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Fuel cell vehicles: Status 2007

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Abstract

Within the framework of this paper, a short motivation for hydrogen as a fuel is provided and recent developments in the field of fuel cell vehicles are described. In particular, the propulsion system and its efficiency, as well as the integration of the hydrogen storage system are discussed. A fuel cell drivetrain poses certain requirements (concerning thermodynamic and engineering issues) on the operating conditions of the tank system. These limitations and their consequences are described. For this purpose, conventional and novel storage concepts will be shortly introduced and evaluated for their automotive viability and their potential impact. Eventually, GM's third generation vehicles (i.e. the HydroGen3) are presented, as well as the recent 4th generation Chevrolet Equinox Fuel Cell SUV. An outlook is given that addresses cost targets and infrastructure needs.

Keywords: Hydrogen; Automotive; Fuel cell; Hydrogen storage; LH2; CGH2

1. Introduction

The most common alternative drivetrain, which is not based on the internal combustion engine (ICE), is that of a battery electric vehicle. Electric vehicles are widely used where the noise or pollution of internal combustion engines prohibits their application, e.g. in the case of indoor or mining vehicles, but also in the absence of air, e.g. in the case of underwater or lunar vehicles. Major shortcomings of this alternative are attributed to the electric energy storage; namely the too low capacity, high cost, long charging time, small operating temperature range and low cycling stability. These insufficient properties have prevented their wider use for propulsion of passenger vehicles.

It should however be recognized that tremendous progress has been made on batteries [1,2] in very recent years. The most advanced batteries with respect to gravimetric energy density and deep cycle stability are those based on Li-ion-technology. On the other hand, even though widely used in consumer products, this technology requires further research & development with a special emphasis on vehicle propulsion applications. Also, battery cost and energy density is still far away from any automotive requirements (Table 1), if a "conventional" passenger car with approximately 500 km range is used as reference. Furthermore, battery recharging might become an issue due to the necessary high electric currents, especially if the required power is drawn from the electric grid.

On-board storage of hydrogen, although showing some drawbacks such as higher cost and lower energy density, compared to a gasoline or diesel tank, is much closer to automotive cost and performance figures. For example, refueling is possible in less than 5 min. Thus, the utilization of hydrogen and fuel cells as electric energy source has attracted researchers for a long time. Although first attempts of vehicle integration of fuel cells have been made as early as 1959 (Allis-Chalmers Fuel Cell Tractor) and 1966 (GM Electrovan; Fig. 1), fuel cells for a long time were considered to be a very exotic topic with no advantage over combustion engines, nor even over batteries. This was mainly due to the very poor power density of the (alkaline) fuel cells of that time.

New electrolyte materials for PEM (proton exchange or polymer electrolyte membrane) fuel cells eventually offered the possibility for more compact and lightweight fuel cells. During the 1990s, triggered by increasing environmental debate, but also by the fuel cell development at Daimler–Benz, several car companies began to seriously work on developing the PEM fuel cell for passenger car propulsion.

At that time, the motivation for the development was mainly emissions reduction, since fuel cell technologies based on hydrogen could eliminate vehicle emissions completely and ultimately

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Table 1
Comparison of energy storage systems for fuel cell and battery electric vehicles [1,2]

	Hydrogen (70 MPa pressure vessel)	Lead acid battery	Ni-MH battery	Li-ion battery
Specific energy	1600 Wh kg^{-1}	35 Wh kg^{-1}	70 Wh kg^{-1}	120 Wh kg^{-1}
Energy density	770 Wh l^{-1}	70 Wh l^{-1}	140 Wh l^{-1}	150 Wh l^{-1}
Energy required for vehicle ranges of approximately 500 km	6 kg H_2 = 720 MJ = 200 kWh		360 MJ = 100 kWh	
Weight	125 kg	2860 kg	1430 kg	830 kg
Volume	260 l	1430 l	710 l	670 l
Cost (at volume production)	US$ 3600	US$ 15,000	US$ 30,000	US$ 40,000
Power required for 8 h overnight charge	–		>12 kW	
Power required for 30 min fast charge	–		>200 kW	

For a battery electric vehicle, the onboard efficiency was assumed to be twice as large (respectively the energy requirement to be half as much) as the value for the corresponding hydrogen fuel cell vehicle. Note that this table may be used for order-of-magnitude considerations only; for a more exact comparison, e.g. the fuel cell system has to be added in the left column, and also for batteries, some system components have to be added. Furthermore, usually only at maximum 70% of the nominal battery capacity may be used in a charge–discharge cycle.

remove the automobile from the environmental debate. Very similar to a pure battery electric vehicle, all emissions occur during fuel production, i.e. on the well-to-tank path, whereas the only emissions created during vehicle operation is water vapor. Though power density had already significantly increased every year, fuel cells were still much heavier and bulkier than conventional drivetrains. Thus, the further technology development still focused on additional size reduction and performance increase.

Although they still won't compare to high-performance vehicles, the power density of fuel cell systems is meanwhile sufficient for the propulsion of a wide range of passenger vehicles. In the next step of knowledge growth, cost reduction, robustness and durability have become equally important development targets. Besides the fuel cell itself, now also other components such as hydrogen storage device, and their interfaces and interaction, are attracting increased attention. Today, not only emissions reduction, but also a reduced dependence on crude oil respectively petroleum has become a strong motivator for the effort that is spent on hydrogen powered vehicles. The whole well-to-tank path is questioned and investigated. Availability of primary energy, well-to-wheel efficiency and greenhouse gas emissions [3] are evaluation criteria of utmost importance. Fuel cells and hydrogen are widely considered as the best overall solution in the long run, but still significant technical improvements are necessary. Optimized internal combustion engines running on diesel, ethanol and natural gas, the hybridization of powertrains, and the introduction of renewable fuels like ethanol and synthetic fuels from biomass are beginning to diversify the portfolio of powertrain and fuel options during the transition phase from today's engine technologies to future hydrogen powered fuel cell vehicles (Fig. 2).

2. Fuel cell system

The fuel cell running on hydrogen is the most attractive long-term option for passenger cars. It eliminates emissions on the tank-to-wheel path, the fuel (hydrogen) can be produced from many sources, and it provides very high average efficiencies. The latter is particularly based on the fact that the fuel cell reaches highest its efficiency at part load. At full load there is almost no advantage against the internal combustion engine anymore. Particularly passenger vehicles are mostly operated at part loads significantly below their rated power, so that the efficiency gain offered by fuel cells can be highest.

However, at very low power output, even the fuel cell system efficiency sharply drops. This is attributed to many balance-of-plant components such as the air compressor or the hydrogen

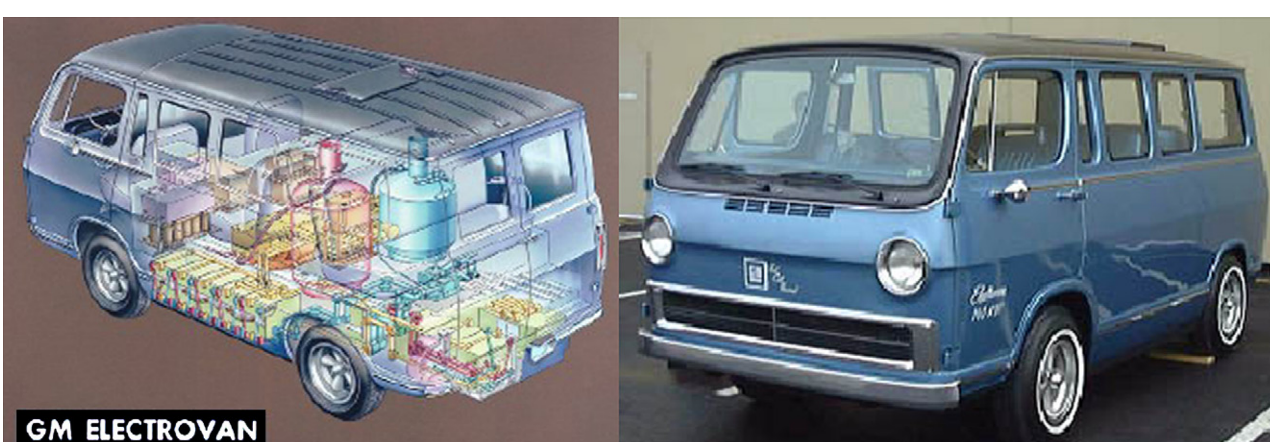

Fig. 1. GM Electrovan (1966), the first fuel cell car, was powered by a hydrogen fuel cell with alkaline electrolyte, liquid hydrogen and liquid oxygen were stored onboard in cryogenic vessels.

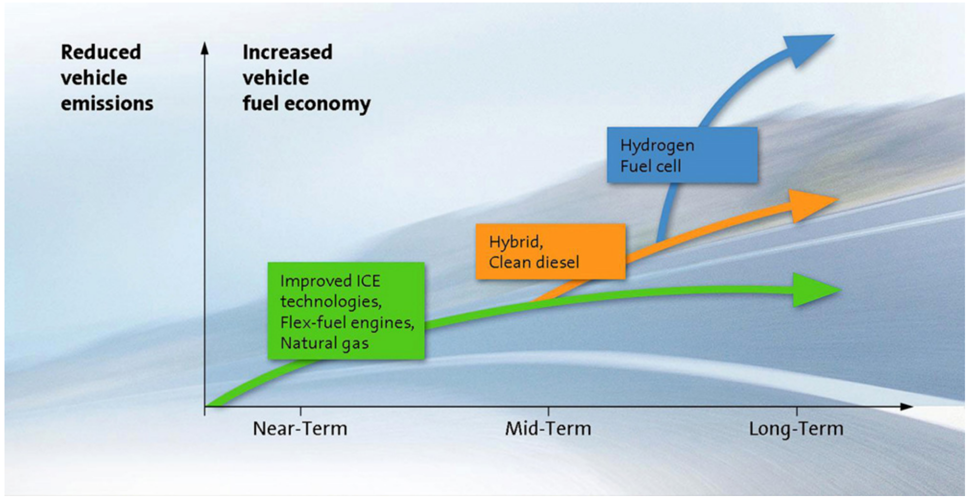

Fig. 2. Diversification of powertrains and fuels.

recycling pump, as those have to be operated even at idle power. Fig. 3 shows the main components of a fuel cell power system. Besides delivering power for the electric propulsion motor, the fuel cell has to drive these auxiliaries. This is analogical to a conventional powertrain. Since the fuel cell system provides electrical rather than mechanical power, many of the auxiliaries are actuated electrically. Their power consumption becomes dominant in the low power region. Hence, the system has to be optimized for low power consumption at idle power, as otherwise the nominal part-load efficiency advantage of the fuel cell is partly being compensated.

Fig. 4 shows the efficiency map of the GM HydroGen3. Lines of equal efficiency (black) are plotted in dependence of torque at the drive shaft and vehicle speed. The orange curve shows the path that the vehicle runs through during a driving cycle, in this case the European Driving Cycle (EDC). For clarification, also the line for constant speed is shown (red dash-dotted line). For periods where the orange curve is below that constant-speed-line, power output is lower than required for constant speed, thus the vehicle is decelerating. For values above, the vehicle is accelerating. As one can see, during acceleration the major part of the EDC-curve is located in a region of efficiencies of around 40%. The average efficiency for the whole cycle is thus as high as 36%, compared to 22% for the corresponding Diesel vehicle.

Performance in terms of high power density and efficiency in terms of high cell voltage have been the main measures for the fuel cell development. In recent years, these were complemented by other major challenges: Lowering the cost at volume production and increasing the reliability and durability are today's most important items on the research and development agenda. The corresponding targets are derived from competing conventional automotive propulsion systems, which are designed for 5500 h

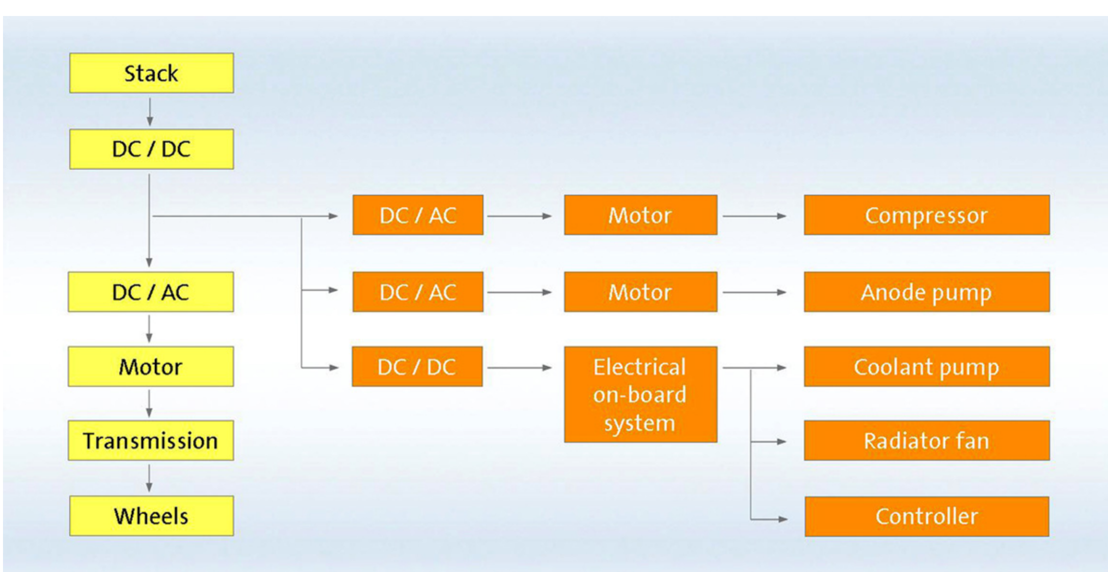

Fig. 3. Fuel cell propulsion system with auxiliaries.

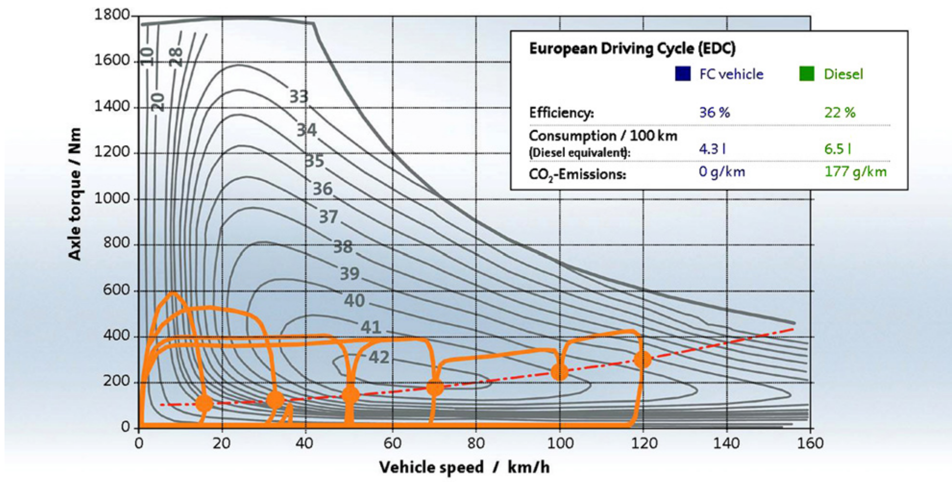

Fig. 4. Fuel cell vehicles efficiency map (GM HydroGen3).

of operation lifetime at a cost of US$ 50 per kW, including fuel storage.

Durability is a major issue for the fuel cell stack, especially if membranes are becoming thinner and catalyst loadings lower, which is necessary for performance and cost reasons. Among the factors limiting the lifetime of PEM fuel cells, chemical degradation has been identified as one of the major problems for fuel cell stacks, although the detailed mechanisms and influencing factors are still under investigation [4–6]. But even though not yet all degradation phenomena in the stack are fully understood, there has been remarkable progress in system reliability. This could be achieved by continuous improvements in the engineering and operation of complete fuel cell systems and vehicles.

Besides the fuel cell stack, another subsystem has turned out to have major influence on vehicle cost and performance: the fuel storage.

3. Onboard hydrogen storage options

There are four major options for onboard hydrogen storage.

(1) CGH2 compressed gaseous hydrogen at 35–70 MPa and room temperature.
(2) LH2 liquid hydrogen at 20–30 K, 0.5–1 MPa.
(3) Solid state absorbers (such as hydrides [7,8] or high-surface materials [9,10]).
(4) Hybrid solutions, utilizing at least two of the mentioned above technologies.

These technologies are described in detail in several other publications and shall therefore be described here only shortly.

It also has to be stated that all values for gravimetric and volumetric energy densities may correspond either to just a materials approach (a) or a systems approach (b) including all required components and carriers. From an engineering perspective, the second approach is preferable; also the target values provided by the US Department of Energy are defined on this basis [11,12].

The options (1) and (2) have been implemented by the automotive industry in recent years. For example, the GM HydroGen3 (a multi-purpose vehicle based on the Opel Zafira mass production architecture) is adaptable to using both storage types. The HydroGen3 vehicles are currently capable of storing either 3.1 kg H_2 (70 MPa CGH2 variant) or 4.6 kg H_2 (LH2 variant). These values correspond to ranges of 270 km, respectively, 400 km in the New European Driving Cycle. The Chevrolet Equinox Fuel Cell, GM's fourth generation fuel cell vehicle incorporates a 4.2 kg 70 MPa CGH2 storage system (see Fig. 12 and Table 2). A completely different approach is pursued in GM's Chevrolet Sequel. This concept car is not based on an existing architecture but was designed around the hydrogen

Table 2
Specifications of the 2007 Chevrolet Equinox Fuel Cell

Dimensions	
Length	4796 mm
Width	1814 mm
Curb weight	2010 kg
Cargo volume	906 l
Electric traction	
Front motor	3-Phase asynchronous
Power	73 kW cont., 94 kW max.
Torque	320 Nm
Fuel storage	
Type	3 CGH2 vessels (type IV)
Service pressure	70 MPa
Capacity	4.2 kg hydrogen
Fuel cell system	
Fuel cell stack	440 cells, 93 kW
NiMH battery	35 kW
Operating life	2.5 years, 80,000 km
Operating temperature	−25 to +45 °C
Performance	
Acceleration	0–100 km h^{-1} in 12 s
Top speed	160 km h^{-1}
Operating range	320 km
Payload	340 kg

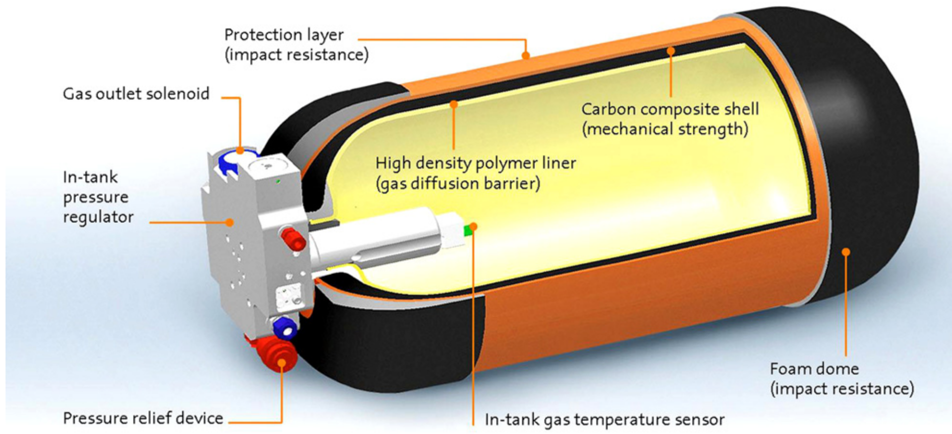

Fig. 5. Type IV compressed gaseous hydrogen vessel [13].

propulsion system. Doing so, the integration of an 8 kg 70 MPa CGH2 storage system (corresponding to a range of 480 km) was enabled.

In all of the cases described above, the storage system for packaging reasons comprises not a single but two, respectively, three pressure vessels. The design of such a vessel (type IV, hence using polymer liner materials) is shown in detail in Fig. 5.

Since the volumetric storage density of a CGH2 tank is rather low (already on a materials basis, see Fig. 6), the packaging of such a fuel system into an existing mass-production vehicle architecture remains a challenge. Because of the comparatively high operating pressure of these vessels, a cylindrical design is both essential and obvious.

Despite all limitations of the CGH2 approach, this option yields today the best overall technical performance and shows the highest maturity for automotive applications.

Until very recently, liquid hydrogen has also been considered to be a technology viable for automotive implementation. But its drawbacks concerning an efficient thermal insulation (see Fig. 7) could not be tackled in a satisfying manner. Due to the low operating temperature of in-between 20 and 30 K, an unavoidable heat flow takes place (2–3 W for the complete tank system). This heat input consists of three fractions:

(1) Thermal conduction
(2) Convection
(3) Thermal radiation

Among these, the thermal conduction through pipes and cables to the inner storage vessel and the heat radiation from the environment to the cryogenic liquid are dominant.

To achieve the low overall values of heat transfer mentioned above, it is very important to also work with cylindrical tank structures (compare to CGH2) because this geometry is very close to the optimal surface-to-volume ratio (only beaten by completely spherical structures). Additionally, it is required to implement a very efficient multi-layer vacuum super insulation consisting of approximately 40 layers of metal foil. Wrapping these foils around the storage vessel in general and around the dome areas (as well as the in- and outlets for H_2 or wires,

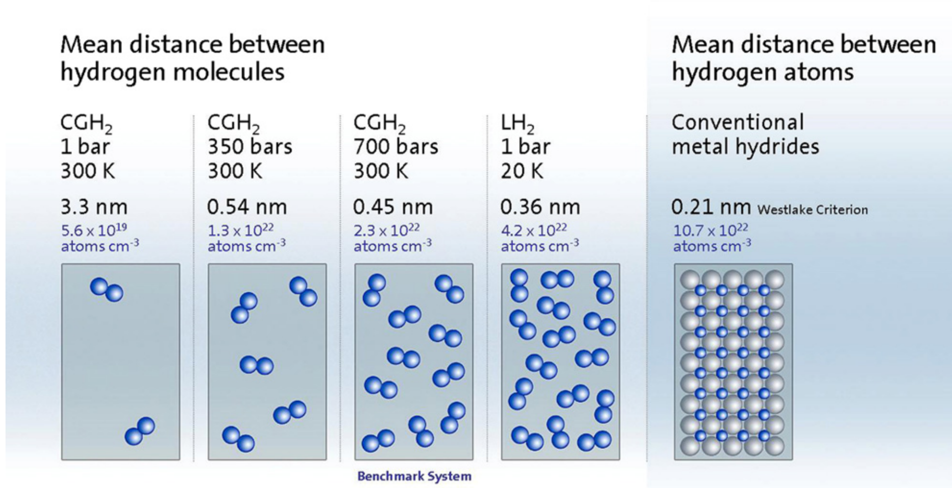

Fig. 6. Volumetric hydrogen densities on a materials basis [11].

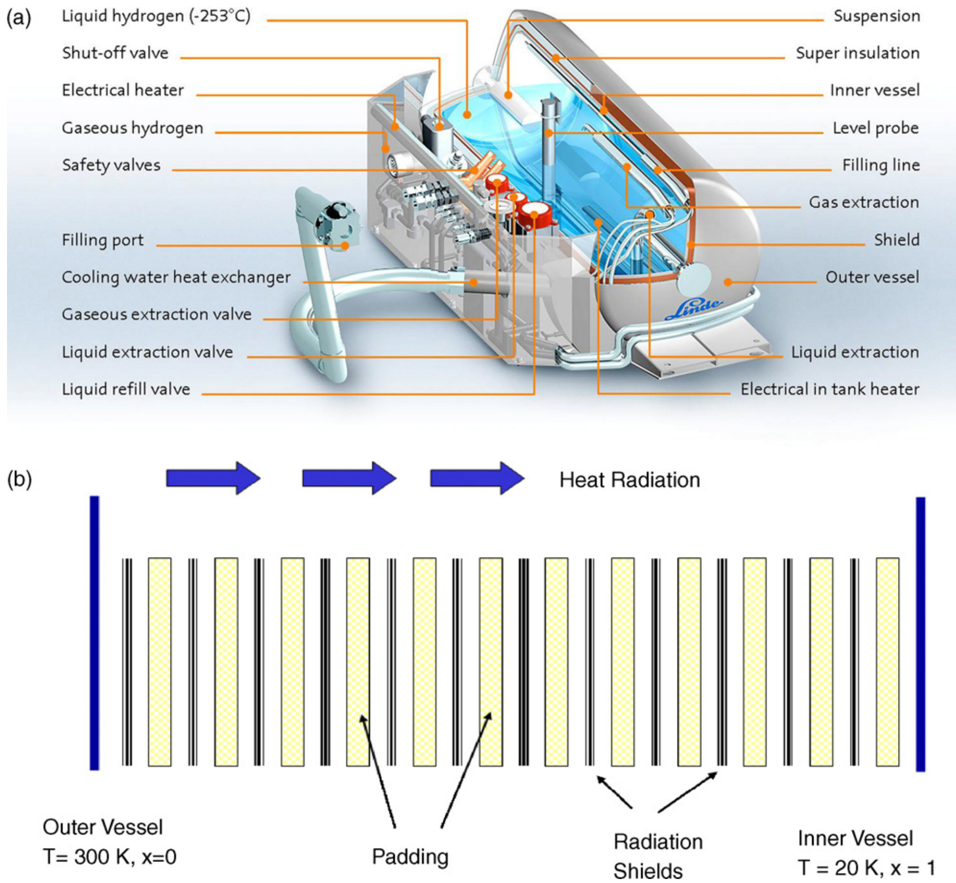

Fig. 7. (a) Liquid hydrogen vessel [14] and (b) multi-layer vacuum super insulation.

respectively, mountings) in particular is time-consuming and highly demanding.

The remaining significant heat input leads to an enhanced evaporation of the liquid hydrogen stored inside which eventually causes a pressure rise. Typically, when a system pressure of about 1 MPa is reached, a valve has to be opened to vent hydrogen. The time period between putting the vehicle into an idle or parking mode and the venting process is usually called "dormancy".

Typical values for this period are several days. After that point in time, hydrogen is continuously lost to the environment. This amount of hydrogen is known as boil-off gas (heat flow multiplied by time period and divided by the H_2 heat of evaporation of 0.45 MJ/kg). A related problem are the cooling-down losses during refueling (due to the evaporation of hydrogen), since all the pipes, dispensers, nozzles, valves have to be cooled down to cryogenic temperatures before a considerable amount of LH2 can be filled into the tank system.

Both effects lead to unacceptable hydrogen losses in the eyes of the customer, respectively, the infrastructure operators. The complexity of the LH2 storage system together with the challenge to reduce the boil-off as much as possible leads to overall LH2 system costs that are – at large scale – not favorable over CGH2 systems. Despite the fact that the volumetric storage density of LH2 systems is slightly higher compared to CGH2 systems, we don't see strong advantages in packaging that might outweigh the above mentioned disadvantages. Besides, the flexibility in the design of LH2 tank systems is not really superior over CGH2 systems.

Since also the energy required to liquefy hydrogen already consumes 30% of the chemical energy stored compared to just 15% for 70 MPa CGH2 (and 12% for 35 MPa CGH2) based on the net calorific value of 120 MJ kg^{-1} H_2, CGH2 was evaluated to be the superior technology. For the time being, thus, a decision at GM was made to concentrate on the development of CGH2 systems at 70 MPa operating pressure for near-term vehicle applications such as the Chevrolet Sequel or other next-generation vehicles, and to establish this technology as the benchmark for any emerging breakthrough technology (such as tank systems based on hydrides, high-surface materials or other advanced solid state absorbers). The gravimetric and volumetric hydrogen densities (based on the systems approach) of current CGH2 tanks are shown in Table 3.

All relevant alternatives have to beat these figures in most of the categories. These other options and their challenges before implementation shall be discussed below. What are the boundary conditions for alternatives? Mainly there are (1) volume restrictions from packaging needs, especially when utilizing an existing vehicle architecture, (2) the operating requirements defined by the fuel cell propulsion system (e.g. extraction rate, supply pressure and temperature) and (3) customer demands (such as cost, overall capacity, refueling time and efficiency).

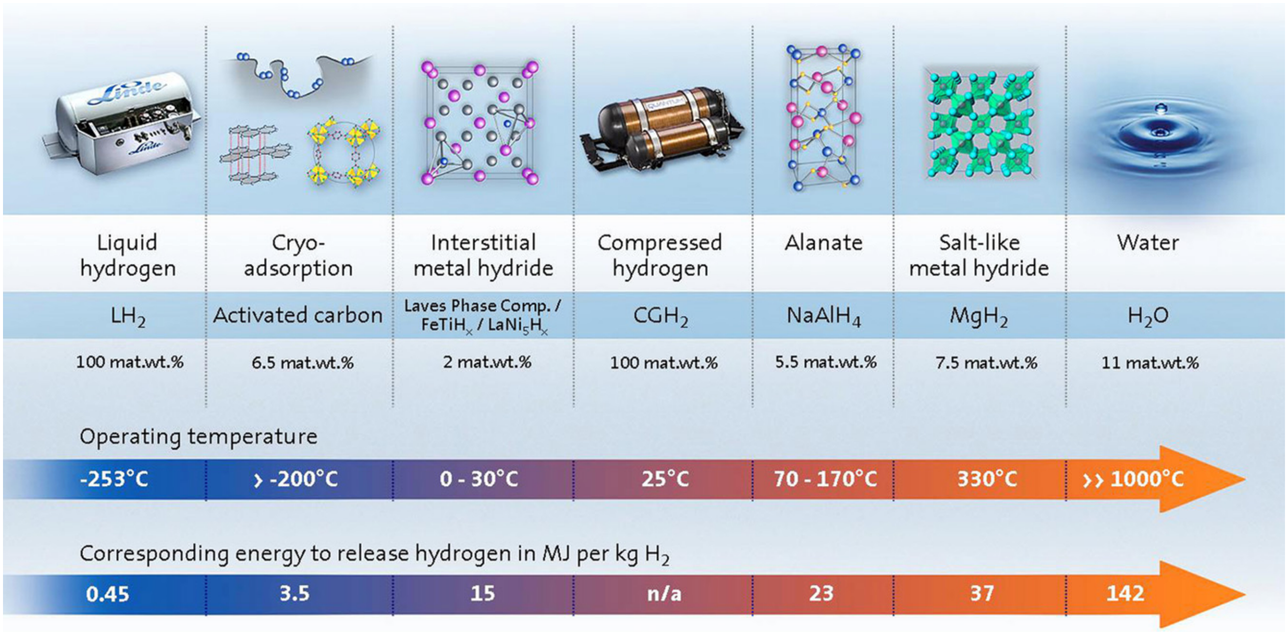

Fig. 8. Typical operating regimes for various hydrogen storage technologies [11,16,17].

As it was shown in Fig. 6, solid state absorbers of hydrogen offer an impressive volumetric hydrogen density on a materials basis. But unfortunately, this is not the complete story. In particular, the very short refueling times of 3 min required by the customer cause a significant engineering burden for the system. When we consider a 6 kg H_2 tank system comprising a storage material M with a heat of formation ΔH of about 25 MJ kg^{-1} H_2 (typical for many hydrides, see Fig. 8), a thermal load of 150 MJ would have to be compensated during refueling:

$$M + H_2 \rightarrow MH_2 + \Delta H$$

That leads to an average heat exchanger power of at least 800 kW. Such a high-performance device is not imaginable to be installed onboard a vehicle due to cost, volume and weight reasons. Typically, values less than 100 kW would be reasonable for an automotive application. Merely to ensure a H_2 supply rate of 2 g s^{-1} to the fuel cell propulsion system under full throttle conditions causes a heat management challenge of about 50 kW.

Table 3
Benchmarking of hydrogen storage technologies: comparison with existing 70 MPa high-pressure storage in carbon-fiber composite vessels (cost figure derived from reference [1], compare to European SRA target [15])

Benchmark system 70 MPa CGH_2	
Capacity	6 kg H_2
Volumetric energy density	260 l/0.023 kg l^{-1}
Gravimetric energy density	125 kg/0.048 kg kg^{-1}
Shape	Cylindrical
Cost (large-scale production)	US$ 3600 (from Table 1, compare to SRA value)
Boil-off losses	Not existing
Extraction efficiency	100%
Maximum extraction rate	>2 g H_2 s^{-1}
Refilling time	3 min
Refilling efficiency	>95%
Heat exchanger capability	0 kW

A further constraint is that many solid state absorber systems (in particular many hydride systems) require operating pressures of about or above 10 MPa (at least during refueling). Hence a pressure container consisting of advanced components and materials is required additionally.

Also the operating temperature of a solid state absorber has to be limited to 70 °C for practical reasons. That temperature level could be provided by using the waste heat of the fuel cell system. To serve higher operating temperatures, hydrogen has to be either burned or converted into electricity. Both options would lower the effective system hydrogen capacity and lower the range of the vehicle since that hydrogen could not be used for propulsion purposes.

Last but not least, hydrogen absorbers often consist of powder materials. Hereby, it has to be evaluated whether the apparent density of the absorber is comparable to the crystal density of a compact block of the base compound. Thus it has to be stated that an empirical rule of thumb exists for many solid state absorbers that roughly describes the relationship between the materials value of the storage density of a storage compound and the systems value: The absorber relates to about 50% of the total weight, whereas 50% are due to the engineering burden (valves, pipes, pressure vessel, heat exchanger, etc.).

What are the lessons to be learned from that behaviour and are therefore the objectives for future research:

(1) Heat of formation has to be reduced as low as thermodynamically possible.
(2) Operating temperature should be limited to 70 °C.

(3) Operating pressure should be limited to values less than 5 MPa for cryogenic temperatures or elevated temperatures (up to 70 °C).
(4) Operating pressure should be less than 35 MPa for room-temperature applications using low ΔH hydrides.

These points should be defined as target values for any breakthrough materials. Currently, three major paths for material scientists exist to achieve those design parameters:

(1) The destabilization of the hydride state through alloy formation or more complex reaction schemes (e.g. $LiBH_4 + (1/2)MgH_2 \rightarrow LiH + (1/2)MgB_2 + 2H_2$) [18,19].
(2) Cryo-adsorption of hydrogen on high-surface materials (such as activated carbon or metal-organic frameworks) [9,10,20].
(3) A hybrid solution combining low-ΔH hydrides approaches with a 35 MPa compressed hydrogen design (e.g. using TiCrMn or related alloys).

The first two points are described in the given references in detail. Using the third pathway and conventional hydrides, the volumetric storage density of a 70 MPa CGH2 systems could already be achieved at an operating pressure of 35 MPa. This could simplify the packaging challenges significantly. Unfortunately, the CGH2 system gets more complex by integrating the storage compound and a heat exchanger into the pressure vessel. That higher system complexity leads to a greater system cost and system weight compared to our defined benchmark systems. A competing technology to the points above, the decomposition of hydrogen-rich but non-reversible compounds (such as sodium borohydride or ammonia borane) is at the moment not considered to be a viable alternative for the automotive industry. This assessment was caused by the inherent complex onboard system design (e.g. concerning the treatment of waste materials), the infrastructure implications (i.e. related to the need for exchangeable fuel cartridges) and the off-board recycling respectively energy issues. So it may be concluded, that a 70 MPa CGH2 system is currently the best-in-class option available for automotive onboard hydrogen storage.

4. Vehicle integration

The integration of the fuel cell system into vehicles can be done similarly to the integration of internal combustion engines (ICE). It has been demonstrated that sufficiently powerful and compact drivetrains could be realized. The fuel cell system of the GM HydroGen3 has been packaged in a way that it fits together with the electric traction system into the same volume as an ICE propulsion module, and can be fixed to the same mounts (Fig. 9). This allows the simple and cost efficient vehicle assembly in existing facilities, so it is a likely scenario for the introduction of

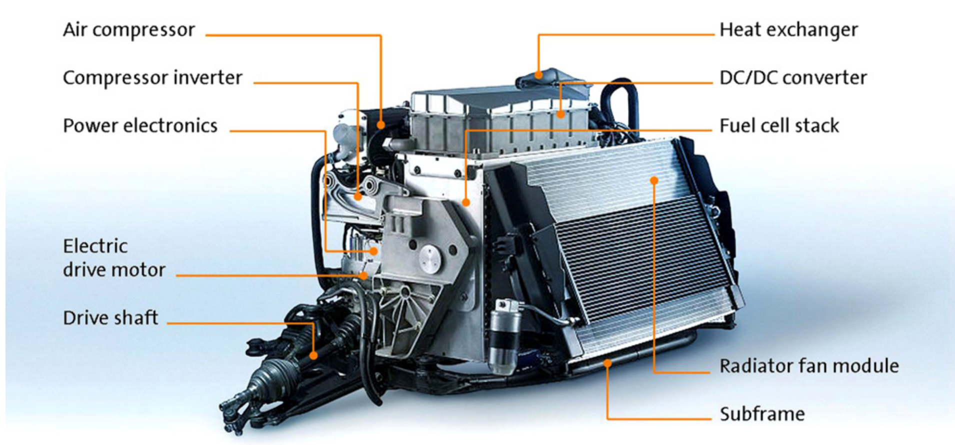

Fig. 9. The 60 kW propulsion-dress-up module (PDU), developed for integration into the GM HydroGen3.

Fig. 10. The HydroGen3 system architecture (60 kW at the wheel) has been downscaled for integration into the Suzuki MR Wagon MR (38 kW at the wheel) and upscaled for propulsion of a Chevrolet Silverado military truck (120 kW at the wheel).

mass manufacturing on the basis of existing car platforms. There is however no technical restriction that won't allow a different distribution of fuel cell components in the vehicle (Fig. 10).

The scalability of the fuel cell system facilitates also the adaption to different vehicle sizes. One example is the fuel cell system that was developed for the GM HydroGen3, and then was adapted to a small vehicle, the Suzuki MR Wagon FCV, using a shorter fuel cell stack with reduced cell count. Later, it was adapted to a GMT 800 truck by doubling the stack and some other components.

Typically, 4–7 kg hydrogen has to be stored onboard. This remains to be a serious issue for the vehicle integration. Furthermore, cylindrical vessels are required for this and most other types of storage. In existing vehicles, without modification there is no space for hydrogen storage devices that could provide sufficient range. Hence, rear body modifications are necessary to integrate the hydrogen storage vessel(s). In an extreme case, one could imagine concepts where the car is built around the hydrogen storage. As mentioned above, designers at GM have developed the Chevrolet Sequel concept car which provides enough space for three compressed gas vessels for 8 kg of hydrogen. By this, a vehicle range of more than 480 km could be achieved. The fuel cell system of the Sequel has been packaged into the vehicle underbody as well, offering flexibility for the interior design. Although the Sequel is a concept vehicle with no production intent at this time, one can imagine that similar vehicles one day will be developed and optimized for the specific characteristics and opportunities that fuel cells can offer.

5. Automotive competitive fuel cell propulsion

The fuel cell vehicle will get to the mass market only if it can be produced at affordable cost. It has to compete with other powertrains, so this number may not be significantly higher than corresponding one for internal combustion engines. That equates to about US$ 50 per kW of traction power, or roughly US$ 5000 for a 100 kW system (including the fuel storage device). Projections show that this is a reasonable target, if fuel cell systems are produced in high volumes.

Fig. 11 shows how cost might scale with production volume. There is a remarkable difference in curve shapes for different components. The best cost projection can be made for components where the construction materials are well known, and also the manufacturing technology is proven. Examples can be found in many places of the fuel cell system, such as the hydrogen recycling pump or the air compressor. These components, based on traditional manufacturing processes, can be machined on existing equipment which is available for different scales of production, and even with quantities well below 1000 units, cost can come down very close to the automotive target.

For new technology elements where there is no established production process, it is uncertain if and at which production volume a new manufacturing process will be invented. As an example, the liquid hydrogen storage is shown in Fig. 11. A first cost degression occurs like in the previous case, since a similar mechanism applies for those parts which can be made with existing manufacturing know-how, e.g. the vessel itself, or valve components and heat exchangers. After this initial decrease, there is a broad plateau, where the development of a new manufacturing technology would be necessary, so during that phase manual assembly might be cheaper. Most technology elements of the cryogenic vessels are well known from airspace application, but no industrial manufacturing process exists, for example, the application of the multilayer insulation. Quantities at which it might be worth to develop such a process might be as large as 10,000 to 100,000 units p.a.

A third scenario comes up if a novel material has to be developed or applied. This could, be the case for the polymer electrolyte membrane. Especially for materials that are used in small quantities – a fuel cell of a passenger car only contains less than 1 kg of polymer electrolyte – very large production numbers are required before the investment into large-scale material processing begins to pay off. Also, high-volume cost projection is most difficult and risky in this scenario, and it might require quantities up to a million fuel cell systems per year to bring the cost down to the automotive target.

However, the cost studies that have been conducted so far did not unveil unresolvable barriers. Only the costs for the hydrogen

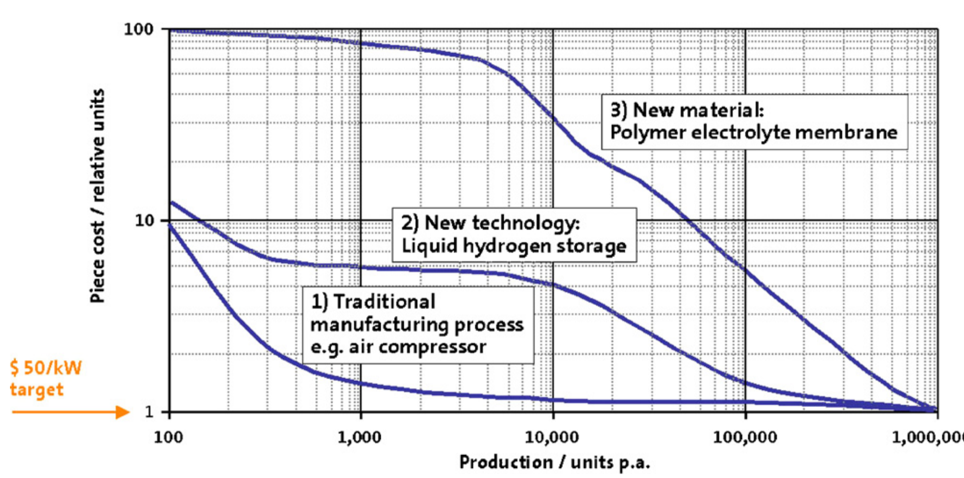

Fig. 11. Cost progression for components of the fuel cell vehicle. Different stages of maturity can be distinguished: (1) new design, existing materials and manufacturing methods, (2) new design, new manufacturing methods, existing materials, and (3) the use of new functional materials.

storage system will probably be higher than desired or projected in the beginning. There is also much work still to be done to get the fuel cell system as reliable and robust, and as durable as the competing combustion engine, but no principal, unresolvable problem could be identified yet.

Thus, the next years of development will be focussing on further technology advancement in order to design and to validate a system that will have the performance, durability, and cost (assuming automotive mass production volumes) of today's internal combustion engine systems.

6. Next steps

The above described development of technology elements is crucial for becoming competitive to conventional and other alternative powertrain options. Equally important, however, is the real-world testing of vehicles. Valuable results and new insights about infrastructure implications, user behaviour, and – later – public acceptance are generated through demonstration activities, and fed back into the technology development. Up to now, hydrogen fuel cell vehicles are on the roads globally for demonstration, but their number is still limited. Based on current knowledge, it is anticipated [21] that the further roll-out of hydrogen vehicles will happen in three phases:

6.1. Phase I (until 2010)

As described above, in this phase, main progress needs to be made in fuel cell technology development and cost reduction. The fuel cell vehicle fleet however will already show real-world capability in demonstration projects. GM's "Project Driveway", for example, comprises the deployment of more than 100 Chevrolet Equinox Fuel Cell, starting in 2007 (see Fig. 12 and Table 2). Due to high cost, the number of vehicles will be limited however. Based on a "lighthouse"-concept, these vehicles are preferably operated in only a few pilot regions. Thereby, the automotive hydrogen demand will be concentrated, which allows the test of a local refueling infrastructure under real-world conditions. This will help to determine whether we are moving towards acceptable hydrogen costs and will generate the necessary learnings for a future large scale production.

Fig. 12. The Chevrolet Equinox Fuel Cell, a five-door front wheel drive SUV.

6.2. Phase II (from 2010 to approximately 2015)

In this phase, the technology development is still in a precommercial phase. There is still room for evaluation of new concepts, for example, regarding hydrogen storage. However, the fuel cell technology of 2010 has to be competitive to conventional internal combustion engines in terms of performance, reliability, and projected cost (based on assumed mass production numbers), so that system will be a robust and powerful benchmark for any alternative concepts that might be in discussion at that time. Deployment of vehicles will be an order of magnitude larger than before, i.e. comprising several thousands of vehicles. These cars still will be costly, but they are needed for market preparation. Besides the vehicles, also a certain hydrogen refueling station infrastructure should be in place for customer convenience. The focus therefore should still be on a few selected regions to achieve a sufficient density of publicly accessible refueling sites.

6.3. Phase III (starting around 2015)

Commercialisation and ramp-up of vehicle production marks this phase. It is obvious that this phase will only be entered if real mass production can be achieved within short. Manufacturing concepts have to be fully developed, and the necessary production capacities have to be in place both at the car manufacturers and the automotive supply industry. Also, the hydrogen infrastructure has to be optimized further on.

7. Outlook

For the next years, one can expect continuous improvement and development of conventional powertrains. Engine downsizing and the hybridization of the powertrain will partly compensate for the low-load efficiency deficit of internal combustion engines. Petroleum will still be available for transportation for quite a while. Other fuel options like 2nd generation biofuels (cellulose-based ethanol, biomass-to-liquid synthetic fuels), will gain an increasing share. Thus, combustion engines will have a significant share on passenger car propulsion in the foreseeable future.

But as electric components have replaced many mechanical parts of the vehicle, hybridization combined with regenerative braking can be seen as an increasing electrification of the powertrain. Battery development has made major progress in the past years, so full hybrids with potential plug-in capability (such as the Chevrolet Volt concept vehicle, presented at the North American International Auto Show in January 2007) will be the next step of development.

Fuel cell vehicles offering zero emissions can be regarded as the final state of development. As many elements of the drivetrain and the refueling infrastructure are new, there are still major improvements needed for the fuel cell electric vehicle to become auto-competitive. Today, cost, range and refueling figures are inferior compared to gasoline powertrains. But it should be pointed out that these figures are much better than for advanced battery electric vehicles, and that projections show that fuel cell vehicles can become cost competitive to internal combustion engines. Ultimately, the major driver for fuel cell vehicles is their inherent high efficiency on a well-to-wheel basis, especially when renewable energy sources are used for hydrogen production. There are many uncertainties on the interplay of all the elements on the well-to-wheel chain, though. Thus, although not all technology elements might be mature, the next logical step of development is an experimental verification of this chain, as intended with above mentioned lighthouse projects.

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