HYDROGEN AS THE FUEL OF THE FUTURE - PRODUCTION; PURIFICATION; STORAGE

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MOTIVATION FOR THE USE OF HYDROGEN AS A FUEL

The current energy system - based on our fossil energy resources - is not a long-lasting solution to the problems of stationary energy supply and supply with fuel for the traffic. We are exploiting these hydrocarbon resources about one million times faster than they can be replaced. In addition, ecological consideration, before all, the changes in climate and environmental pollution caused by the emission of harmful substances and the greenhouse gas carbon dioxide through the conventional fossil-fueled energy transformation processes, are rapidly gaining importance.

At the beginning of the fast technological development of our civilization, the reserve of combustible hydrocarbons was easily accessible and easy to use. Today, especially the traffic bases nearly completely on the use of fossil fuel. Although, the reserves have not been totally consumed, but only a limited time span remains in which, still relying on the well-established conventional fuels, further development of alternatives has to be carried out.

The challenge now is the development of a new energy and fuel supply system which must be driven by solar radiation in any form, such as direct use of solar radiation, wind, water and geothermal energy. In sharp contrast to the present system, which consumes only long-stored reserves, the new one must base on incoming primary energy. Additionally, the new system must be a closed system based on non-polluting cycles. The incoming primary energy must be stored in a secondary energy carrier. The most advantageous carrier known is hydrogen.

ADVANTAGES AND DISADVANTAGES OF HYDROGEN

Compared to fossil fuels, hydrogen offers enormous advantages. Referred to its weight, it has the highest energy density with 35,7 kWh/kg. It is easily accessible in any amount necessary. It can be produced pollutant-free from water with any renewable energy source. It recombines pollutant-free with oxygen from the air back to water. It can be used equally in adapted combustion engines and new energy supply systems such as a fuel cell system. The technology of hydrogen-fueled combustion engines and turbines is already developed ready to the market. The development of fuel cells is ongoing very fast and promising. The safety aspects of hydrogen are very well-known, and an approved safety technology is existing and developed continuously since decades.

On the other hand, hydrogen has a series of disadvantages. Referred to its specific gas volume, hydrogen has a very low energy density with 600 kWh/m^3 at 200 bar. This is, only, 5,5 % of the energy density of gasoline. Hydrogen is a gas, which can only be stored in gaseous form or, at a very low temperature of 20 K, as a liquid. All safety aspects are completely different from the well-known safety technology of liquid fossil fuels. A reuse of the existing fuel supply infrastructure is not possible, a new one has to be installed. Especially with the use of fuel cell systems in cars, they need a complete redesign of the complete drive chain. At the current development stage of storage methods and requiring the same operating range and load, either the cars would need much bigger storage tanks or new light-weight cars will have to be developed. The refueling procedures and its safety at the fuel station are completely different from the existing ones.

Nevertheless, the advantages of a closed-loop hydrogen system, basing on renewable energy sources and operating pollutant-free as long as the sun light irradiates the earth's surface are overwhelming.

HYDROGEN SAFETY

It has been mentioned before that the safety aspects for hydrogen are completely different from those of the currently used combustible hydrocarbon gases or liquids. Theses differences are based on three main aspects:

- Hydrogen is lighter than air.
- The ignition energy of hydrogen is very low.
- The ignition limits in air are very wide.

The important safety-relevant values of hydrogen are summarized in table 1 in comparison with two other well-known hydrocarbon gases.

Nevertheless, hydrogen is widely used in the industry in very large quantities, e.g. for the production of sugar, hardening of fat, production of metal alloys and of semiconductors. Today, the hydrogen-consuming industry receives it mainly from three sources, thermal and catalytic splitting of natural gas, chlorine-alkaline electrolysis and water electrolysis. Mainly water electrolysis is always used at the consumption site if the transportation of hydrogen is too expensive. For production as well as consumption an approved

	HYDROGEN	METHANE	GASOLINE
MINIMAL IGNITION ENERGY	0,02 mWs	0,29 mWs	0,24 mWs
SELF IGNITION TEMPERATURE	585°C	540°C	228 - 501°C
IGNITION LIMITS IN AIR	4 - 75 Vol.-%	5,3 - 15 Vol.-%	1,0 - 7,6 Vol.-%
EXPLOSION ENERGY (with gas)	2,02 kg TNT/m^3	7,03 kg TNT/m^3	44,22 kg TNT/m^3
LOWER HEATING VALUE	120 kWs/g	50 kWs/g	44,5 kWs/g
FLAME TEMPERATURE	2045°C	1875°C	2200°C
DIFFUSION COEFFICIENT	0,61 cm^2/s	0,16 cm^2/s	0,05 cm^2/s

Table 1:   Revelant Safety Properties of Hydrogen, Methane and Gasoline

hydrogen safety technology including sensors, actuators, relief valves, metal and plastic materials and handling procedures is established, available and laid down in well-defined regulations and laws.

It has already been proven since more than 20 years by research organizations like DLR and car OEMs like BMW and DC that the industrial safety technology can be used equally in cars. This aspect of introduction of hydrogen as a fuel is, only, a matter of continuous adaptation of existing technology to the specific requirements of a car and of its price.

PRODUCTION OF HYDROGEN

Besides the production from fossil resources and its role as a by-product during the chlorine production, the emission-free production of hydrogen through water electrolysis plays today, only a subordinate role in industry with about one per cent of the yearly total production. But in this case, only, the availability of hydrogen as a chemical raw material is dominant. If hydrogen is used an emission-free fuel, its role is that of a secondary energy carrier. It needs to be produced with high efficiency from renewable energy sources, which, generally, have a much lower input energy density and deliver its energy mostly discontinuous.

In order to fulfil the requirements of hydrogen mass production at a convenient price level, compact production plant design and with high purity, the splitting of water with electric energy into its constituents hydrogen and oxygen through the so-called alkaline water electrolysis is actually best choice. In principle an electrolysis cell consists in two electrodes, anode and cathode in a housing filled with an electrolyte mixture of water and potassium hydroxide (KOH). Both electrodes are separated by a gas-tight but hydrophilic membrane. If both electrodes are connected to a direct current (DC) electric energy source , the water in the cell will be decomposed. At the cathode, hydrogen is evolved, at the anode pure oxygen. The KOH makes the water conductive for OH.-ions but remains unchanged in the cell. The process takes place at a cell voltage of 1,23 V, the dissipation voltage. In a technical electrolyzer, the cell voltage is much higher due to several ohmic losses. In industry, cell voltages between 2,2 and 2,5 V are used. Newly developed advanced and

intermittently operating electrolyzers as presented e.g. in figure 1 (10 kW DLR test electrolyzer in Stuttgart, Germany), the cell voltage comes down to 1,6 V. Assembling several cells in series to a block - about 150 cells are technically feasible - operating voltages between 250 and 300 V DC voltage can be reached. Since the production rate of hydrogen is no matter of the voltage but of the current, the electrode area and the current density play the major role. Current densities of 2 - 3 kA/m^2 for commercially available and up to 10 kA/m^2 for advanced electrolyzers are used. With a maximum electrode area of 4 m^2, a single block can take as much as 5 MW of electric energy.

Advanced electrolyzers for the dynamic operation with renewable energy sources like a photovoltaic field are in operation over several years now at a level between 0,3 and 0,5 MW e.g. in the frame of the German- Saudi Arabian program HYSOLAR.
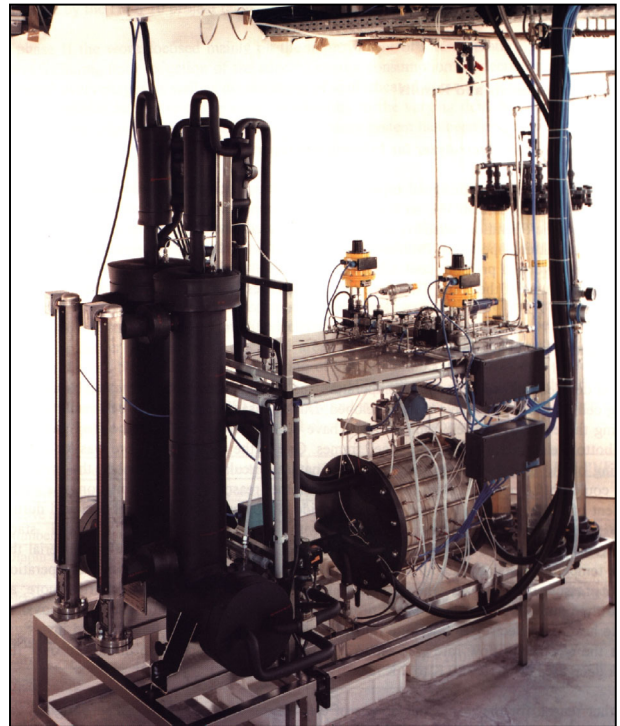

Fig. 1:   Advanced 10 kW DLR Test Electrolyzer

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Besides the electrolysis block, an independently operating electrolysis facility includes as a minimum water supply, electrolyte circuit, cooling circuit, hydrogen/oxygen gas circuits, gas/electrolyte separation, safety and operation sensor equipment and a control.

Atmospheric pressure as well pressurized electrolyzers up to 30 bar are available as commercial plants and prototypes delivering the hydrogen at costs between 0,05 (low efficient chemical plant) and 0,50 Euros (high efficient advanced prototype). The reported lifetime comes to about 30 years before renewal of major parts. Regular maintenance intervals in industry move within 7 and 10 years.
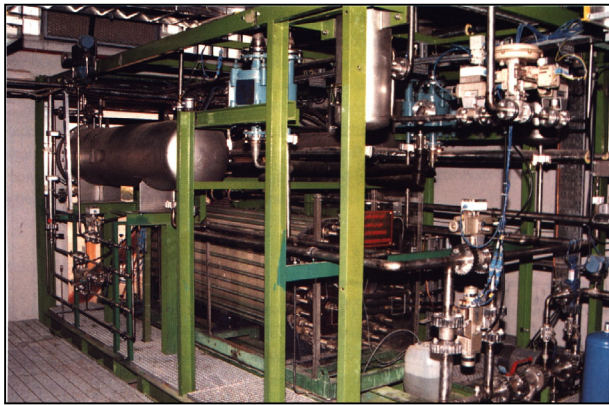

Fig. 2:   350 kW Pressurized Electrolyzer

A major advantage of electrolysis facilities is its up- and down-scalability in terms of electric power and hydrogen output. A good example is the HYSOLAR 350 kW pressurized electrolyzer in Riyadh/ Saudi Arabia as presented in figure 2 whose technical block concept stems from the 10 kW prototype. With the same cell/ block design and, also, operating concept, the whole input power range between 1 kW and 1 MW can be covered.

This type of electrolyzer reaches an efficiency between 70 % (350 kW) during intermittent solar operation and about 90 % at constant operation (10 kW). Hereby, efficiency is defined as the ratio between hydrogen gas output (reference: higher heating value) and electric input energy. The exact measurement of the total energy consumption of the 350 kW plant over a time period of nine months showed additional promising results: About 91,5 % of the total input energy of the plant were used for hydrogen production. 5,1 % were consumed for subsystem cooling and gas purification and another 1,6 % for electrolyte cooling, only. Operation control and water treatment took another 1,2 %. For hydrogen compression, from an operating pressure of 10 bar to the bottle storage pressure of 150 bar which is usual in Saudi Arabia, only 0,6 % of the total plant input energy were consumed. As an input energy source for both, the 10 kW and the 350 kW electrolyzer as well, a photovoltaic field has been used, whose semiconductor

plates convert sunlight directly into electric energy. In figure 3, the 350 kW concentrating and two-axis tracking photovoltaic field (PV) at the so-called Solar Village near Riyadh in the Kingdom of Saudi Arabia is shown. Since the electric output of a photovoltaic cell directly follows the intensity of the sunlight, and the electrolyzer is directly connected to the PV-field, both operate under very strict boundary conditions. Electric power changes of 50 %/sec are normal.

Fig. 3:   350 kW Photovoltaic Field

Since the advanced electrolyzers have been developed for the use with photovoltaic, and other renewable energy converters show a much slower output energy change, they can be used with any other renewable energy facility without any change in technology.

A major disadvantage of photovoltaic is its low energy conversion efficiency. It is defined as the ratio between electric output and input energy. Yearly PV-field efficiencies between 8 and 15 % are normal at single cell efficiencies between 15 and 25 %. Consequently, PV-fields with high power output cover large areas. In the example of the 350 kW field, 160 two-axis trackers with 32 concentrating PV-modules of four PV-cells each cover a land area of approximately 40.000 m^2.

In figure 4, the consequence of the low efficiency is shown in graphical form presenting the energy curve shapes of a typical solar operation day of the 10 kW PV-electrolysis facility in Stuttgart.

From the 1135,6 kWh on the plain area of a 144 m^2 10 kW-PV-field, it delivers only 88 kWhrs at its mains output. So the PV efficiency is about 7,8 %, only. Through ohmic cabling and connector losses between PV-field and electrolyzer, only 78,4 kWh are used for hydrogen production. The efficiency comes down to 6,9 %. After electrolysis, hydrogen purification and compression, the bottles contain compressed hydrogen with an energy content of 57,9 kWh.

Consequently, the total plant efficiency comes to 5,1 %. Nevertheless, the good news are that these results were obtained with a PV-field of 1986. With newer technology reaching as much as 15 % of daily efficiency, the plant efficiency increases to 9,8 %. On

the other hand, photovoltaic has some major advantages

HYSOLAR 10kW test facility
INSTANTANEOUS POWER   JULY 20, 1989

PV operation mode:
FULL DC/DC 81V

energy balance

Insolated energy	1135.6 kWh
PV-field output	88.0 kWh
Electrolyzer input	78.4 kWh

PV-field outp./ electrol. outp. [kW]

Insolated power [kW]
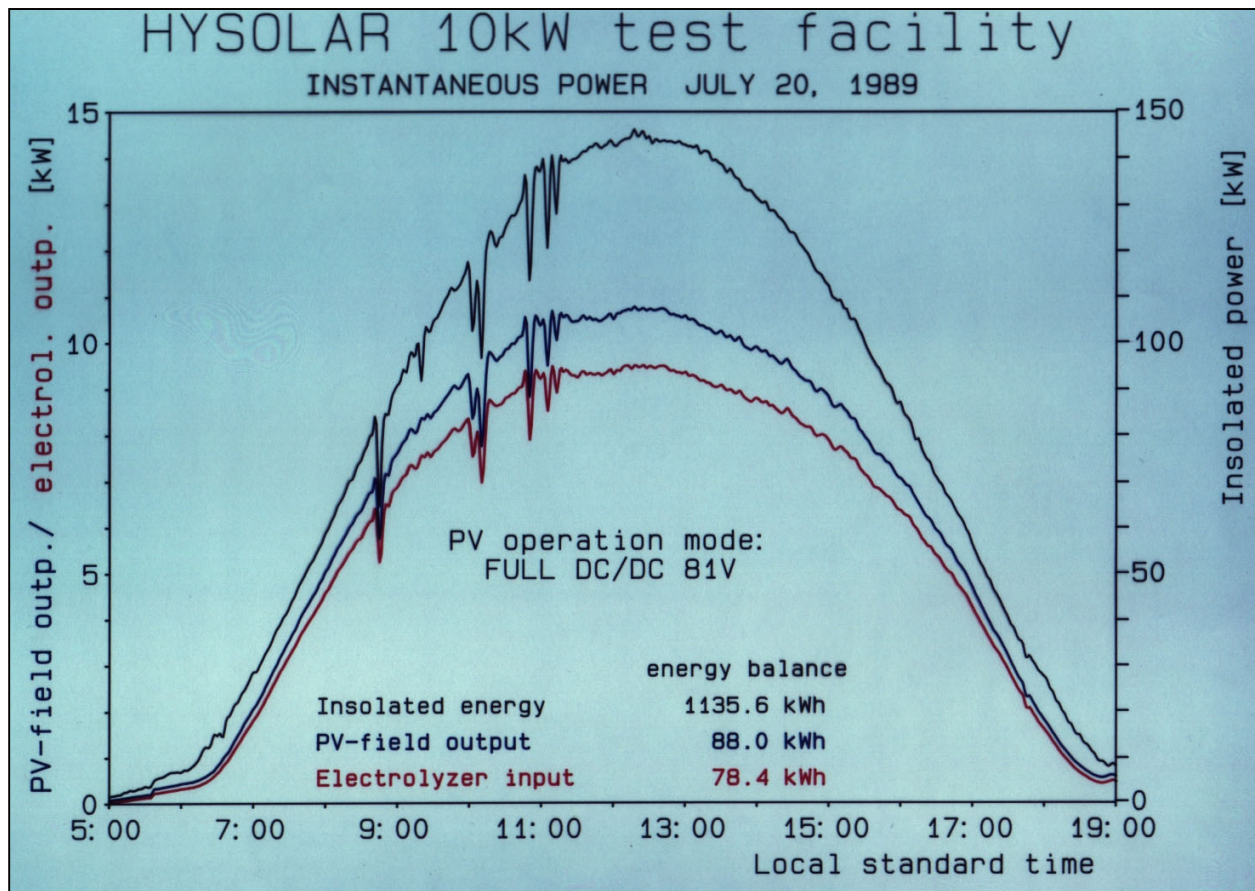
Local standard time

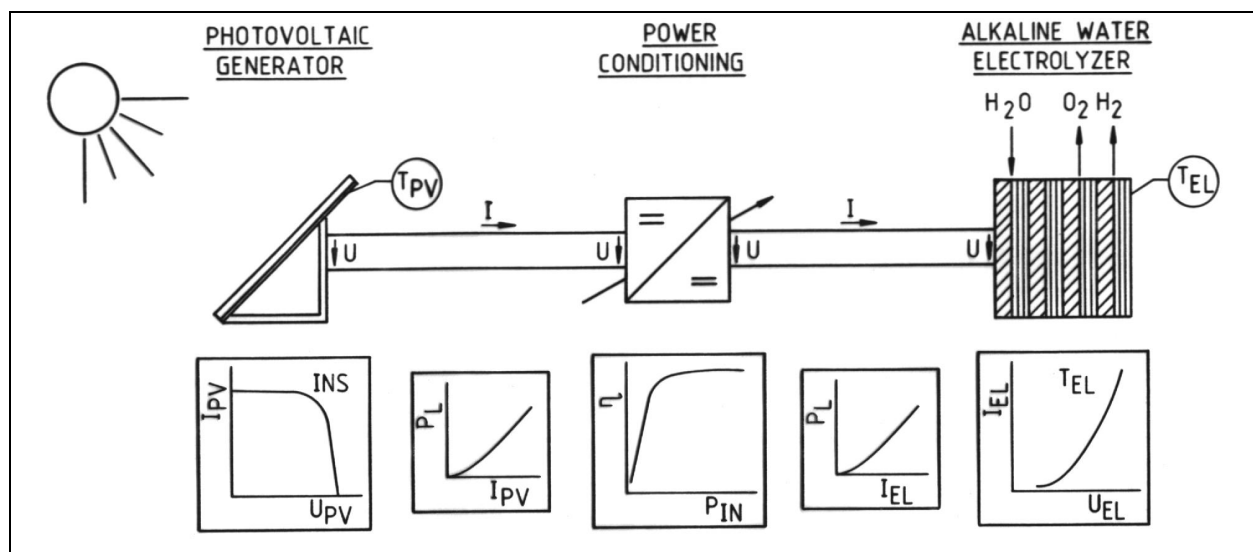Fig. 4:   Typical Energy Curve Shapes during Solar Operation

Fig. 5:   Principle of a PV-Electrolysis Plant

as no maintenance costs and very high lifetime (350 kW field now 22 years and 10 kW field now 16 years without degradation).

Figure 5 shows the principle of a PV-electrolysis plant as a block diagram. Through a so-called power conditioning unit, the PV-field is indirectly connected to the mains connectors of an electrolysis block. The power can be a simple direct two-wire connection of the plus and minus poles of PV-field and electrolyzer or - with the advantage of higher PV energy output during an operating day - it can be a DC/DC-converter which operates the PV-field always at its maximum power point (MPP) which varies with the sun insolation and PV operating temperature. Also mixed concepts between a directly-connected PV part and a MPP-tracked part were tested successfully. The practice of operation has shown that the energy loss of the direct connection is negligible compared to all other concepts. The graphic also shows another fact. Through the simple electric concept of the plant it is possible to operate the electrolyzer from any other electric energy source. Even concepts with different sources connected in parallel to the electrolysis can be realized. Using a controllable highly efficient AC power supply, the electrolysis facility can be operated independently from a single power source connected to an AC-grid which is fed at different locations from various renewable power sources.

HYDROGEN PURIFCATION AND PRODUCTION STORAGE

The operation of an electrolyzer together with a PV-field or another dynamically operating power source has to follow several requirements. By hands of the typical operating curve shapes in figure 6, they can be explained shortly. Specifically these are:

Start up and shut down shall not be restricted by a high startup or shutdown power level of the electrolyzer.

In case of "solarized" electrolyzers, the minimum startup power level is smaller than 5 % compared to about 20 % of conventional ones.

The electrolyzer must follow any changes of electric input power throughout the day without any shutdown.

The gas impurities of hydrogen in oxygen (H_2 in O_2) and oxygen in hydrogen (O_2 in H_2) which are caused by the solubility of the gases in the electrolyte shall never exceed the shutdown safety limit of 2 Vol.-%. The O_2 in H_2-impurity shall always move below 1 Vol.-% in order to guarantee a simple and safe purification. In this example, the H_2 in O_2-impurity moves always below 0,2 Vol.-%. The O_2 in H_2-impurity is, only, about half of this value.

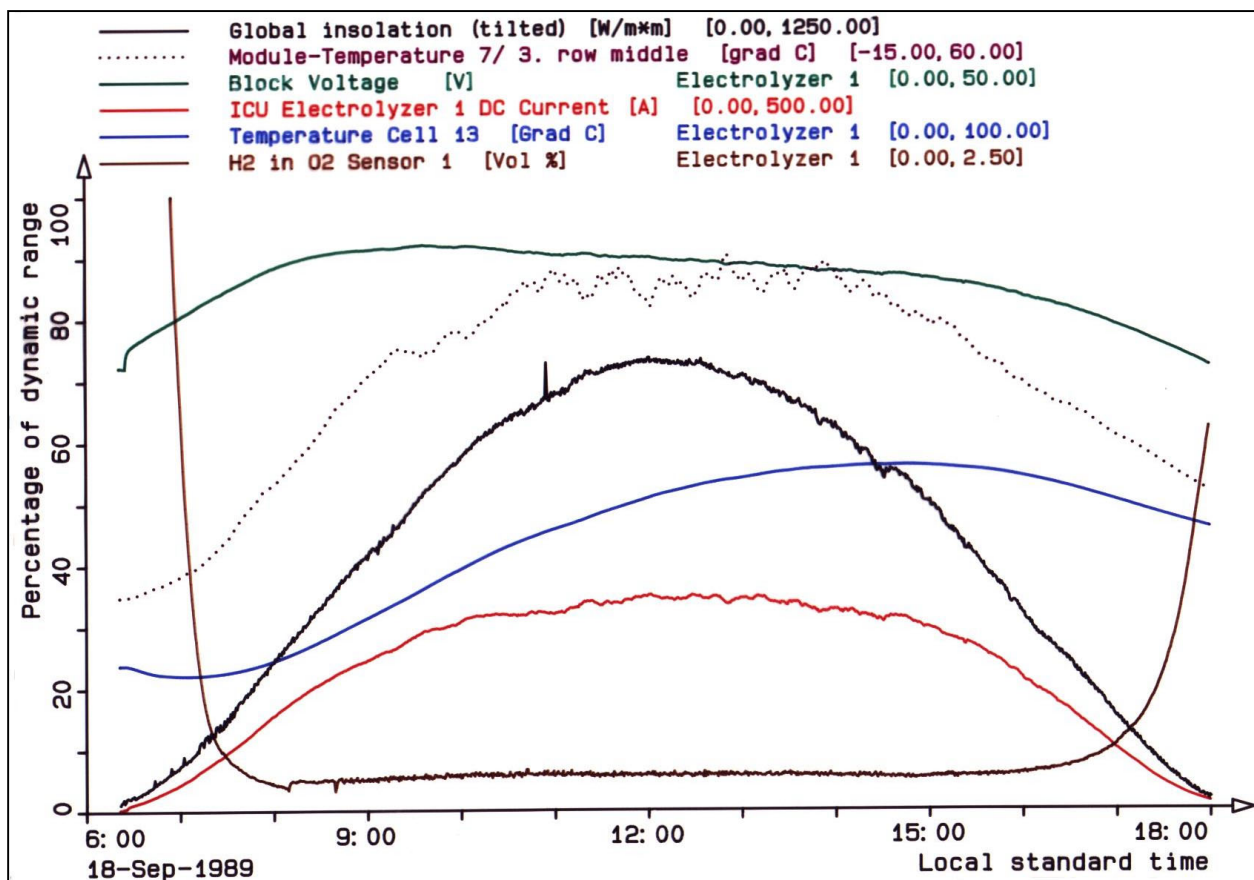Last but not least, independently of the changes of

Fig. 6:   Curve Shapes of a PV-Electrolysis System

input current, the electrolyzer cell voltage shall move between 1,6 and 1,9 V as a maximum to guarantee a high conversion efficiency between 81 and 65 %.

From its principle of operation, electrolysis hydrogen is much purer than that produced by other chemical processes. At the electrolysis output it, only, contains water vapor, a small amount of oxygen and the gases which are soluble in water. The concentration of these gases moves usually in the very low parts-per-million range (ppm) and, thus, is acceptable even for the operation of sensitive fuel cell systems.

Consequently in this case, the main duties of a purification system are the removal of oxygen, water vapor and liquid water, rests of potassium hydroxide in case of alkaline electrolysis and particles. Additionally, purification and final storage system have to follow the boundary conditions of discontinuous hydrogen production.

Measurements with three different electrolyzer types at the DLR 10 kW PV-electrolysis test facility have shown that the "raw" hydrogen of solar-adapted electrolyzers fulfills the requirements of industrial hydrogen with the German quality standard 3.0 corresponding to 99,9 % purity in terms of hydro-carbons, N_2, CO and CO_2.

The basic purification and storage system for electrolytic hydrogen, therefore, consists in:

- Hydrogen collection piping,
- Filter for particle removal,
- Washing bottle for KOH-removal,
- Intermediate storage vessel to de-couple discontinuous hydrogen production from continuous gas compression,
- Compressor with gas cooling device and filling station for bottles or bottle racks. Its usual filling pressure is 200 bar in Germany.
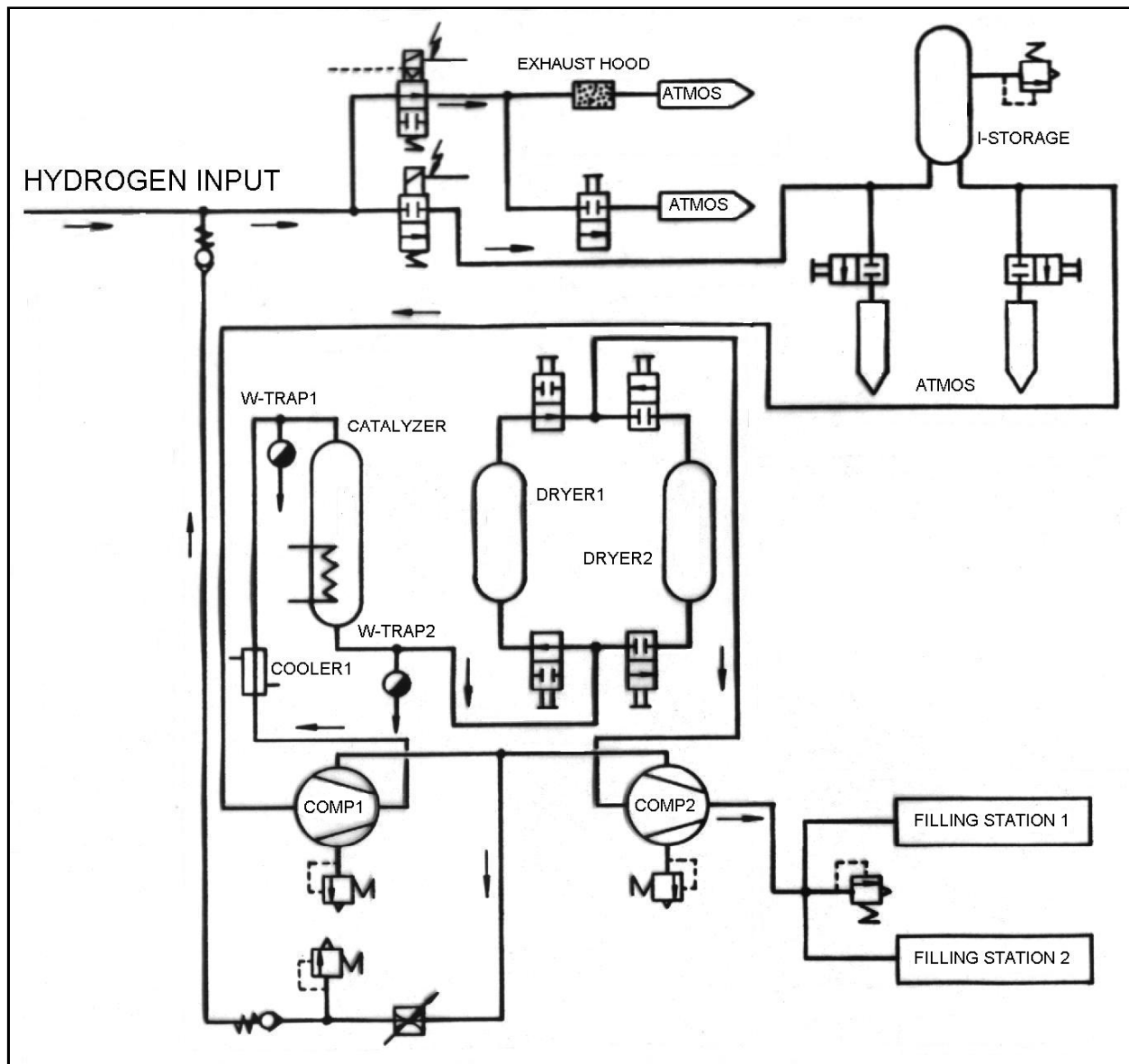

Fig. 7: Hydrogen Purification and Storage System

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In order to update the quality 3.0 to 5.0 for the use with fuel cell systems, it is necessary to extend this basic system with oxygen recombination catalyst, gas cooler, water vapor dryer and liquid water trap.

The result of the development efforts at the 10 kW facility is shown in figure 7 as a block diagram.

After collection, filtering and washing, the hydrogen is stored in the intermediate storage volume (**I-STORAGE**). Since at the 10 kW facility, the hydrogen is collected at 1,1 bar$_a$, a cheap gas balloon with inert PTFE-coating and outer conductive hull is completely sufficient. From the balloon, a two-stage compressor sucks the hydrogen and compresses it in its first stage (**COMP 1**) to a maximum of 16 bar. At its outlet, the hydrogen is cooled (**COOLER 1**) and passes through a first automatically operating water trap (**W-TRAP 1**) into the following externally heated platinum-rhodium catalyst (**CATALYZER**). Herein, the oxygen content is recombined with hydrogen to water vapor. The catalyzer has, only, to be heated at the plant startup. During operation, the reaction waste heat keeps the temperature constant. Since the temperature of this device depends on the reaction rate, the oxygen content in the hydrogen shall not exceed 1 Vol.-%. Otherwise, the device has to be cooled externally. At the a.m. impurity, 2 Vol.-% of hydrogen are necessary for complete oxygen removal. After the catalytic device, a second water trap (**W-TRAP 2**) is located for final removal of liquid water drops. The final step of purification is the surface adsorption of water vapor in a dryer. In this case, two dryer (**DRYER 1, 2**) are installed for alternately purification. Whilst one dryer is in use, the other is connected to ambient air at its outlet and unloaded from the absorbed water with a heater and a small hydrogen flow. The outlet of the active dryer is connected to the second compressor stage (**COMP 2**) which compresses the hydrogen to the final pressure of 200 bar in one of the filling stations (**FILLING STATION 1, 2**). Either maximum six bottles in parallel or one bottle rack can be filled at each line. The independent control of the purification and storage system switches automatically between the filling stations depending on their filling pressure. If one of the components of the system is damaged, the hydrogen production must not be shut down but it can pass to atmosphere through an exhaust (**exhaust hood**) at the system inlet. This bypass is, also, used for a short time period - about 10 minutes always at solar operation startup or shutdown - if the hydrogen impurity exceeds 1,0 Vol.-% and must be released to atmosphere. This startup/shutdown behavior is included in figure 6 as the H_2 in O_2-content. Compressor losses of both stages from the frequent shutdowns are collected and recovered with a separate line back into the gas balloon.

The compressor is an industrially available oil-free membrane compressor with integrated coolers, water traps and safety valves and can take a maximum flow of 10 Nm³/h. For inclusion of the purification system, the direct inter-stage piping was extended. The compressor is designed for frequent startup and shutdown cycles. The same reliable configuration and type with an enforced motor is used at the 350 kW facility. In this case, a varying hydrogen flow up to 65 Nm³/h must be compressed to 150 bar, finally.

The purification location at the intermediate pressure level turned out to be optimal for a constant outlet gas purity.

This kind of storage system can, also, be used to fill hydride storage vessels at a lower pressure level or to serve as delivery system for hydrogen liquefaction.
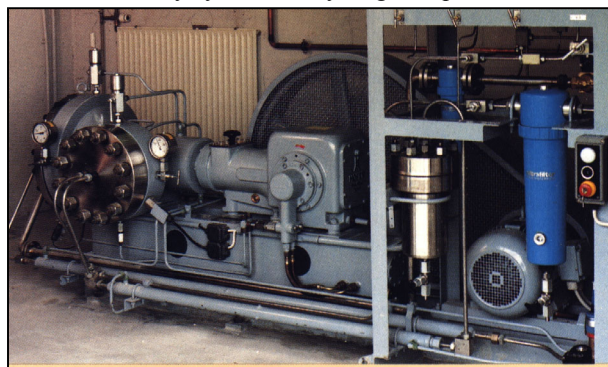

Fig. 8:   200 bar Hydrogen Compressor

STORAGE METHODS FOR MOBILE AND STATIONARY CONSUMERS

Hydrogen is in use since the days of the first public street lighting and public house heating plants basing on gas at the late 19th century. It was used as a hydrogen-rich gas mixture -about 60% - of H_2, CO and CO_2 known as "city gas". Enormous masses were produced from coal and water which were stored at nearly atmospheric pressure in giant expandable steel vessels with fixed bottom and wall and an up and down moving cover which was lifted by the content of hydrogen. These vessels are called gas-o-meters. Also very early, it became obvious that these vessels contained an extremely low percentage of hydrogen compared to its weight, and they were only stationary devices. Consequently, from the piston motors a development of hydrogen compressors basing on piston movement was derived in the very early 20th century. Today, this kind of compressor reaches as much as 6000 bar. Nevertheless, the compressors as well as storage vessels are impractical in public. From the development of hydrogen-safe steal alloys, a durable compromise was found at a level of 150 - 200 bar of hydrogen. This is still the usual bottle pressure level of today.

Taking a 50 l standard bottle with a filling pressure of 200 bar and a tare weight of 65 kg, its content is only 8,9 Nm³ corresponding to 795 g. This means, only a storage density of 1,2 wt.-%. Far too low for mobile

state of the art		new concepts		state of the art	
liquid hydrogen storage		adsorber storage	metal hydride storage	gas pressure storage	

(Figure content)

Hydrogen storage (T = specific capacity, stationary systems; R = vehicle range, mobile systems)

cryogenic storage

21 K — LH$_2$

65 K — e.g., active carbon

40° to 70°C — e.g., Fe Ti

80° to 300°C — e.g., FeTi+MgNi

GH$_2$

| large volume storage, optimum for T > 50 $\frac{kWh}{kW}$ | mobile storage for R > 180 km | large volume storage, optimum for 30 < T < 45 $\frac{kWh}{kW}$ | large volume storage, optimum for T < 3 $\frac{kWh}{kW}$ | mobile storage for R < 180 km | large volume storage, optimum for T < 30 $\frac{kWh}{kW}$ | underground storage |

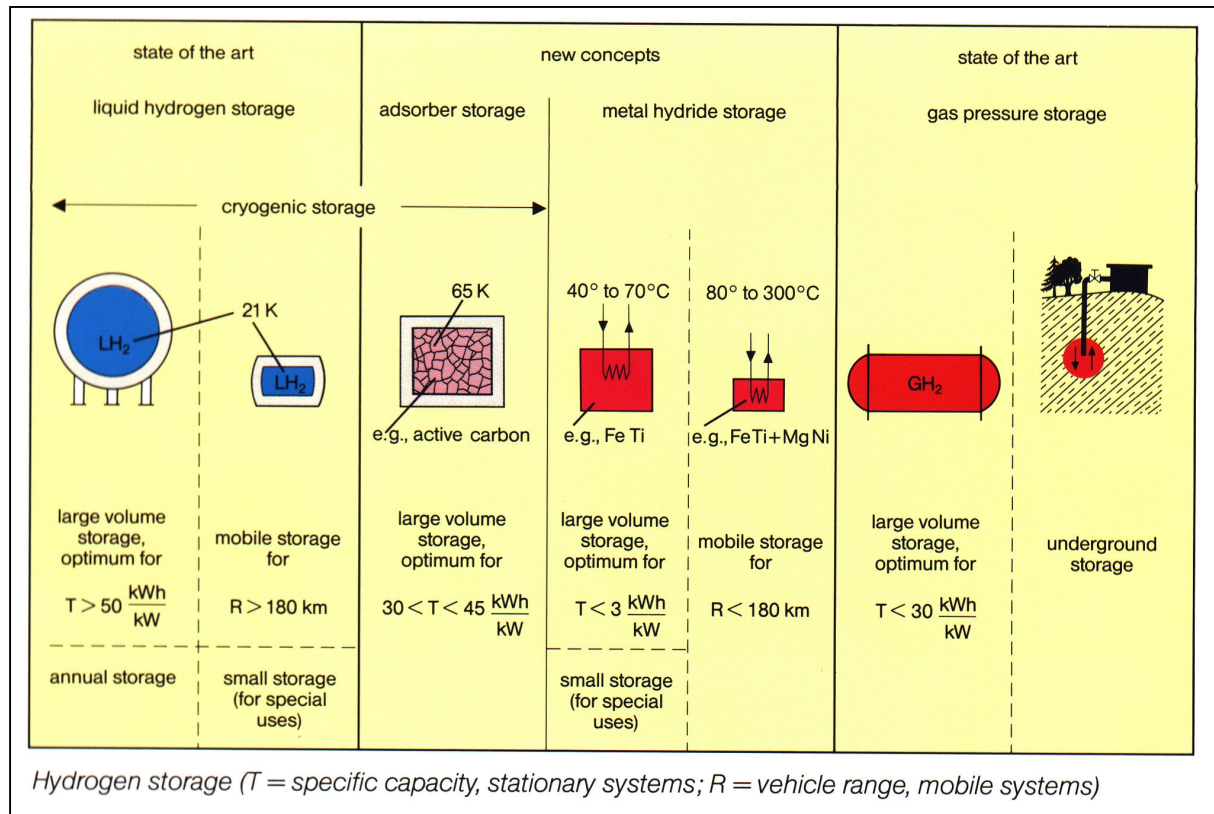annual storage | small storage (for special uses) | | small storage (for special uses) |

Fig. 9:   Industrial Hydrogen Storage Methods

applications or even efficient gas transportation on the road. In figure 9, now, the currently used storage methods for stationary and mobile applications with their characteristic temperature levels, storage capacity or ranges respectively as well as areas of use are presented. They will be explained shortly starting from left to right in this figure.
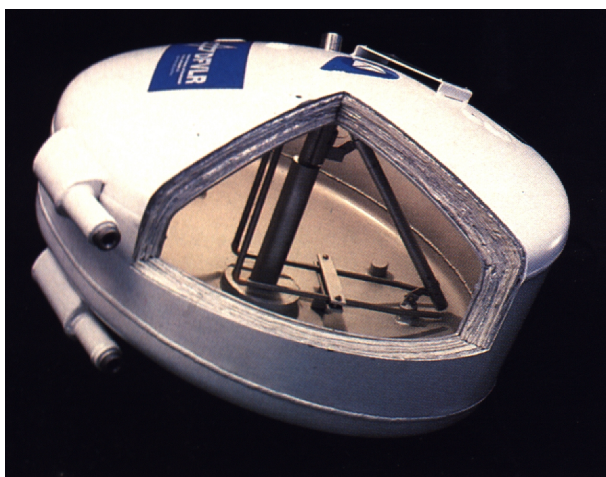

Fig. 10: Liquid Hydrogen Tank of DLR

The most common storage device in cars is the cryogenic storage of liquid hydrogen in vacuum-super-isolated Dewar-tanks. Figure 10 shows a partly

cut open example of such a vessel. A 120 l tank as shown in this figure contains 8,4 kg of hydrogen which corresponds to 277,2 kWh or about 24 l of gasoline. In terms of volume, such a tank is about four times bigger as a gasoline tank. In terms of weight, the aluminum version is only two times heavier than gasoline tank with the same energy content. But three main problems arise from the use of liquid hydrogen:

- The energy amount for liquefaction is high. Although theoretically, the energy amount is, only, 3,92 kWh/kg of liquid hydrogen, the practice delivers values between 10 and 30 kWh/kg of primary energy amount.
- The hydrogen evaporates from the tank with a rate between 2 and 5 % of the content.
- The hydrogen is stored as a super-cold liquid at 20 K or -250°C which makes the handling difficult to the public.

This storage method offers acceptable ranges for cars between 180 km for conventional ones and up to 400 km for new drive train concepts and light-weight cars. The risks of this technology have been examined very carefully and are gradually small at the current stage of development.

The absorber storage method at low temperatures with e.g. active carbon combines the advantages of

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compressed gas with its low energy amount for storage and liquefaction with the high specific energy density. In this case, a pressure vessel contains an active carbon powder or carbon nanotubes with high inert surface and reactivity to absorb hydrogen at the surface. A storage pressure of 50 bar and a temperature -130 and -210°C give storage densities between 2 and 6 wt.-%. This kind of storage does not have the difficulties of the high hydride storage weight and does not need a high temperature level of thermal power for hydrogen de-sorption from the storage material surface. Nevertheless, this technology is still under development in the laboratories and, only , in small volumes available to the market.

Metal hydrides are alloys of two up to five alloy components having a highly porous, ceramic-like consistency. The hydrides store hydrogen in gaseous form adsorbed within the material. The alloy group of hydrides can be divided into three main groups which are classified by its temperature level for a hydrogen dissociation pressure ≥ 1 bar.
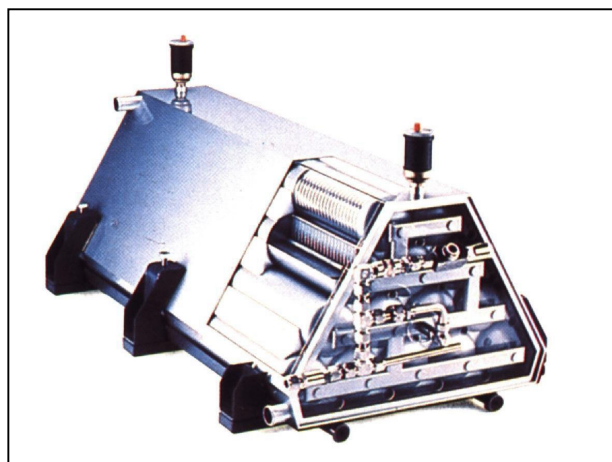

Fig. 11: Metal Hydride Storage of Daimler Benz

The **low temperature hydrides** have a temperature range between -30 and about 70°C. Fe-Ti or Ti-Cr systems are typical examples. Reversible storage densities between 1,5 and 2,3 wt.-% were measured with storage tanks. The disadvantages of these alloys are the low storage density and the loading pressure level between 10 and 50 bar. These devices may be used for highly efficient energy converters such as fuel cells in combination with a low car weight to reach convenient ranges.

Middle temperature hydrides work between 100 and 200°C. La-Ni or Fe-Ni are typical representatives. Since the storage density of maximum 2,5 wt.-% is, only, gradually higher than the a.m. one, they may be interesting because of the low loading pressure level of ≤ 5 bar, only. The practical relevance for cars is very small. The main market area may be the storage of heat for household purposes.

For combustion engines, the **high temperature hydrides** with its temperature above 200°C and the high storage density of up to 8 wt.-% were a matter of intensive research. Typical alloy examples are Mg-Cu and Mg-Ni systems. An additional advantage of this hydride family is the loading pressure around or below 1 bar. Nevertheless, the operation of these hydrides is difficult in cars due to the necessity of thermal energy at a high temperature level for hydrogen de-sorption especially at startup. This kind of storage system needs a highly efficient thermal management system. Figure 11 shows a technical storage vessel from Daimler-Benz which was used in combustion engine cars.

All hydride storage devices have the disadvantages of high weight, necessity of cooling during the loading procedure and heating during operation.

On the other hand, its operation risk is very low and well known. At a leakage, the hydrides freeze very soon after release of small amounts of gas and deliver afterwards only small flows.

The storage of compressed gas has been described at the beginning of this chapter for the level of 200 bar. Today, also stationary and mobile vessels for 300 up 350 bar are usual. The latest development goes as high as 700 bar. So, storage densities up to 8 wt.-% can be achieved. Even the weight of these high-pressure tanks is reduced by the usage of composite materials such as aluminum-carbon fiber. But the energy amount for high pressure is high and the filling pressure can go as high as 1000 bar. This is a technology which needs new developments, ideas and time.

The risk of pressure storage is very high. Additionally to the risk of burning and detonation of big amount of gaseous hydrogen, the risk of vessel detonation has to be considered before all.

Other storage methods of high interest are graphite nanofibers – currently of high scientific interest – with a loading pressure up to 120 bar, sponge iron inoculated with a catalytic noble metal to reach operating temperatures between 80 and 200°C. The viability of this method has not yet been seriously investigated. Glass microspheres with a storage density of about 10 wt.-% but for loading conditions of 200 – 400°C and pressures up to 630 bar are necessary and, finally, aerogels as a type of open-cell foam with ultra-fine pores and a high surface area. A storage density of 3,7 wt.-% at 83 bar was reported so far.

CONCLUSIONS

Compared to other fuels, production and utilization methods, hydrogen has convincing advantages. It can be produced emission-free. It can be used emission-free. It can be made available in any amount necessary. The technology is ready to the market in many cases. Many automobile OEMs have long-term experience with hydrogen. The hydrogen technology can start now and not, only, after long development.