7 FUEL CELLS

Content

7.1 Introduction

The usual methods to obtain power and heat from fossil resources involve some successive conversion processes. The main stages are heat generation by fuel combustion and power generation from heat with turbines and electrical generators. Among these processes, the heat transformation into electricity has the lowest efficiency. Besides the low efficiency, the processes based on the fossil fuel combustion produce large emissions of CO_2 and solid waste, those long time accumulation in the environment are followed by serious climatic and ecological changes.

To maintain under control these dangerous evolutions, intensive research and development works were carried out towards the renewable energy resources utilization. At the same time, new technologies of fossil fuel utilization were developed viewing those importance in the world energy consumption at least for the next decades. The main aimed progresses are an increased efficiency and lower emissions.

Some new processes like photoelectric conversion of solar radiation, electrochemical conversion, thermoelectrical conversion, were considered of first importance. However, the most promising process remains the nuclear controlled fusion what will be the long term solution to cover the world energy demand.

7.2 Operating principle

A direct conversion of chemical energy of substances into electricity is possible through electrochemical reactions, avoiding the thermodynamic stage. Some advantages arise in this case:

- large and expensive equipments like boiler, turbine, electrical generator and auxiliaries are not involved;
- because the process temperature is constant, the conversion efficiency is no more limited by the thermodynamic laws. As consequence, a doubling of efficiency comparatively with the conventional conversion is expected (up to 80%).

The electrochemical energy conversion develops in the „fuel cell”. This name comes from the fact that the primary energy source is a fossil or synthetic fuel like hydrogen, methane, methanol, hydrazine etc. These substances are submitted to oxidation and reduction reactions with secondary emissions similar to those of burning processes.

A fuel cell has two electrodes, separated by an electrolyte (fig.1).

At the anode, called „fuel electrode”, the combustible (H_2) suffers an oxidation process, resulting protons and electrons.

At the cathode, called „oxygen electrode” or „air electrode”, is supplied with atmospheric air or with oxygen. At cathode takes place a reduction reaction of the molecular oxygen in the presence of protons transmitted via electrolyte and electrons which come through the external circuit.

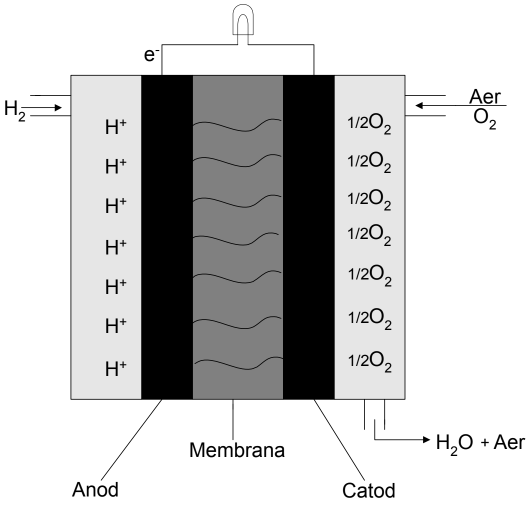

Fig.1 The $H_2 - O_2$ fuel cell

The chemical reactions in the H_2-O_2 fuel cell are:

- Anode $2H_2 \rightarrow 4H^+ + 4e^-$ (1)
- Cathode $4H^+ + O_2 + 4e^- \rightarrow 2H_2O$ (2)
- Aggregate reaction $2H_2 + O_2 \rightarrow 2H_2O$ (3)

While the hydrogen ions pass through the electrolyte toward the cathode, the electrons flow by the electrical circuit directed by the electromotive force of the chemical reactions. This tension represents the potential difference between the electrodes in equilibrium with the electrolyte. The tension is independent from the electrodes size and the inner impedance but depends on the electrodes material and structure and on the electrolyte concentration, too.

7.3 The electromotive force

The generated power of a fuel cell originates in internal energy of the entered substances. The energy balance equation of a fuel cell is:

$$\Sigma n_i U_i = zFE + Q + W . \quad (4)$$

In equation (4):
- n_i represents the amount of substance *i* (mol). $n>0$ if the substance *i* enter the reaction and $n<0$ for the resulted substances;
- U_i represents the internal energy of the substance *i*;
- *z* is the number of electrons released by the oxidation reaction;
- $F = eN$ is the number of Faraday (where N =6,023.10 atoms/ mol) what represents the electrical charge of the electrons arising from all the atoms in a mol of substance;
- *E* is the reaction electromotive force;
- *Q* represents the reaction heat;

W is the mechanical work of the entered substances.

The energy quantities are positive if are issued from the cell and negative if enter the cell.

If the pressure and the temperature of the gases are known, the mechanical work can be written as:

$$W = - \Sigma p_i \Delta V_i = -\Sigma n_i p_i V_{\mu i} \quad (5)$$

where:
- p_i is the partial pressure of the gas *i*;
- n_i is the quantity from the substance *i* (mol);
- $V_{\mu i}$ is the molar volume of the substance *i*, at the reaction temperature *T* and pressure *p*.

According to the second principle of the thermodynamics, all the irreversible energy conversion processes are associated with an entropy increasing

$$\Delta S \geq 0. \quad (6)$$

For a fuel cell, the entropy changes are:
- a growth arising from the chemical conversion

$$\Delta S_1 = -\Sigma n_i S_i , \quad (7)$$

where S_i is the molar entropy of the substance *i*;
- a growth of the environment entropy

$$\Delta S_2 = Q/T \quad (8)$$

owing to the heat released by the reaction.

The electricity generation and the mechanical work consumption are free of entropy changes. So, results

$$\Delta S = \Delta S_1 + \Delta S_2 = - \Sigma n_i S_i + Q/T \geq 0. \quad (9)$$

By extracting the heat *Q* from the equation (4), results

$$Q = \Sigma n_i U_i - zFE - W. \quad (10)$$

With *W* from the equation (5):

$$-T\Sigma n_i S_i + \Sigma n_i U_i - zFE + \Sigma n_i p_i V_{\mu i} \geq 0$$

$$zFE \leq - T\Sigma n_i S_i + \Sigma n_i U_i + \Sigma n_i p_i V_{\mu i}$$

$$zFE \leq \Sigma n_i (-TS_i + p_i V_{\mu i} + U_i) \quad (11)$$

The last equation can be put in the next form:

$$zFE \leq \Sigma n_i G_i \quad (12)$$

where $G = U + pV - TS$ is so-called free energy, introduced by Gibbs. Finally, the electromotive force becomes:

$$E \leq \frac{\Delta G}{zF}. \tag{13}$$

Equation (12) verifies even when the electrochemical reaction develops in the sense of energy storage (with consumption of electricity like for the case of batteries), but the equation sign changes.

Because the thermodynamic functions of the reaction depend on the temperature, the electromotive force depends on the temperature, too. The actual potential difference between the electrodes differs from the theoretical value, owing to other reaction at the electrodes surface than the basic reactions. These parasite reactions reduce the cell voltage and provoke supplementary substances consumption so must be eliminated or slowed down, at least.

When the fuel cell operates with a consumer, the delivered voltage decreases because the voltage drop on the internal impedance and owing to the polarization processes on the electrode surfaces:

$$U = E - rI - \Sigma\Delta U \tag{14}$$

Polarization manifests in three forms: electrochemical, chemical, concentration.

The electrochemical polarization represents the slowing down of the reaction at electrodes, what depends on the reaction form and the electrode structure. The reduction of this phenomenon can be possible using better catalysts, growing the active surface, increasing the temperature and the substances concentration.

The concentration polarization results from the slowing down of the substances in the reaction area as well as the evacuation velocity of the residual product. Its effect can be reduces using porous electrodes.

The chemical polarization is induced by the low velocity of the reactions on the electrodes.

All kinds of polarization intensify if the current density growth, the temperature decrease and the reactants concentration decrease too. On the external V-A curve for a fuel cell, three zones can be observed (fig.2):

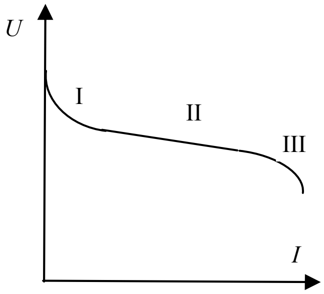

Fig.2 The external characteristic of the fuel cell

- zone I, where the electrochemical polarization has the main influence;
- zone II, where the internal voltage drop and the electrochemical polarization act together;
- zone III, where the voltage decrease faster owing to the chemical and concentration polarization.

7.4 Energy parameters of the fuel cell

The specific energy production represents the total energy amount related to the mass of the spent fuel

$$W = \frac{qE}{m} \tag{15}$$

where:
q is the electrical charge issued in the reaction;
E is the electromotive force;
m is the spent fuel mass.
For 1 mol of substance

$$q = zF,$$

so, for the quantity „m”, q becomes

$$q = zF\frac{m}{M}$$

where M is the molar mass of the fuel.

Results

$$W = \frac{zFE}{M} \tag{15}$$

Finally, considering the limit situation $zFE = \Delta G$:

$$W = \frac{\Delta G}{M} \quad \text{(J/kg)}. \tag{16}$$

For an accurate evaluation of the fuel cell performances, the entire cell mass must be considered, not only the fuel mass. The obtained value W from the equation (16) must be multiplied with the proportion of the fuel mass to the cell mass. Also, the real voltage value must be considered instead of the theoretical value.

The specific power of a fuel cell can be different ways defined:

- related to the electrodes surface area

$$P_s = \frac{P}{S} = Uj \quad (\text{W/m}^2) \tag{17}$$

where j is the current density at the electrodes surface;

- related to the entire cell mass:

$$P_m = \frac{P}{M_c} \quad \text{(W/kg)};$$

- related to the cell volume

$$P_V = \frac{P}{V_c}(\text{W/m}^3).$$

7.5 The fuel cell efficiency

During a direct energy conversion process like that in fuel cell, the process temperature remains constant, so the reaction enthalpy is converted into electricity, except an entropic quantity owed to the heat release.

Using the formula of the free energy (Gibbs), the efficiency can be written:

$$\eta_{iz} = \frac{\Delta G}{\Delta H} = 1 - \frac{T\Delta S}{\Delta H} \tag{18}$$

where $H = U + pV$ represents the reactants enthalpy.

The efficiency can be higher than that of the thermodynamic conversion processes of the heat into electricity, limited by the second principle. Actual performances of the fuel cell exceed 50% efficiency but a level of 80% is considered as possible in the future.

By selecting the reactants, becomes possible a reducing of the released heat. Even a global endothermic reaction was realized with heat consumption from an external source. If that heat quantity originates in residual heat of other processes, the global conversion efficiency will be higher. Such a secondary source may be the cooling water of a power station.

Another way to increase the overall efficiency is to deliver the generated heat to an external consumer, that is this loss becomes an useful energy.

7.6 Fuel cell technology

7.6.1 The electrodes

The electrodes structure and material are of main importance to obtain good performances. In order to grow the energy density (Wh/kg), the electrodes must have a as much possible active surface for the electrochemical reaction. Also, the nature of the surface has to accelerate these reactions. This demand is accomplished by the catalyst elements, called in this case electrocatalyst.

The nature of utilized catalyst depends on the fuel nature and the operating conditions. For example, higher the cell temperature is, the catalyst chemical activity may be lower because the level of activation energy may be easier overtaken by the reactants. For temperatures under 100^0C, the platinum is the best catalyst.

Besides the high chemical activity, the catalyst must have structural and chemical stability adequate to the operating temperature, to be inactive with the electrolyte.

For the entire electrode, the next qualities are necessary:

- structural stability in order to maintain constant the contact area between gases and electrolyte;
- maximum contact area between gases and electrolyte in order to allow higher current densities;
- good electrical conductivity to facilitate the electron transfer towards the external circuit;
- good thermal conductivity to facilitate the transfer of the released heat to the environment or cooling device.

The best qualities offer the pure or allied platinum. By economical reasons, other metals like palladium, iridium, gold, silver or nickel may utilized, too.

7.6.2 The electrolyte

The slowest stage of the electrochemical process is the transport of positive ions through the electrolyte. As consequence, is important to have a higher ionic conductibility of the electrolyte. The perfect situation is that all the positive ions reach the anode, without losses because of parasite reactions. From this point of view, an ions exchange membrane seems to be the ideal electrolyte.

The electrolyte nature has to be correlated with the operating temperature of the cell. For the cold cell, operating at the ambient temperature, the electrolyte consists in water diluted acid or hydroxide solution.

For the warm cells, which operate at about 300^0 C, concentrated solutions or pure liquids as phosphoric acid or potassium hydroxide are used.

For the hot cells, which operates at 350-700^0 C, the electrolyte may be a molten carbonate. There are very hot fuel cells, which operate at temperature over 1000^0 C. For this case, the electrolyte is a ceramic solid.

7.6.3 The fuel

Viewing the high efficiency of electrochemical conversion, a major consequence could be a more advantageous utilization of fossil fuels. However, these substances present a too low reactivity to be possible a profitable operation of fuel cells. For now, is more efficient to use some substances resulted from chemical processing of natural fuels, as hydrogen, methanol, ammonia or synthetic substances as hydrazine.

Except hydrogen, the most interesting fuels are methanol and ammonia. The hydrazine is very expensive owing to the very low efficiency of its synthesis. However, the hydrazine has the highest reactivity comparatively with other fuels of interest, being favourite for some applications like cosmic or military devices.

Between methanol and ammonia, which are equal expensive, preferred is the first, because it’s higher reactivity.

Today, the majority of research and development works are focused on hydrogen as fuel.

According the fuel processing method, three types of fuel cell can be distinguished:

- direct fuel cell, where the fuel is „burned” without a preceding processing;
- indirect fuel cell, where the fuel is chemically processed before enter the cell, using an attached device to be transformed, usually, in hydrogen;
- regenerating cell, where the fuel is obtained by reaction product processing, using energy from other source, especially renewable. In this way, the fuel travels through a closed circuit so that the cell generates electricity by transforming the energy utilized to process the reaction output.

The regeneration process may use electric, thermal or radiating energy. If this energy is a residual output of other conversion processes, the overall efficiency of the conversion will be higher. Also, the fuel regeneration may be considered as an electricity indirect storage process.

7.7 Different types of fuel cells

Alkali fuel cell (fig.3) operates with compressed hydrogen and oxygen. They generally use a solution of potassium hydroxide (chemically, KOH) in water as their electrolyte. Efficiency is about 70 percent, and operating temperature is 150 to 200 degrees C, (about 300 to 400 degrees F). Cell output ranges from 300 watts (W) to 5 kilowatts (kW). Alkali cells were used in Apollo spacecraft to provide both electricity and drinking water. They require pure hydrogen fuel, however, and their platinum electrode catalysts are expensive. And like any container filled with liquid, they can leak.

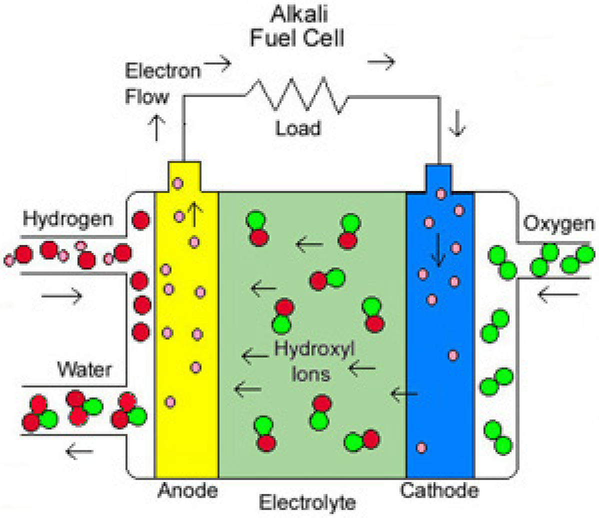

Fig.3 Drawing of an alkali cell.

Molten Carbonate fuel cell (MCFC) (fig.4) uses high-temperature compounds of salt (like sodium or magnesium carbonates (chemically, CO_3) as the electrolyte. Efficiency ranges from 60 to 80 percent, and operating temperature is about 650^0C). Units with output up to 2 MW have been constructed, and designs exist for unit up to 100 MW. The high temperature limits damage from carbon monoxide “poisoning” of the cell and waste heat can be recycled to make additional electricity. Their nickel electrode-catalysts are inexpensive compared to the platinum used in other cells. But the high temperature also limits the materials and safe uses of MCFCs—they would probably be too hot for home use. Also, carbonate ions from the electrolyte are used up in the reactions, making it necessary to inject carbon dioxide to compensate.

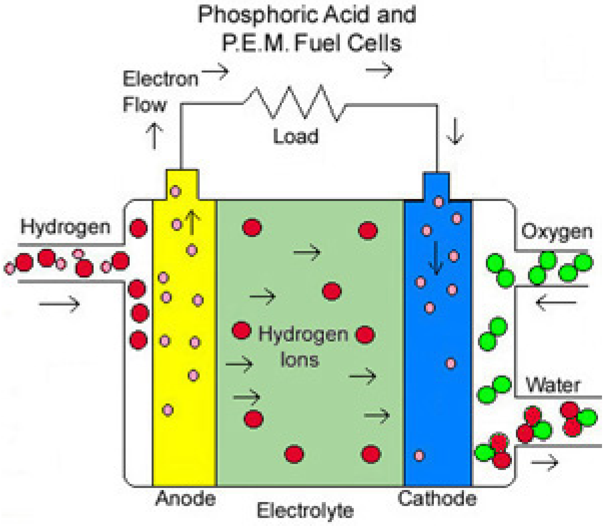

Fig. 4 Drawing of a molten carbonate cell

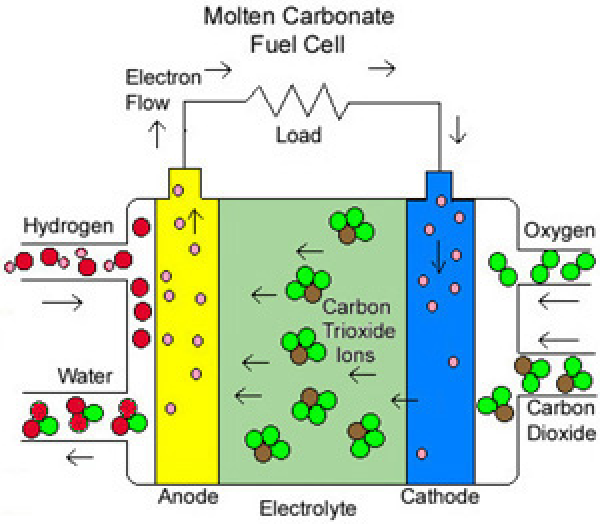

Fig. 5 Drawing of how both phosphoric acid and PEM fuel cells operate.

Phosphoric Acid fuel cells (PAFC) (fig.5) use phosphoric acid as the electrolyte. Efficiency ranges from 40 to 80 percent, and operating temperature is between 150 to 200 degrees C.Existing phosphoric acid cells have outputs up to 200 kW, and 11 MW units have been tested. PAFCs tolerate a carbon monoxide concentration of about 1.5 percent, which broadens the choice of fuels they can use. If gasoline is used, the sulfur must be removed. Platinum electrode-catalysts are needed, and internal parts must be able to withstand the corrosive acid.

Proton Exchange Membrane (PEM) (fig.5) fuel cells work with a polymer electrolyte in the form of a thin, permeable sheet. Efficiency is about 40 to 50 percent, and operating temperature is about 80 degrees C. Cell outputs generally range from 50 to 250 kW. The solid, flexible electrolyte will not leak or crack, and these cells operate at a low enough temperature to make them suitable for homes and cars. But their fuels must be purified, and a platinum catalyst is used on both sides of the membrane, raising costs.

Solid Oxide fuel cells (SOFC) (fig.6) use a hard, ceramic compound of metal (like calcium or zirconium) oxides (chemically, O_2) as electrolyte. Efficiency is about 60 percent, and operating temperatures are about 1,000 degrees C (about 1,800 degrees F). Cells output is up to 100 kW. At such high temperatures a reformer is not required to extract hydrogen from the fuel, and waste heat can be recycled to make additional electricity. However, the high temperature limits applications of SOFC units and they tend to be rather large. While solid electrolytes cannot leak, they can crack.

7.8 The advantages of fuel cells - summary

- **high power efficiency**

The direct energy conversion in fuel cells reaches overall efficiency between 30% (for the beginning) and 90% (in the future), depending on its type and residual heat utilization. Because the cell operates at constant temperature, the second principle of thermodynamics limits its efficiency no more.

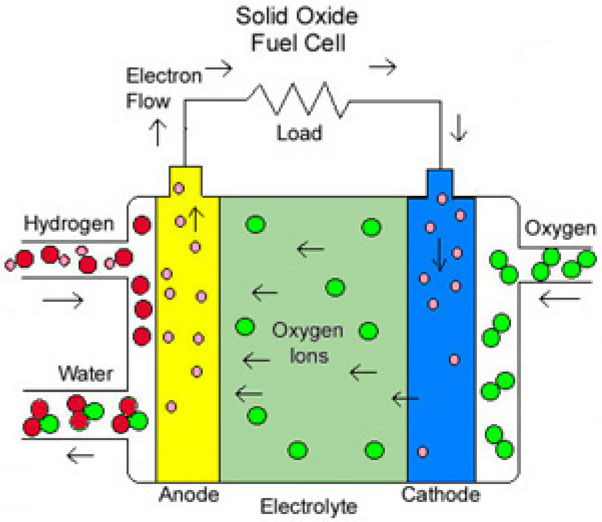

Fig. 6 Drawing of a solid oxide cell

- **Low emissions**

If hydrogen is the fuel, electricity, heat and water are the reaction outputs. The heat can be recovered and water is a clean substance for the environment.

If fossil fuels like methane or oil are processed to obtain hydrogen, appear emissions of carbon dioxide, sulphur oxides and other pollutants, but of lower level like the same amount of electricity is conventionally produced from the same fuels.

- **Reduced environmental damages in mining areas**

The fuel cells utilization can reduce substantially the methane and oil extraction, if hydrogen is obtained using renewable sources of energy. This is a clear difference from the damages produced by drilling, transporting, storage and processing the fossil fuels.

- **Location**

Fuel cells may be located everywhere, inside or outside buildings, because they operate noiseless and clean.

- **Cogeneration**

If the residual heat of electrochemical reaction is recovered, it can be used for water heating, space heating or cooling. In this way, the overall efficiency reaches 90%.

- **Elastic operation**

To grow the electricity output, the fuel flow must be increased. The answer to charge changes is similar with pushing the acceleration pedal of a vehicle.

- **Structural simplicity**

A fuel cells is a solid-state device. The lack of motion allows a simpler design, higher reliability, noiseless operation.

- **Energy safety**

The necessary hydrogen for fuel cells may be obtained from large and various substances like coal, methane, oil, water electrolysis, using renewable energy sources like sun and wind. the local generation of electricity and heat reduces the subordination to external oil and gas resources, which are mostly located in politically unstable areas.

Being the most abundant element in the universe, the feeding with hydrogen is practically endless. Starting the evolution to a hydrogen economy, the mankind can avoid a major energy crisis.

- **Independence from public networks**

A home energy system based on fuel cell allows the owner to be protected from the blackouts or power quality changes what can damage computers and other electric devices. If combined with other renewable energy conversion processes, the energy independence can be more complete.

7.9 HYDROGEN

7.9.1 General

Hydrogen gas (molecular hydrogen) is highly flammable and will burn in air at a very wide range of concentrations, between 4% and 75% by volume. The enthalpy of combustion for hydrogen is −286 kJ/mol (sign minus means the reaction heat is released):

$$2\ H_2 + O_2 \rightarrow 2\ H_2O + 572\ \text{kJ}\ (286\ \text{kJ/mol} = 68.3\ \text{kcal/mol})$$

Under ordinary conditions on Earth, hydrogen exists as a diatomic gas, H_2. However, hydrogen gas is very rare in the Earth's atmosphere (1 ppm by volume) because of its light weight, which enables it to escape from Earth's gravity more easily than heavier gases. However, hydrogen is the third most abundant element on the Earth's surface. Most of the Earth's hydrogen is in the form of chemical compounds such as hydrocarbons and water. Hydrogen gas is produced by some bacteria and algae.

7.9.2 Preparation and Costs

Hydrogen (H_2) can be obtained from different sources:

- fossil fuels (natural gas reforming, coal gasification);
- renewable and nuclear energy: biomass processes, photo-electrolysis, biological production, high temperature water splitting;
- electricity (water electrolysis).

At present, H_2 is produced largely from fossil fuels without CCS –Carbon Capture and Storage- (48% from natural gas, 30% from refinery/chemical off-gases, 18% from coal, the rest from electrolysis). Most of today’s production (some 65 million tones per year) is for captive use in the chemical and refinery industries. In the future, H_2 could be used for power generation and in transport by fueling gas turbines, fuel cells and combustion engines. Used in FCV (fuel cell vehicle), H_2 could significantly increase efficiency and emission reduction in transport.

However, using H_2 for energy applications requires more efficient, less costly production processes, ideally with no CO_2 emissions. Decentralized production is the best choice for market uptake as it minimizes the needs for distribution infrastructure. But it is less efficient than large-scale, centralized production, and it makes CCS impractical.

Electrolysis is a well-known electro-chemical process to split water into H_2 and oxygen (O_2) using electricity. Alkaline electrolysers with potassium hydroxide (KOH) electrolyte are commercially available. Efficiency is a key parameter for electrolysis, as costs are largely determined by electricity costs. Best-practice efficiency could be higher than 85% (Gcal H_2/Gcal electricity), but commercial devices achieve between 55% and 75%. New advanced electrolyzers may approach the upper limit. At high temperatures, heat consumption increases while electricity needs decrease. High-temperature electrolysis (800ºC-1,000ºC) may therefore offer higher efficiency, in particular using residual heat. Also, high-pressure electrolysis can make H_2 pressurization unnecessary and improve efficiency. New electrolyser concepts are based on fuel cells working in reverse mode. Small-scale polymer electrolyte membrane FC (PEMFC) electrolyzers (60°C-80°C, 15 bar, 50% efficiency) are commercially available. Solid oxide FC (SOFC) electrolyzers functioning at 700°C-1,000°C need more research. Current electrolysis costs are typically above \$125/Gcal H_2, but could drop to below \$85/Gcal (including pressurization) over coming decades, assuming electricity at \$35/MWh and 80% process efficiency. Use of off-peak electricity and large-scale plants may reduce costs, although the cost of CCS is expected to increase the cost of electricity.

Natural gas reforming is a mature technology used in the refinery and chemical industries for large-scale H_2 production. Small-scale reformers are currently used in demonstration H_2 refuelling stations (decentralized production). Reforming options include catalytic ***steam methane reforming*** (SMR), ***partial oxidation*** (PO) and other variants under development. In SMR, methane reacts with steam at 700°C-850°C to produce syngas, a mixed H_2 and carbon monoxide (CO) gas.

$$CH_4 + H_2O \rightarrow CO + 3\,H_2$$

CO is then converted into CO_2, producing additional H_2 by water-gas shift reaction.

$$CO + H_2O \rightarrow CO_2 + H_2$$

In the PO process, methane reacts initially with pure O_2 to provide syngas.

$$2\,CH_4 + O_2 \rightarrow 2\,CO + 4\,H_2$$

SMR offers efficiencies of up to 80%-85% in large-scale units (excluding H_2 compression). If residual steam is re-used, total efficiency may be higher. Small units have lower efficiency (at least 10-15 percentage points lower) and higher unit costs. Producers have recently much improved the compactness of small scale reformers (10x3x3m) and their capacity (25-30 Gcal/hour), but further R&D is needed to reduce costs and increase efficiency. H_2 compression and CCS (eventually, in large units) may each further reduce net efficiency by some 5-10 percentage points. CCS in small plants is probably not practical. At current natural gas prices, (\$25-\$40/Gcal), the cost of H_2 from natural gas reforming ranges from between \$40 and \$60/Gcal H_2 (in large-scale production for captive use) to more than \$125/Gcal, with high sensitivity to natural gas prices, processes and economy of scale. Small-scale decentralized production may exceed \$200/GJ. Compressed H_2 in tubes may cost \$350-\$400/Gcal delivered). Projected CCS costs are expected to add \$4-\$10/Gcal, depending on process and scale.

Coal gasification produces a gas mixture of H_2, CO, carbon dioxide (CO2) and methane (CH_4). The basic reaction is

$$C + H_2O \rightarrow CO + H_2.$$

The CO can then be converted into CO_2 and additional H_2 through a water-gas shift reaction. In addition to H_2, the final product offers relatively pure CO_2, ready for pressurization and storage (CCS). Final H_2 purification is needed for most applications.

Although a mature process, coal gasification is currently more expensive than natural gas reforming because of the gasifier and the need for O_2 for the reaction process. Large-scale, integrated gasification combined cycles (IGCC) are considered an attractive option for centralized cogeneration of electricity and H_2, with comparably low CCS costs. Assuming costs of \$4-\$6/Gcal for coal and \$35-\$40/MWh for electricity, with 45% electrical efficiency, projected H_2 production cost with CCS would range between \$30 and \$40/Gcal H_2. IGCC demonstration plants are operating today in several countries to produce electricity (no H_2). They have proved more expensive and less reliable than conventional coal power plants. Cheaper gasifiers and new processes to produce O_2 could make IGCC plants more economically attractive. H_2 is also produced as a by-product from catalytic reforming in refineries, or through off-gas reforming in petrochemical plants, also from ethylene crackers, from chlorine plants and from coke oven gas.

Thermal water-splitting occurs at very high temperatures exceeding 2,500°C, but thermochemical processes such as sulphur-iodine (S-I) or bromine–calcium (Br-Ca) cycles may reduce temperatures to below 1,000ºC. These processes require low-cost high-temperature heat from nuclear or solar sources, also corrosion-resistant materials. The S-I process is the most promising, with about 43% efficiency and an operating temperature of 950ºC. Cost projections suggest a H_2 cost of \$40-\$80/Gcal using nuclear heat from nuclear high-temperature gas reactors (HTGR), and a cost of \$80-\$120/Gcal using heat from advanced, megawatt-scale ***concentrating solar power*** (CSP) systems. Both technologies are unlikely to be commercial before 2030. □

H_2 from Biomass is the only direct way to produce H_2 from renewable energy without major technology breakthroughs. Biomass can be converted into H_2 via various processes (pyrolysis, gasification, anaerobic digestion etc.). While R&D focuses on gasification, synergies with other fuel production processes (biofuels) could open the way to other options and accelerate market uptake. But H_2 production from biomass would compete with biofuels and ***combined heat and power*** (CHP) production. In general, as basic feedstock availability is limited, production from biomass will not benefit from large economies of scale. Costs are expected to be high compared with coal gasification or gas reforming. □

Photo-electrolysis produces H_2 using sunlight to illuminate a water-immersed semiconductor that converts the light into chemical energy to split water into H_2 and O_2. This method promises lower capital costs than combined photovoltaic-electrolysis systems and it holds considerable potential for technology breakthroughs. Test-scale devices have shown solar-to- H_2 conversion efficiencies of up to 16%. But cost estimates are premature.

□

Biological processes derive H_2 from organic matter using microalgal photo-synthesis and cyanobacteria. These processes require genetic engineering to achieve significant levels of H_2 production. Much research is still needed to demonstrate feasibility. □

Projected H2 production costs in Table 1 reflect a range of different technologies, economies of scale and energy prices

7.9.3 Distribution

Pipelines are considered the only option to move large amounts of H_2. They have been used to transport H_2 for more than 70 years. Several thousand km of H_2 pipelines are currently in operation world wide. The energy required to pump H_2 through pipelines is some 4.5 times higher than for natural gas per unit of delivered energy. As a consequence, long distances H_2 transportation for energy use may not be economically competitive. Transportation costs to deliver gaseous H_2 to refueling stations are in the range of \$4-\$8/Gcal, assuming that H_2 compression to refueling pressure is included in the cost of the refueling station.

Liquid H_2 transport by truck, rail or ship is more expensive than gas piping. In current plants, the electricity required for H_2 liquefaction at -253°C is about 10-12 kWh/kg H_2, with potential for future reduction to 7 kWh/kg. The cost of liquefaction in large systems is about \$30-\$40/Gcal, 75% of which comes from the cost of electricity. Transportation of liquid H_2 by ship over long distances is also more expensive than for ***liquefied natural gas*** (LNG) since very low-temperature cryogenic technology is needed. Fast ships are required to reduce boil-off losses (0.2%-0.4% of liquid H_2 per day, which could be recovered, however, and used to fuel the ship).

Refueling Stations – Some 140 H_2 refueling stations are in operation world wide (90 under construction) to fuel some 400 FCV and 100 buses used in demonstration projects. Most stations deliver gaseous H_2 at 350 bar. H_2 is either produced on-site from electrolysis or steam reforming, or received from centralized plants. Costs of refueling stations are estimated between \$12/Gcal H_2 and \$40/Gcal with centralized H_2 production and on-site production, respectively. These costs include investment and H_2 compression. Transportation, distribution and refueling stations may add some \$20-\$50/Gcal to H_2 production costs.

7.9.4 Storage in FCV

On-board H_2 storage for fuel cell vehicles (FCV) is challenging and may have significant impact on H_2 distribution infrastructure and standards (e.g. operating pressure). The target is to store 4-5 kg of H_2 (sufficient for a drive range of 400-500 km) while minimizing volume, weight, storage energy, cost, and refueling time, and providing prompt H_2 release on demand. Storage requires energy-intensive compression at high pressure (350-700 bar) or liquefaction at -253°C. Electrical energy required for compression or liquefaction represents, respectively, some 12% or 30% of the H_2 energy content. Current commercial options do not fully meet requirements for compactness, drive-range, and cost. Liquid or gaseous storage at 700 bar both require more space than gasoline with equivalent energy content. The tank costs more than \$3,000-4,000 per vehicle. H_2 storage in solid materials may offer decisive advantages, but this is still under development, with a number of materials under investigation. On-board reforming to produce H_2 from fossil fuels has also proved challenging and expensive.

7.9.5 Infrastructure

Estimates of H_2 infrastructure investment are complicated by significant uncertainty. The cost of H_2 supply infrastructure for road transport is estimated to be in the order of several hundred billion dollars. Assuming large-scale, centralized H_2 production, the cost of worldwide pipeline-based distribution systems for road transport could range from \$0.1 to \$1.0 trillion. The *incremental* investment in refueling stations would be somewhere between \$0.2 for centralized H_2 production and \$0.7 trillion for decentralized production. A full H_2 economy (i.e., widespread use of H_2 in transport and stationary sectors) would require global pipeline investment in the order of \$ 2.5 trillion, the bulk of which would be to finance supplying commercial and residential customers. Assuming early retirement or partial replacement of existing natural gas pipelines, a significant part of this cost would be *incremental*. The level of investment needed for H_2 infrastructure is not insurmountable when compared with the \$20-trillion investment in energy supply systems that is estimated to be needed if growth in energy demand up till 2030 is to be met.

7.9.6 Potential and barriers

Environmental consequences of the production of hydrogen from fossil energy resources include the emission of greenhouse gases, a consequence that would also result from the on-board reforming of methanol into hydrogen.

Studies comparing the environmental consequences of hydrogen production and use in fuel-cell vehicles to the refining of petroleum and combustion in conventional automobile engines find a net reduction of ozone and greenhouse gases in favor of hydrogen.

Hydrogen production using renewable energy resources would not create such emissions or, in the case of biomass, would create near-zero net emissions assuming new biomass is grown in place of that converted to hydrogen. However the same land could be used to create biodiesel, usable with (at most) minor alterations to existing well developed and relatively efficient diesel engines.

H_2 is likely to gain significant market share over the coming decades if the cost of H_2 production, distribution and end-use fall significantly, and if effective policies are put in place to increase energy efficiency, mitigate CO_2 emissions and improve energy security.

H_2 production costs should be reduced by a factor of 3 to 10 (depending on technologies and processes) and fuel cell cost by a factor of 10 or more. At the same time, emission reduction incentives of \$25-\$50/tCO_2 (depending on fossil fuel price) would help to make H_2, fuel cells and other clean energy options more competitive economically.

Under these assumptions, emissions growth over the coming decades could be reduced in proportions that would bring annual emissions in 2050 down to half those projected in a business-as-usual scenario.

Use of H_2 for energy applications would grow during the years starting from 2020 to reach some 12.5 EJ per year (0.3 Gtoe) by 2050, concentrated mostly on the transport sector. Thanks to the high efficiency of FCVs, this relatively limited input of H_2 (2%-3% of projected total primary energy supply) could fuel some 30% of the global fleet of passenger cars (about 700 million cars). If H_2 for FCV is combined with H_2 used in other applications (refinery and chemicals industries), total H_2 use by 2050 would amount to some 22 EJ (almost four times today's annual use of H_2). Under less optimistic assumptions regarding technology and CO_2 reduction policies, H_2 is unlikely to gain significant market share as alternative fuel and technology options (biofuels, Fischer-Tropsch synfuels, hybrids, batteryelectric vehicles, etc.) could play a more important role in future.

In addition to costs and competition from other technologies, barriers to H_2 market uptake include the need for dedicated infrastructure. However, no single fuel or technology is likely to meet the expected fast growing demand for clean transport fuels. Various options are therefore expected to play complementary roles in regionally diversified markets.

Table 1 - Typical Data and Figures for H2 Production & Distribution Technologies

Data Confidence – Industrial H_2 production is based on well known technologies, but new processes with higher efficiency, lower costs and eventually CCS are needed to produce H_2 for energy use. Typical figures for these technologies are more uncertain. H_2 costs are highly sensitive to coal, gas, biomass and electricity prices.

Current H_2 Annual Production: 65 million tones per year, equivalent to 8EJ (less than 2% of world total primary energy supply); 48% from natural gas, 30% refinery-gas/chemicals, 18% coal, 4% electrolysis

Efficiency of H_2 production from electrolysis (incl. auxiliaries, no compression

Technology	Alkaline large-scale	Alkaline high-pressure	Advanced Alkaline	PEM	SOFC
Status	Commercial	Commercial	Precommercial	Precommercial	Prototype
T (ºC) P (bar)	70-90 atm. to 25	70-90 up to 690	80-140 up to 120	80-150 up to 400	900-1000 up to 30
kWh/kgH_2	48-60	56-60	42-48	40-60	28-39

Efficiency of H_2 production from natural gas reforming (figures in brackets do not include compression)

Technology	Steam reforming, large-scale 50 PJH2/yr, 80 bar		Steam reforming small-scale 0.02 PJH2/yr, 340 bar		Partial Oxidation	Auto-thermal Reforming
Status	Commercial no CCS	Future with CCS	Commercial no CCS	Future no CCS	Commercial no CCS	Precommerc. no CCS
Efficiency, %,	72-77 (76-80)	61-70 (62-78)	47 -55 (60-65)	60-65 (70-75)	66-76	66-73

Efficiency of H_2 production from coal gasification without electricity cogeneration (IGCC) - H_2 at 75 bar

Technology	Current Gasification		O_2-blown Gasification		Advanced CO_2 Membrane Separation	Cogeneration		Cogeneration Membrane Separation
	no CCS	CCS	no CCS	CCS	CCS	no CCS	CCS	CCS
Efficiency, %,	57	51	67	62	64	83	70	77