highly dependent on the bound and

free water in the polymer structure. Nafion is the most commonly used material<sup>1</sup>.

Large quantities of hydrogen can also be obtained as a by-product from chlorine-alkali electrolysis for production of chlorine and sodium hydroxide.

■ **Thermo-chemical Water Splitting** – Thermal splitting of water into oxygen and hydrogen occurs at very high temperatures, but the temperature level may be relatively reduced using thermo-chemical cycles at around 900°C, based on chemicals such as sulphur and iodine. Main issues associated with these processes is the hydrogen capture and the low efficiency (around 43%) as well as the associated corrosion induced by the chemical elements at high temperature, and the sustainable generation of the required high-temperature heat. In regions with high solar potential, one option for sustainable heat generation could be the use of concentrated solar power (ETSAP E10). The use of renewable heat could also help to overcome the efficiency issue.

■ **Photo-electrolysis** - Photo-electrolysis is a process to produce hydrogen using sunlight to illuminate a water-immersed semiconductor that converts the light into chemical energy to split water into H<sub>2</sub> and O<sub>2</sub>. While promising lower capital costs than a combined photovoltaic-electrolysis systems, this process needs a technology breakthrough to reach the market. Test-scale devices have shown solar-to-hydrogen conversion of up to 16% and cost estimates are premature.

■ **Hydrogen from Biomass** – In general, the processes for converting biomass or biomass-based products (e.g. biogas, biofuels) into hydrogen are similar to the processes used for hydrocarbons conversion. The hydrogen production from biomass feedstock is a carbon-neutral process as the carbon content of biomass is assumed to have been subtracted from the atmosphere during the biomass life cycle. The main challenges to adapt the existing processes to run on biomass relate to biomass availability and logistics for regular supply of the basic feedstock. However, hydrogen production from biomass is in competition with biomass use for heat and power, biofuels and biogas production (see ETSAP E05, P11, P10 respectively), the latter presenting a significant cost advantage in comparison with hydrogen.

■ **Biological Production of Hydrogen** - Research and development on biological production of hydrogen have increased significantly over the past decade and includes

<sup>1</sup>With operation voltages 0.7–0.75 V, the maximum efficiency of PEM fuel cell can be as high as 64%, though losses and ancillary equipment may decrease significantly the actual efficiency. Research focuses on minimizing losses and reducing costs through the use of non-exotic, inexpensive materials, and increasing lifetime.

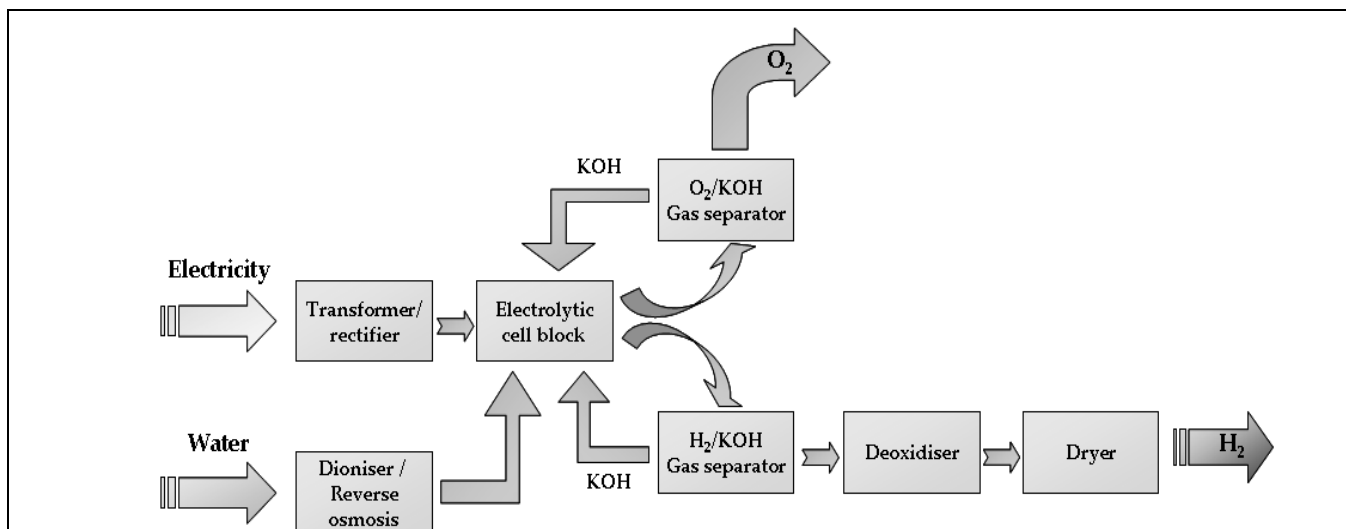


Figure 1 - Process Diagram of the Alkaline Electrolysis

a number of processes that are still in the research phase, e.g. water photolysis by green algae or cyanobacteria, fermentation by anaerobic bacteria, photo-fermentation, microbial electrolysis cells, photo-biological hydrogen. These technologies could draw on a huge resource base, but still need significant R&D effort to reach the market. Practical feasibility is to be proved.

## HYDROGEN PRODUCTION COSTS

The hydrogen production costs by production technology are presented in Table 2 (Summary Table). They not only reflect different technologies, but also different feedstock (hydrocarbons) and prices, economies of scale and production capacities. As a consequence, rather than market-based costs, they are to be considered as order of magnitude of international cost estimates. A typical cost breakdown for each production technology is also given in Table 2 where *material* means the cost impact of the basic feedstock, *process* means the impact of the equipment (capital) cost, and *labour* accounts for man power cost. Cost estimates in Table 2 have been based on an electricity cost of 0.8 €/MWh, a natural gas cost of 0.7 €/Nm<sup>3</sup>, and a coal cost of 250 €/t. Based on these assumptions and on market practice, steam-methane reforming (SMR) results to be the most competitive technology for commercial production of hydrogen, which covers the largest share of global production (almost 48%). Gasification of coal and other hydrocarbons rank second and third, with significant lower shares, followed by partial oxidation. Electrolysis is by far the most expensive production technology and accounts for a few percentage points of today's global hydrogen production. Very significant quantity of hydrogen are produced (and used) by the refinery industry, by steam reforming of either natural gas, oil by-products, refinery gases, or directly as a refinery by-product.

In general, hydrogen production from fossil fuels offers competitive production prices and potential for large-scale production. However, because of the associated CO<sub>2</sub> emissions, hydrogen from fossil fuels could hardly be considered a viable fuel for mass transport, particularly in the absence of effective carbon capture and storage (CCS) technologies.

In contrast, electrolysis offers the key advantage of no or negligible CO<sub>2</sub> and pollutants emissions (apart from those associated with electricity generation), and high purity of the final product. It also is a flexible process to meet either small and medium hydrogen demand, and can be operated at basically any place where sufficient electric power is available. Water electrolysis is economically penalised by the low conversion efficiency and high cost of electricity. It requires at least 47 kWh<sub>e</sub> per kg of hydrogen (at full efficiency) while typical electrolyzers consume up to 77 kWh<sub>e</sub> per kg of hydrogen. While R&D efforts aim to increase the efficiency and size of electrolyzers, electrolysis is not yet regarded as a viable option for large-scale production. To avoid corrosion, most of the available electrolyzers work at temperatures lower than the water boiling point and do not exceed the pressure of 50 bar. Technology projections suggest that remarkable cost reductions are possible for electrolysis, assuming increasing production capacity, industrial learning and economies of scale. Other technologies for hydrogen production are still used for just niche applications or demonstrations, and cost estimates are premature or uncertain.

## HYDROGEN DISTRIBUTION AND STORAGE

Hydrogen storage, transportation and distribution may well be the biggest challenges for integrating hydrogen into the energy system. The low hydrogen volumetric

energy density at room conditions (around 30% of methane at 15°C, 1 bar) along with the ability to permeate metal-based materials pose serious constraints.

■ **Hydrogen Storage** - There are basically three techniques for hydrogen storage. The most traditional ones are compression at high pressure and liquefaction at cryogenic temperature (i.e. gaseous and liquid storage, respectively). The most advanced technique is hydrogen storage in solid materials (solid storage).

Hydrogen **compression** for transportation by tube trailers or pipelines is often operated directly after production. The impact of compression on hydrogen cost is due to the cost of electricity to run the compressor and the capital cost of the compressor itself. It is widely assumed that compression energy amounts to about 10%-15% of the hydrogen energy content (HHV) (depending on final pressure), with an electricity consumption of €0.3–0.45/kg. As for the equipment, a 300-bar compressor with capacity of 20 Nm<sup>3</sup>/h would cost typically between €45,000 and €90,000, and translate into a hydrogen cost of €0.63–1.3/kg. Therefore, electricity cost and capital costs make up a total compression cost of about €0.9–1.75/kg<sup>2</sup>. It is worth noting that economy of scale and wider use might lower compressors' prices.

Hydrogen **liquefaction** for transportation by liquid tankers is an expensive process consuming between 30% and 40% of hydrogen energy content. However, liquefaction increases hydrogen density by around 800 times compared to gaseous hydrogen at atmospheric pressure, and allows for hydrogen storage at relatively low pressure whereas gaseous hydrogen would need very high-pressure compression to contain the same amount of energy as liquid hydrogen. In terms of capital costs, small to medium scale liquefiers would cost in the region of €0.5 to 1.1 per kg. As liquefaction requires a very large amount of energy, its total cost is very sensitive to the cost of electricity.

Hydrogen **solid storage** offers in principle a number of advantages in terms of compactness, handling, energy consumption, but still is under development, with a number of materials and technical solutions under investigation, some of which are already being used in experimental or demonstration projects, or in very niche markets. At present, none of these solutions seems to be ready for high-power applications nor for large-scale

<sup>2</sup>This applies to commercial pressures of up to 300-350 bar. Higher pressures (up to 700 bar) would be needed to achieve high gravimetric (up to 6 wt%) and volumetric storage densities. However, high pressures require higher capital costs and compression energy, new expensive pressure vessel materials (high-strength, carbon-fibre composites) as well as gas diffusion barriers (polymer liners) to minimise hydrogen leakage, and new standards to be implemented.

markets because of either technical or commercial reasons.

■ **Hydrogen Transportation** - Gaseous hydrogen is usually transported by either tube trailers and pipelines while liquid hydrogen is moved by road tankers. For short distances and small amounts, delivery of gaseous hydrogen by tube trailers is usually the option of choice. For medium amounts and long distances liquid tankers are likely preferred, while large amounts over long distances are usually moved by pipelines, if available.

**Tankers** have typically a capacity of 400 to 4000 kg of liquid hydrogen. Should hydrogen become a widely used fuel for transport, tankers could likely be used for refueling filling stations though liquid supply would be significantly costly to customers. It is estimated that delivery by liquid tankers can cost around €0.13/kg, which is agreement with the US-DOE estimate of €0.15/kg.

**Tube trailers** typically contain 300 kg of gas, stored at a pressure of up to 200 bar. They are used for small deliveries to customers who usually are close to the hydrogen production plant in order to reduce the high cost of carrying small amounts of product. A key advantage of tube trailers is the flexibility: for example, they can also be used for delivering hydrogen to new users if they are not (yet) connected to a distribution pipeline. The cost of transport by tube trailers excluding compression is estimated at approximately €0.6/kg over a distance of 100 km. It is suggested that tube trailer transportation cost including compression could be as high as €2.2/kg.

**Pipelines** for hydrogen transportation are typically 25-30 cm in diameter and operate at a pressure of 10-20 bar. Current systems are based on steel pipes, but there is potential for cost reduction and better performance using fibre-reinforced polymer pipes. Pipeline supply can be effective for delivering hydrogen to a large number of high capacity users. However, the energy required for compressing and pumping hydrogen is considerable. It is also possible to mix up to 20% hydrogen in natural gas pipelines, without important supply and end use modifications.

A summary of the hydrogen transportation cost by pipeline is given in Table 1. It should be noted that these estimates apply only to large volumes of hydrogen of at least 5 billion m<sup>3</sup> per year.

■ **Hydrogen Storage in Fuel Cell Vehicles** – Hydrogen-based fuel cell vehicles (FCV) are widely seen as a possible carbon-free alternative to internal combustion engines running on fossil fuels. Apart from the need of reducing the cost of fuel cells, a key challenge for this development to materialize is the on-board storage of hydrogen and its implications for the hydrogen distribution infrastructure and standards (e.g.

operating pressure). The target is to store 4-5 kg of hydrogen that is sufficient to drive a FCV for 400-500 km) while minimizing volume, weight, energy use, costs, and refueling time, and providing prompt hydrogen release on demand. To meet all these requirements, hydrogen needs to be stored at very high pressure (from 350 bar up to 700 bar) or as a liquid at -253°C. In this case, the electricity required for compression is from 15% to 30% of the hydrogen energy content (up to 40% for liquefaction), and current commercial options do not fully meet the requirements for compactness, drive-range, and cost. For example, both liquid storage and 700-bar gaseous storage still require more space than gasoline storage to get an equivalent drive range. In addition, for both high-pressure and liquid storage, on-board tanks are rather expensive (in the range of a few thousand dollars per vehicle).

As mentioned, a possible alternative to compression and liquefaction could be hydrogen storage in solid materials. This could offer sufficient compactness, drive range and safety for automotive applications as well as easy charging and refueling procedure, and fuel release on demand. However, no commercial solution is currently available on the market neither for traditional internal combustion vehicles nor for advanced fuel cell vehicles, and further research is needed to achieve this target. Another alternative which could avoid the hydrogen storage issue is the use of on-board reforming to produce hydrogen from e.g. fossil fuels. This option has also been investigated for years by car makers, but also proved to be challenging and rather expensive.

### **HYDROGEN FOR ENERGY STORAGE**

Energy storage (particularly, seasonal renewable energy storage, which could enable full exploitation of solar and wind energy potential) still represents an unsolved technical challenge where hydrogen can ideally play a useful role. Hydrogen can be used as an energy storage medium for variable renewable energy sources especially in off-grid installations (islands), but also in grid-connected systems. Hydro power plants, wind turbines and PV plants could be equipped with water electrolyzers that use excess electricity generation (e.g. overnight) to produce hydrogen. When renewable resources are not available, the stored hydrogen can be used to produce electricity (e.g. by fuel cells) or as a transport fuel. In spite of the undeniable poor efficiency and high costs, these systems represent at present one of the few technical options (along with batteries) to provide a continuous supply of electricity and fuel based on renewable sources. They include a hydrogen production section, a storage section, and a re-electrification section. A schematic of these systems is illustrated in Figure 2. The hydrogen production section can be based on either an alkaline or a proton exchange membrane (PEM) water electrolysis units. Storage can be based on 200-350 bar

Gm <sup>3</sup> /y	€/1000 m <sup>3</sup>	€/kg
5	23.47	0.261
10	16.62	0.185
20	13.64	0.152
30	12.47	0.139

compressed hydrogen that is commercially available and consistent with industrial standards. Possible re-methanisation is also an alternative under investigation to solve the storage problem. Re-electrification can be based on PEM fuel cells.

### **POTENTIAL AND BARRIERS**

Hydrogen is repeatedly mentioned and seen as an attractive, clean and versatile energy carriers (*hydrogen economy*). It can be obtained from a range of energy sources and technologies (fossil fuels, renewables, biomass, electricity, biological process) and used as a carbon-free fuel for both stationary and automotive applications. If produced from primary renewable energy or by electrolysis using renewable electricity, hydrogen materialises a 100% carbon-free fuel, and is perfect for distributed generation and use. However, several technology challenges need to be overcome for this to happen: energy efficiency of production processes should be increased; production costs should be significantly reduced; cost-effective technical solutions need to be found for transportation and storage; not least, effective CCS technologies are needed for hydrogen production from fossil fuels.

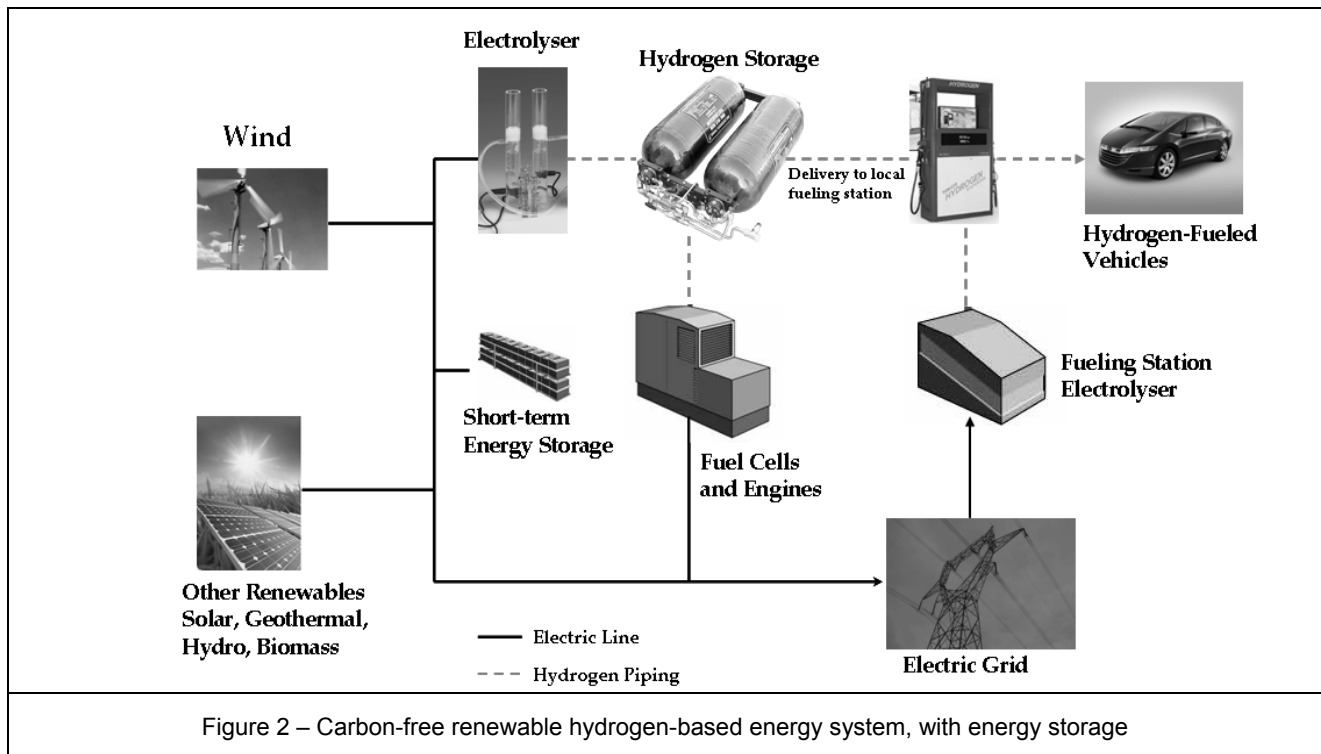
At present, hydrogen is almost entirely used as a basic feedstock in refining and chemical industry, and could be added to other fuels to form energy enriched and or cleaner fuels. Also under development and demonstration is the possible use of hydrogen production as an energy storage system when renewable energy generation exceeds demand (e.g. overnight hydro and wind power production, daily solar power).

Looking at hydrogen across end-use sectors, it could be noted that in transport, the development of hydrogen-based FCV is currently challenged by electricity and electric vehicles (hybrids, plug-in electric vehicles), but large-size electric batteries for vehicles also face their own technical and economic issues, and FCV are still an option under consideration. In the building sector, future applications of hydrogen seems to be less important than previously thought, if heating/cooling demand is met by other options, e.g. the rapid commercial penetration of heat pumps and increased district heating.

As mentioned, hydrogen also needs a specific storage and distribution infrastructure to be timely developed, which also calls for careful consideration. It is currently

unclear in which volumes and form (gaseous, liquid) hydrogen will be handled and used, and system costs/benefits analyses have not been fully worked out. A key question is whether hydrogen is needed to achieve a sustainable low-carbon energy system in the light of increasing electrification and possible use of advanced biofuels. What clearly emerges at present is that energy storage (particularly, seasonal renewable energy storage, which could enable full exploitation of solar and wind energy potential) still represents a technical challenge where hydrogen might play a useful role. Apart for continued R&D to overcome the hydrogen storage technical challenges, near term initiatives to introduce hydrogen in the energy system may include the establishment of a regulatory framework for blending hydrogen with natural gas, including metering, quality standards and investigations of the impact on end-use devices, as well as international standards and safety

codes for hydrogen handling, and design codes for refuelling stations. The knowledge of the relationship between large-scale integration of variable renewables and energy storage needs also to be improved to identify the possible role of hydrogen. Research and development on FCV and on-board solid-state hydrogen storage need to be continued to prepare for possible alternatives to electric mobility and biofuels. Hydrogen-based FCV demonstration projects (*early adopter cities*) need to be continued. To minimise costs, these demonstration could be done in cities with existing hydrogen infrastructure (e.g. used by chemical or refining industry), which could also be used for hydrogen mobility projects. High-temperature stationary fuel cells also need to improve durability and efficiency of electrodes, and reduce production costs



**Table 2 - Summary Table - Key Data and Figures for Hydrogen Production**

Technical Performance	Typical current international values and ranges			
by Technology Variants	SMR	POX	Electrolysis	Gasification
Energy input	Natural Gas + Electricity	Hydrocarbons + Electricity	Electricity	Hydrocarbons + Electricity
Energy efficiency (%)	70 - 85	60 - 78	62 - 82	50 - 70
Typical size (Nm <sup>3</sup> /h)	10.000 – 20.000	10.000 – 20.000	0.5 - 10	10.000 – 20.000
Technical lifetime	2 – 5 years	2 – 5 years	40.000 hours	2 – 5 years
Market share (%),(2012)	48%	30%	4%	18%
Costs (€2011)				
Production cost, (€/Nm <sup>3</sup> H <sub>2</sub> )	0.05 – 0.1	0.07 – 0.15	0.16 – 0.30	0.05 – 0.1
Typical cost breakdown, (%) (material, process, labour)	30% material, 40% process, 30% labour	30% material, 40% process, 30% labour	50% material, 30% process, 20% labour	30% material, 40% process, 30% labour
Data Projections 2015 - 2030				
Efficiency (%),	70 - 85 (2015) 70 - 85 (2020) 75 - 85 (2030)	60 - 78 (2015) 60 - 80 (2020) 65 - 80 (2030)	50 - 80 (2015) 55 - 80 (2020) 60 - 85 (2030)	50 - 70 (2015) 55 - 70 (2020) 60 - 75 (2030)
Product cost (€/Nm <sup>3</sup> H <sub>2</sub> ),	0.090 (2015) 0.085 (2020) 0.080 (2030)	0.110 (2015) 0.105 (2020) 0.100 (2030)	0.15 – 0.27 (2015) 0.13 – 0.20 (2020) 0.10 – 0.15 (2030)	0.095 (2015) 0.090 (2020) 0.085 (2030)
Lifetime,	2 – 5 years (2015) 2 – 5 years (2020) 2 – 5 years (2030)	2 – 5 years (2015) 2 – 5 years (2020) 2 – 5 years (2030)	40,000 hrs (2015) 45,000 hrs (2020) 65,000 hrs (2030)	2 – 5 years (2015) 2 – 5 years (2020) 2 – 5 years (2030)
Market share (%),	48% (2015) 45% (2020) 40% (2030)	30% (2015) 25% (2020) 20% (2030)	5% (2015) 15% (2020) 30% (2030)	17% (2015) 15% (2020) 10% (2030)



### References and Further Information

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