Technology II
Utilization

Extract from "Hydrogen – a world of energy", TÜV Süddeutschland Holding AG
www.hydrogenperspectives.com
Hydrogen has been used in a variety of ways for more than 100 years. Besides its role as an energy source it is put to industrial use, most frequently as a raw material in the chemical industry.

One of the best-known uses for hydrogen is in air transport. Because of its low density hydrogen is a very effective lift-inducing agent, and was used as such by aviation pioneers in the 18th century. The French nature researcher Charles took off from Paris in the first manned hydrogen balloon in 1783. Count Zeppelin operated the largest airships to date on the gas at the beginning of the 20th century.

Main customer – chemical industry
More than 500 billion m³ of hydrogen are consumed worldwide today, a large part of that by the chemical industry in the production of ammonia fertilizers and methanol. The versatile element increasingly plays a role in the production of conventional fuels with reduced sulfur content. Hydrogen is also used for metal processing, for example for the reduction of ores. Furthermore, H₂ is required for the production of aniline and phenol as well as ultra-pure water vapor.

Ultra-pure water vapor
H₂ is an important basic substance in the semiconductor industry – the ultra-pure water vapor required for production is obtained not from water, but from a hydrogen / oxygen mixture. Welding torches work on H₂ as the heating gas for the flame. The optical industry uses the soot-free hydrogen flame for polishing and melting high-grade optical glasses and the telecommunications industry uses it in the production of glass fibers.

From an environmental point of view, hydrogen plays a key role in drinking water treatment. A certain type of bacteria is, for example, "fed" with hydrogen to lower the nitrate content in the water.
Space engineers recognized back in the 1950s that liquid hydrogen met almost all of the criteria for use in rocket propulsion. In 1963, the RL 10 propulsion unit developed by Pratt & Whitney in the USA made its successful maiden voyage in the upper stage of an Atlas Centaur rocket and thus introduced hydrogen technology in space travel.

Since 1981, the American Space Shuttle has also been flying with 3 high-pressure hydrogen propulsion units. The basis of this propulsion is the staged combustion cycle developed in the 1960s by Messerschmitt-Bölkow-Blohm (MBB, now Astrium). The Ariane went into space for the first time in 1979 with a cryogenic upper-stage propulsion system developed by MBB.

Larger satellites require higher propulsion unit capacities

Launchers put satellites into orbit; the development of the rockets and their propulsion systems depends to a large extent on the satellite market. In recent years, increasingly larger and heavier satellites have been built. For example, Envisat – the environmental satellite of ESA – is as large as a school bus and weighs about 8 metric tons. The space industry is therefore working on increasingly more powerful propulsion systems for higher-performance launches. More thrust means more payload and thus better acceptance in the market.

While Ariane 4 is designed for payloads of up to 5 metric tons, Ariane 5, an ESC-A (Etage Supérieur Cryotechnique A) is going to put satellites weighing up to 10 metric tons into orbit. Ariane 5 utilizes 2 hydrogen propulsion units – a cryogenic main propulsion unit – the Vulcain – and a cryogenic upper-stage propulsion unit.

By the year 2006, the performance of Ariane 5 will have been further enhanced. With Vinci, the first re-ignitable cryogenic upper-stage propulsion unit in Europe, its payload capacity will increase to 12 metric tons. This increased performance becomes possible only through the use of hydrogen. For comparison – the upper-stage propulsion unit of Ariane 5 currently operates on what are known as storable fuels, and yields a thrust of 1350 kN. Liquid oxygen is injected into the combustion chamber. Liquid hydrogen (at below –253 °C) is first pumped through cooling channels to cool the thrust chamber, then also injected into the combustion chamber in finely atomized form. An ignition system initiates the combustion of the hydrogen / oxygen mixture; this drives the pressure in the combustion chamber to 115 bar at a temperature of approximately 3,000 °C. Once ignited, the fuels continue to burn as they are constantly supplied. The hydrogen in the thrust chamber wall cools the inner base body to 500 °C, thus preventing burn-through of the thrust chamber. Hydrogen serves both as fuel and coolant for the propulsion unit.

Hydrogen is almost indispensable

Of all fuels, hydrogen provides the highest energy yield per unit of mass. If the hydrogen-based liquid propulsion units were replaced by solid-fuel propulsion systems, several times more fuel would be needed. More fuel means more weight and thus less payload. In this context, hydrogen has an excellent cost / benefit ratio for space travel. Moreover, hydrogen is a very environmentally friendly fuel. The only product of combustion is water.

H₂ double function: fuel and coolant

The heart of every rocket motor is the thrust chamber, where the fuel is ignited and the energy for thrust is released. The Vulcain 2 thrust chamber of the Ariane 5 main propulsion unit developed by the Astrium Space Group, yields a thrust of 1,350 kN. Liquid oxygen is injected into the combustion chamber. Liquid hydrogen (at below –253 °C) is first pumped through cooling channels to cool the thrust chamber, then also injected into the combustion chamber in finely atomized form. An ignition system initiates the combustion of the hydrogen / oxygen mixture; this drives the pressure in the combustion chamber to 115 bar at a temperature of approximately 3,000 °C. Once ignited, the fuels continue to burn as they are constantly supplied. The hydrogen in the thrust chamber wall cools the inner base body to 500 °C, thus preventing burn-through of the thrust chamber. Hydrogen serves both as fuel and coolant for the propulsion unit.

Propulsion unit solution with future prospects

The highest-performance Ariane propulsion unit Vulcain 2, with a mass throughput of more than 300 kg/s, produces a power of more than 4 million hp. That means that every 3 seconds the weight of a small automobile is consumed in the combustion chamber, generating a thrust equivalent to more than 4,000 Formula 1 race cars. Hydrogen will continue to play a central role in future space travel applications, above all when it comes to developing reusable space transport systems. Astrium is currently working on a concept for an unmanned transporter, the Hopper. The Hopper could put satellites into orbit for the first time in 2020 – with a hydrogen propulsion unit.
Ingrid Paulus, Audi AG

The driving force for an automobile manufacturer is the customers’ desire for individual mobility. Traditionally, drive concepts have made great progress during the past decades. Fuel consumption and pollutant emissions have reached a very low level. Performance and reliability constantly improve. Fuel-cell drives with hydrogen as a future fuel are important aspects of a resource-conserving development strategy. But there is still considerable room for improvement. Customers and market penetration. Automobile producers have a great responsibility to pursue and develop viable alternatives to conventional drive systems. This requires consideration of a large number of criteria.

Not a patent solution – a very low level.

Vehicle concept
Consumption
Life span
Operability
Efficiency
Emissions
Paying infrastructure
Noise
Volume
Weight
Production
Costs
Performance

Vehicle drive

Alternative drive systems also have a tradition at Audi, as even greater fuel savings can be achieved with them. As early as 1989 Audi presented the Audi duo which was the first model with a hybrid drive system; it has since been followed by two further development stages.

Audi is examining and testing on its own, and in joint research within the VW Group, a whole range of possibilities. These include:

- the optimization of the combustion processes
- the optimization of exhaust gas after-treatment
- the development of new fuels (syn fuels and sun fuels)
- battery-powered electric vehicles
- hybrid vehicles
- fuel-cell driven vehicles

Efficiency as a yardstick. The achievable efficiency of various drive concepts plays an important part in the assessment of the technical potential. Today’s internal combustion engines are highly efficient and, with further development, they will surely remain technically and commercially competitive for a long time to come with regard to their cost/benefit ratio and their reliability. Although a further reduction of pollutant and CO2 emissions can be assumed, the question of a suitable drive concept for the future remains.

Audi is pursuing the goal of developing a highly efficient fuel-cell drive which will not raise costs or compromise everyday operability, comfort and performance for the customer. Two major hurdles still to be overcome are fuel storage in the vehicle and the distribution infrastructure for hydrogen. Certain other customer-relevant criteria also require further intensive work. These include the starting characteristics, the dynamics of the power output and the operation of the fuel cell at temperatures below freezing. The equipment is still expensive, and it must compete successfully with existing technologies. Hydrogen concepts represent an essential variant in the drive strategy of Audi AG.

The Audi A2 with fuel-cell drive
Liquid hydrogen storage unit with 3.3 kg contents
800/700 PEM fuel cell
Synchronous motor
6.5 Ah NiMH battery

Hydrogen has a special role to play in the future of the automobile through the progressive development of new eco-friendly vehicle concepts are technical feasibility, a high degree of acceptance by the customers and market penetration. Automobile producers have a great responsibility to pursue and develop viable alternatives to conventional drive systems. This requires consideration of a large number of criteria.

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BMW has been carrying out research into engines and vehicles that operate on liquefied hydrogen since 1978. The first practical experience with passenger car prototypes came a year later. In 1984 the second generation went onto the roads; this was in turn replaced in 1988. In 1996, internal trials were begun with the fourth generation of hydrogen vehicles. In 2000, BMW built a small series of 15 hydrogen test vehicles of the BMW 750hL model. These have already covered more than 170,000 kilometers, and have proven themselves in everyday operation.

The BMW 750hL demonstrates that the combination of hydrogen and combustion engine is an appropriate concept for the journey into a clean future, one that guarantees the high standards of vehicle dynamics customers expect. The qualities of the BMW 750hL will be introduced to series production with the new hydrogen 7 series. The BMW Group will hand over the first series-produced hydrogen-powered vehicle to a customer before the current 7 series terminates.

The BMW Group also makes use of the innovative technology of the fuel cell. The increasing use of electronics in various automotive systems makes ever higher demands on the efficiency of on-board power supply networks. Moreover, the electric energy converters used so far (electric generator and lead-acid battery) are not optimal in terms of weight and efficiency. The BMW 750hL uses a PEM fuel cell as an extremely efficient power unit for the on-board power supply network. This unit, which is referred to as the “auxiliary power unit” (APU), has a 5 kW output, ensuring that the automobile is adequately supplied with environmentally friendly electric power even when the engine is not running. Air-conditioning, auxiliary heating, communications systems, lighting or by-wire technologies can thus be operated independently of the engine in future. Efficient 42 volt on-board power supply networks are presently being developed based on the fuel cell.

The vast majority of experts today agree that hydrogen is the best option for a future fuel. The BMW Group has been taking this into account for some years now by performing ongoing development work on hydrogen vehicles. The company places its trust in the combustion engine as the driving unit, a sophisticated technology that has been optimized over decades of experience.

The BMW 750hL is provided with a fuel cell APU (auxiliary power unit) with a power of 5 kW.

**The technical characteristics of the BMW 750hL**

**Engine:**
- Type: 12 cylinder V-engine
- Cubic capacity: 5.4 l
- Power: 110 kW/204 hp
- Torque: 300 Nm at 4,500 r.p.m.
- Acceleration 0 – 100 km/h: 9.6 s
- Maximum speed: 250 km/h
- Range: approx. 300 km with hydrogen plus 600 km with gasoline

**Tank:**
- Volume: 140 l of H₂, equivalent to approx. 40 l of gasoline
- Service pressure: 1–4 bar
- Service temperature: –250 °C

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**Bivalence ensures everyday capability**

The engine of the BMW 750hL is designed to operate both on liquid hydrogen and on gasoline (bivalence). Only the hydrogen combustion engine offers this option. In the introductory phase of hydrogen as an energy source, bivalence guarantees customer mobility – whether powered by gasoline or hydrogen. The hydrogen infrastructure need not be fully in place.

The vehicle has, in addition to its 140-liter hydrogen tank, a gasoline tank which extends its drive range from 300 to 900 kilometers.

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Commitment to infrastructure

In Germany, there are today about 16,400 service stations for gasoline and diesel, and only one public station for hydrogen, at Munich Airport. A prerequisite for the area-wide introduction of hydrogen-powered cars is, however, a close-meshed network of filling stations. In order to foster its development, the BMW Group is committed to the “Verkehrswirtschaftliche Energiestrategie” (VES = Transport Energy Strategy), the aim of which is an area-wide supply network for the new environmentally friendly energy. Leading companies from the automotive and the power industries have united in this matter. The BMW Group helped initiate VES in 1988. The German Federal Government supports and oversees the work of this group.

Clean Energy Partnership

One of VES’ cooperation projects is the Clean Energy Partnership (CEP), a joint project of Aral, BMW, BVG, DaimlerChrysler, Ford, GHW, Linde, MAN and Opel. Founded in June 2002, CEP’s goal is to test the everyday capability of hydrogen. Within the project’s five year time frame, a hydrogen filling station will be constructed in Berlin; hydrogen will be both produced from water on the spot and delivered in the liquid state and stored. An elementary objective of the project is to produce evidence of the positive effects of hydrogen fuel on the environment. The hydrogen is therefore to be produced as far as possible by means of renewable energy sources such as electricity from hydroelectric or wind power. Hence, the entire cycle from generation to utilization will be virtually free of undesirable or environmentally harmful emissions.

The new technology, however, still remains very costly. At present, only hydrogen that has been produced at least partly from natural gas, and that is tax-free, compares favorably with taxed gasoline at the service station. If one uses biomass, wind energy or the sun as the primary energy source, the gasoline filling station price of about 11 cents / kWh (with taxes) is markedly exceeded. However, the costs of generating hydrogen from renewable energies are likely to fall as a result of further research and development. As European energy taxation is harmonized and development proceeds, hydrogen from renewable energy sources should become much more affordable in the medium to long term.
Since the early 1990s, Daimler-Chrysler has been developing and testing various fuel-cell concepts for passenger cars, light-duty commercial vehicles and buses. Hydrogen and methanol are used as energy sources. In international cooperative projects and fleet tests by customers the equipment and the necessary infrastructures are now being tested on a large scale.

**Concept vehicles and demonstration of feasibility**

The advantages and potentials of the fuel-cell drive were already demonstrated in the mid 1990s with the first concept vehicles (NECAP 1, NECAR 2). Further development led to NECAR 4, the first A-class with a fuel cell, in 1999. NECAR 4 travels in the NEDC (New European Driving Cycle) with an efficiency of 37% and consumes at a nominal power output of 70 kW only 3.7 l of diesel equivalent for 100 km. The complete fuel-cell system already fits into the sandwich floor. The first low-platform bus (NEBUS) was developed in 1997 with a nominal power output of 250 kW.

NECAR 3 (1997) and NECAR 5 (2000) are based on the technology of chemical hydrogen storage in the form of methanol. This concept seems promising for wide use in individual transport, particularly in terms of achieving high ranges and for cost minimization during the changeover to the necessary supply infrastructures. The tank, the power generating system and the reformer unit also fit into the sandwich floor in NECAR 5.

Light-duty commercial vehicles which are mainly operated in fleet use represent an ideal application for hydrogen fuel-cell vehicles. In 2001, the feasibility of fuel-cell drives in this vehicle segment was demonstrated with the Mercedes-Benz Sprinter.

Now that the feasibility and specific advantages of such vehicles have been demonstrated, the first test carriers are being driven under everyday conditions. DaimlerChrysler has also initiated parallel cooperative projects to examine questions on the infrastructure for alternative fuels for the fuel cell. One example is the California Fuel Cell Partnership which was initiated in 1998 together with Californian government authorities, the Ford Motor Company and Ballard Power Systems. All the large automobile companies, mineral oil corporations and a number of technology firms are active partners. In Germany, DaimlerChrysler is committed to work in the Clean Energy Partnership (CEP). Within the scope of this cooperation, a hydrogen filling station is being set up in Berlin. It will be used by various vehicle manufacturers for the operation and testing of test fleets.

**Everyday test:**

**Hermes Delivery Services**

The world’s first fuel-cell vehicle in the customer’s hands is a Mercedes-Benz Sprinter, now undergoing a two-year test (2001 to 2003) in daily parcel service. The vehicle delivers to approximately 60 end-customers a day. Half way through the project period, the vehicle had clocked up a mileage of 15,000 km, without any serious problems in the fuel-cell system.

As a genuine zero-emission vehicle with an electric motor output of 55 kW, the Mercedes-Benz Sprinter achieves a maximum speed of 120 km/h.

The on-board fuel-cell equipment (yellow) does not restrict the useful space of the Sprinter panel van.
Everyday driving test: NECAR 5 “Coast to coast”
A further milestone toward the development of a fuel-cell-powered vehicle for everyday use was the successful crossing of the American continent by NECAR 5 between May 20 and June 4, 2002. The 12-day, 5,250 km trip from San Francisco to Washington D.C., at an average speed of 61.7 km/h, represented a new long-distance record. Moreover, the successful crossing of the Rocky Mountains set new altitude records. The vehicle reached 2,675 m above mean sea level and traveled more than 1,200 km at altitudes higher than 1,800 m above mean sea level. It performed under “real world conditions” at temperatures ranging from –1 °C to 35 °C, in snow, rain and hail, on the highways and in stop & go city traffic. This impressively demonstrated the technical achievement of Daimler-Chrysler and its development partner Ballard Power Systems.

Fleet test: 30 buses in ten European cities
The European bus project encompassing CUTE and ECTOS represented the first large fleet test of Citaro fuel-cell buses based on the Mercedes-Benz Citan. Thirty buses will operate in line service in ten European cities from 2003 to 2005. For this test the public transportation companies of Amsterdam, Barcelona, Hamburg, London, Luxembourg, Madrid, Porto, Reykjavík, Stockholm and Stuttgart have purchased three buses each. This project will offer experience under highly varied climatic and topographical conditions and in many different traffic situations. Aspects of a hydrogen infrastructure will be evaluated along with the technical performance of the vehicles: besides decentralized natural gas reforming, 40 % of the hydrogen is to be produced from renewable energy sources.

Fleet tests: 60 fuel-cell A-class cars
Any mass production of fuel-cell technology for vehicles has to take place in the passenger car sector on account of the unit volume and market potential. While technical synergy potentials for the bus drive are obvious, obstacles with regard to fuel infrastructure for fuel-cell powered passenger cars are considerably higher. DaimlerChrysler is taking the first step with its A-class vehicles, fuel-cell powered passenger cars based on compressed hydrogen technology. Several small fleets will soon be in use with selected customers in Germany, the USA, Japan and Singapore.

Outlook
Along with hydrogen storage technology, the fuel cell is a key technology for a future hydrogen industry. Its use in automobiles is the driving force because of the large number of units and the market potential.

From the vehicle technology point of view, cost cutting, development of production processes, durability and the reliability of fuel-cell systems are the main tasks for research and development in the next few years.

DaimlerChrysler is pushing ahead these applications with the goal of commercializing in a ten-year horizon. Fleet tests and cooperative projects involving governments, the fuel industry and the automobile parts industry are absolutely essential. Experience gained in these projects will help answer the remaining questions concerning the technology, the selection of fuel and the associated setting up of a new infrastructure.
Hydrogen-powered buses as pioneers of future transport

Christian Gruber, MAN Nutzfahrzeuge AG

What was still considered a vision only a few years ago has now become visible reality: hydrogen-powered vehicles in daily use. The best example are three buses which have been in service on the airport apron in Munich since 1999. So far practical experience with hydrogen amounts to more than 300,000 km travelled. Just as positive is the result of trials of the fuel cell as a vehicle drive system – the first MAN fuel-cell bus was tested in use for six months and met with quite positive acceptance from drivers and passengers alike.

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Since the early 1990s, MAN has been developing hydrogen drive systems primarily for urban buses. Buses in fleet operation can be fueled via a limited number of filling stations making it possible to use this drive system before hydrogen is available on a national basis. Moreover, low-floor buses provide additional space on the roof to integrate novel drive systems with increased volume requirements.

The world’s first hydrogen-powered bus with a liquid hydrogen storage system was used for two years starting in 1996 in regular public transport services in Munich and Erlangen. It clocked up a total of about 42,000 km. Since mid-1999, three MAN low-floor articulated buses with hydrogen in- ternal combustion engines have been in operation at Munich Airport, where they convey passengers safely and reliably over the apron. With more than 300,000 km covered during the period 1996–2002, MAN has proved the day-to-day operability of drive technology using hydrogen as the fuel.

All of the hydrogen-powered buses were completely integrated into the operator’s fleet and driven and fueled by the company’s staff. As experience shows, practical trials of this kind are a real challenge for every new drive system and count as an important milestone on the way to series pro- duction.

Drive concept of the fuel cell

The power supply equipment for the low-floor bus consists of a PEM fuel-cell unit which provides an electric power output of 120 kW with a voltage range of 450–600 V for the electric traction. The unit consists of four modules arranged in series with a total of 640 individual cells. The high efficiencies in the part-load range are seen as an essential advantage of fuel-cell drive systems. Overall system efficiencies of more than 50 % can be achieved. Both low-noise operation and jolt-free driving. Depending on infrastructure and/or customer requirements, hy- drogen can be stored in liquid form at −253 °C or as highly compressed gas at pressures > 250 bar in the vehicle.

While the first hydrogen-powered bus was fu- eled with liquid hydrogen, both the airport buses and the fuel-cell powered bus are equipped with storage systems for compressed hydrogen gas. The high efficiencies in the part-load range are seen as an essential advantage of fuel-cell drive systems. Overall system efficiencies of more than 50 % can be achieved. Both low-noise operation and the low part-load consumption make fuel cells attractive for urban vehicles.

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In the case of electric drive systems, MAN favors the central motor concept. This has already repeatedly proved its worth in diesel/electric-powered vehicles and falls back on series produc- tion solutions. For future city buses with a design adapted to new drive technologies, wheel-hub drives open up a variety of options for the design of the passenger compartment.

Future prospects for the internal combustion engine

Improvement of efficiency is an issue for the inter- nal combustion engine too. By direct injection of hydrogen into the combustion chamber a combust- ion process like that in diesel engines can be achieved. Even in the first prototype applications efficiencies of more than 40% were obtained. In overland and long-haul transport uses with a high- er proportion of full load during operation, the in- ternal combustion engine will be able to maintain its predominance.

While the internal combustion engine can look back on more than a hundred years of experience, fuel cells still need intensive development with re- gard to commercial vehicle-specific requirements and to cost reduction. With hydrogen MAN Nutz- fahrzeuge has set the course for the future and will over the next few years continue to develop further vehicles with fuel-cell drives and hydrogen-fueled internal combustion engines.

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To identify the best alternative to current drive system concepts, General Motors and Opel in the USA and Europe respectively carried out what are known as “well-to-wheel” studies. These involve examination and comparison of different fuel pathways from primary energy source to use in the vehicle in terms of energy consumption and greenhouse gas emissions. Fuel-cell vehicles powered by hydrogen proved to offer the greatest potential for saving energy and for drastically reducing and eventually eliminating greenhouse gases.

In the year 2000, GM and Opel presented the “HydroGen1”, the first test vehicle with a hydrogen-powered fuel-cell drive, based on the series-production model Zafira. This vehicle set 15 world speed and distance records for fuel-cell vehicles. The further development of the technology led to the “HydroGen3”. The engineers succeeded in making some decisive improvements, eliminating the need for a buffer battery to cover power peaks. The improved drive system permits an optimized arrangement of vehicular components. The hydrogen is stored in the vehicle either liquid at −253 °C or compressed at a maximum pressure of up to 700 bar. The HydroGen3 will undergo the same tests as series-produced vehicles and is now serving in the first fleet demonstrations.

The United Nations estimate that the number of motor vehicles in existence worldwide will double by the year 2030, reaching about 1.6 billion cars. Today, about half of the world’s petroleum production is combusted in spark ignition and diesel engines. Hydrogen-powered fuel-cell vehicles offer an alternative to this resource-depleting technology. Fuel-cell drive combined with by-wire technology allows for completely new design concepts.

Environmentally friendly technology – undreamed of design freedom

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Skateboard chassis creates space for new ideas

Fuel-cell vehicles will probably be technologically ready for series production by the end of this decade. They will, however, become established only if the appropriate infrastructure for hydrogen also develops. In Germany, approximately 1,500 hydrogen filling stations would be necessary for a country-wide supply base. In order to set up such a network support is needed from the government and from energy-supply companies.

Even greater possibilities open up if fuel-cell technology is combined with by-wire technology, in which vehicle functions such as steering, accelerating and braking are controlled electronically instead of mechanically. For example, in the "GM AUTOnomy" concept vehicle, the entire drive system is accommodated in a skateboard-like chassis. A docking station in the middle of the chassis provides a quick and reliable connection between the chassis and all of the vehicle’s control systems. This allows a wide range of models to be developed based on easily replaceable bodywork superstructures.

In the "GM AUTOnomy" the whole drive system is housed in a skateboard-like chassis. The advantage is that a wide range of models can be achieved by simply exchanging the easily replaceable bodywork superstructures.

Fuel-cell vehicle with by-wire technology “GM Hy-wire”

The Hy-wire is steered, accelerated and braked by means of one control unit. This drive control unit is based on the by-wire technology which is also used in aviation. With this module the Hy-wire can be operated both as a left-hand and as a right-hand drive vehicle. A further advantage – the driver’s view is not obstructed by a conventional engine.
Toyota began developing fuel-cell hybrid vehicles in 1992 by pursuing two basic policies on technology development: an independent development of all core technologies, and various approaches in preparing for changes in social circumstances. Fuel cells were no exception and comprehensive research and development began on everything from materials, parts and structures through to manufacturing technologies.

The first prototype vehicle, based on a hydrogen-absorbing method that extracts the hydrogen stored in a titanium alloy, was developed in 1996. In the following year, Toyota developed the world’s first prototype vehicle with an on-board methanol reformer. However, neither technology was a match for the existing power sources.

Efficiency improvement through Hybrid Technology

The performance of the Toyota Hybrid System (“THS”), announced in 1997 showed that the technical concept was very promising. Market reaction to the Prius, which uses THS, was extremely positive. Next Toyota applied the concept of THS to fuel cell vehicles. Fuel cells are most efficient during low- to medium-speed operation (40 to 80 km/h). Toyota improved vehicle efficiency by using batteries to make up for the weak areas of fuel cells. As development of the THS advanced, the merging of fuel cells with hybrid technologies such as regenerative brakes became highly significant. The vehicle efficiency of the FCHV-4, which was announced in 2001 and used high-pressure hydrogen as fuel, is approximately 3 times that of gasoline vehicles in the same class, and approximately 1.7 times that of hybrid vehicles under 10–15 mode, the Japanese test mode for fuel consumption and emission.

Toyota’s concept for CO2 reduction

CO2 reduction

Alternative energy

Fuel cell hybrid vehicles – Toyota’s strategy of diversity

Kaushik Sekhar*, Toyota Motor Corporation

In a world that is increasingly aware of the fragility of its environment, Toyota’s goal is to bring the so-called “ultimate ECO car” to market. From the company’s experience in developing fuel-cell hybrid vehicles (“FCHV”) and in response to the social challenge involved, Toyota’s assumption is that today’s cars, with their history of over 100 years of development and refinement, cannot instantly be replaced by FCHVs. With more than 700 million conventional vehicles worldwide, mainly running on gasoline or diesel, the first priority is to make these vehicles more energy efficient and with cleaner emissions. Toyota believes that the best way to meet this challenge is to pursue various lines of enquiry into a range of technologies concurrently.

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Hydrogen FCHV running on public roads

Toyota began testing the FCHV-4 on public roads in Japan and the U.S. in 2001. Seven units of the FCHV-4 have accumulated a total distance of 130,000 km, thereby providing valuable data toward the commercialization of FCHVs. Based on these successful results, on December 2, 2002 Toyota started leasing the "TOYOTA-FCHV" to four central government agencies in Japan and two universities in California, and became the world’s first automaker to launch a FC vehicle.

TOYOTA-FCHV is an advanced version of the FCHV-4 equipped with a fuel cell independently developed by Toyota. It has a maximum output of 80 kW, a maximum speed in excess of 155 km/h, and a range of over 300 km. This performance is state-of-the-art in world standards. Moreover, Toyota and Hino Motors made announcements in June 2001 and September 2002 first about the development of the FCHV-BUS1 and then about BUS2. This is a large bus intended for scheduled routes and is currently undergoing tests on public roads.

An FCHV for varied energy sources

In the longer term, Toyota considers that hydrogen is likely to become the most promising clean fuel. However, it is difficult to establish a hydrogen infrastructure within a short period. Given this fact, Toyota is currently developing FCHVs with on-board reformers. This produces hydrogen onboard from fuel that can be used by conventional internal combustion engine vehicles. In October 2001, Toyota announced the development of FCHV-5, equipped with a reformer of clean hydrocarbon fuel (CHF). FCHV-5 is still under development: it requires many further improvements, such as a reduction in reformer size and in the start-up time. Toyota is pushing ahead with research in view of possible fuels such as methanol and CHF.

The keys to acceptance – collaboration of vehicles, fuel and infrastructure

From Toyota’s point of view, fuel cell vehicles must overcome many obstacles before they can improve on the cost, durability, and reliability of conventional vehicles with internal combustion engines. Fuel selection will also require cooperative technology development by fuel producers. As for fuel supply infrastructure, a government agency in Japan has just begun a model experimental hydrogen station. Vehicle regulations and standards, as well as campaigns to increase public awareness about hydrogen and its potential as a fuel for vehicles, are also essential. Toyota believes that limited test marketing in 2002 will contribute much towards solving these issues.

Due to the cost, cruising distance and infrastructure, initial applications of FCVs will be limited. Broad acceptance of fuel cell vehicles is expected to take place over the next two decades.

Becoming a pioneer in automobile technologies in the 21st century

Society is expected to move towards zero emissions by overcoming environmental and resource issues through energy diversification. With that in mind, the potential of hydrogen is attractive and fuel cells will undoubtedly play an important role as a power source for automobiles. In combining fuel cells with hybrid technologies, a system can be created that behaves like a living organism, storing and consuming energy efficiently. Toyota may not match the wisdom of nature but hopes to pioneer automobile technologies for the energy-diversified age by responding enthusiastically to the various challenges facing the FCHV.

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### Issues for market penetration of FCVs

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Local public passenger transport in German cities is, with only a few exceptions, characterized by two systems: electric rail-bound vehicles (trams, underground, urban rail systems) and diesel-powered buses. Both systems have specific advantages and disadvantages. Fuel-cell buses combine the advantages of the two systems without, however, having to accept the disadvantages.

Fuel-cell buses are a new means of transport – the fuel-cell bus – can combine the advantages of the two systems and avoid their disadvantages. In this bus, energy is converted in the fuel cell which, apart from ancillary units, works soundlessly; an electric current is generated without any waste gases. The use of an electric drive system permits maximum driving comfort as well as very dynamic driving performance, leading to shorter times per distance covered and hence fewer buses in service on a given route. The use of electric intermediate storage permits the recovery of braking energy (see illustration) and allows the fuel cell’s power output to be adjusted in accordance with the time-mean power output (instead of the peak power). Buses with such a storage unit need only about half of the fuel cell capacity of buses without it. The recommend-ed technology is a magneto-dynamic flywheel stor-age unit (MDS). Double-layer capacitors (“Super cap”) also increasingly provide possibilities for intermediate storage of braking energy. The replacement of the mechanical drive train by an electrical one also permits new vehicle concepts such as the “Bus Train” with its considerably enlarged passenger compartment and improved comfort.

In Bavaria, Germany, the fuel cell manufacturer PROTON MOTOR in Starnberg has established with the first bus drive systems with intermediate storage for local transport. These are to be followed in 2003 by, among other things, a 48-kW net fuel-cell system of the type Xcellsis® HY-80 with a volume of 220 l and a weight of 220 kg can today be installed unobtrusively in a small car. In 1994 the entire loading space in a transporter was required for a fuel-cell system with a gross power output of 50 kW.

Fuel-cell drives work, particularly in the normal-ly used tariff range, with high efficiency (up to 50 %). In the European driving cycle, which simu-lates the typical characteristics of a vehicle on our roads, fuel-cell-powered vehicles achieve an effi-ciency of 37 %, twice that of a normal gasoline-engine vehicle (18 %).

The history of the fuel-cell drive – a mere 20 years – is relatively short. Further technical improvements are not all that is needed before the widespread use of fuel cells in vehicles becomes a reality.

High efficiency – fuel-cell drive systems for vehicles

The power density of the Ballard fuel-cell sys-tems has been increased by more than 60 % in the past four years alone. Additionally, the efficiencies of the overall system of fuel-cell stack and periph-erary such as reformer, compressor and control units have constantly improved. For example, a 68-kW net fuel-cell system of the type Xcellsis® HY-80 with a volume of 220 l and a weight of 220 kg can today be installed unobtrusively in a small car. In 1994 the entire loading space in a transporter was required for a fuel-cell system with a gross power output of 50 kW.

Fuel-cell vehicles are far more emis-sion-friendly than conventional vehicles. They work reliably under different condi-tions – evidence of this has come from several test journeys, for example a trip across the United States from San Francisco to Washington covering a distance of 5,250 km in May 2002. In 2002, Ballard Power Systems supplied more systems and fuel-cell modules worldwide than in all of the previous years together. Customers in-cluded DaimlerChrysler, Ford, Honda and Nissan. The cells used are proton exchange membrane fuel cells (PEM) fueled by hydrogen which can be stored as a liquid, as a compressed gas or in chem-ical compounds such as methanol.

Within the scope of a European bus project (Eu-ropean fuel-cell bus project), 30 hydrogen-powered buses are to be equipped with fuel-cell systems of 205-kW power output each and tested for about two years in transport service in ten European cities. In 2004, three low-floor buses made by Gillig will start a 2 year operation in San José, California.

Pre-requisites for market penetration

Besides the existing advantages such as little or no emissions (depending on the fuel), high efficiency, low noise level, driving enjoyment and new capa-bilities, the further development of the systems will be decisive for a successful market launch. The main focus of attention will be cold start char-acteristics, resistance and reliability, weight and volume, service life and cost cutting.

Besides further technical development, certain conditions will be needed for a change of concept and further commercialization. Basic prerequisites include supportive environmental and energy poli-cies, and an appropriate infrastructure for alter-na-tive fuels.
Fuel-cell propulsion is the ideal solution for non-nuclear submarines. It meets the highest demands in terms of extreme energy conversion and ensures minimal signatures: it generates neither noise nor heat that can be externally detected. Hence fuel-cell technology is a genuine non-nuclear alternative for air-independent propulsion.

Submarine in first trial phase

The world’s first submarine with fuel-cell drive is the German Navy’s “U 31”. This submarine, of the 212 A class developed by HDW, was launched in April 2002 and is in its first trial phase. The German Navy will be receiving four submarines of this class. In addition, HDW has also developed an export version of the submarine class 214 and has already won supply contracts from the navies of Greece and South Korea. HDW fuel-cell propulsion systems are available from the shipyard not only for newly developed submarine classes, but also for retrofitting in existing diesel-electric submarines.

It was a long road to series produced fuel cells. In the late 1970s, the Howaldtswerke Deutsche Werft AG, Ferrostaal AG and the Ingenieurkontor Lübeck recognized the potential of fuel cell technology and started to work on the development of a fuel cell unit. The convincing successes achieved in the 1980s, first in an onshore pilot plant and then at sea in a converted submarine, led to the order from the German Navy – the first navy in the world to operate fuel-cell powered submarines.

Use of reformer technologies also possible in the future

Siemens AG, the manufacturer of the fuel cell, has examined many different cell types. Testing has demonstrated the high efficiency of PEM cells, and this fuel cell type has hence been used in submarine classes 212A and 214. The boats store their supply of oxygen in pressure-resistant tanks and the hydrogen in metal hydride cylinders outside of the pressure hull. Looking to the future, HDW is working on reformer technologies in order to generate the hydrogen on board from other energy sources such as methanol, natural gas, kerosene or diesel fuel.

Today, “air-independent propulsion” (AIP) is the key phrase in the world of submariners. Only nuclear submarines can continue to sail submerged for an almost unlimited length of time. Diesel-electric ships so far have had to surface after two to three days to recharge their batteries. The new, fully tried and tested fuel-cell propulsion system from HDW extends this interval to several weeks.

April 30, 2002 – “U 31” launched for the first time on the synchrolift at HDW.

Arrangement of the fuel cells in the test unit as later in the submarine.
### Miniature fuel-cell systems – a substitute for batteries?

Christopher Hebling, Fraunhofer-Institut für Solare Energiesysteme ISE / Ulf Groos, Fraunhofer-Institut für Solare Energiesysteme ISE

The miniature fuel cell – a system split two ways

A fuel-cell system can be construed as an engine (power source) and as a fuel storage unit. In fuel cells, power output and energy capacity are independent variables. In a battery, by contrast, the functions of energy supply and capacity are inseparably connected. A battery, as a rule, must be completely replaced when exhausted, whereas a fuel-cell system can continue to work, once the fuel cartridge has been replaced or refilled. Moreover, small fuel-cell systems have the potential for higher energy densities than rechargeable batteries. They can house the same capacities with significantly less weight and volume. This significantly extends the operating time of electrical equipment.

Evidence of operability in actual practice still has to be produced

Further development is still required to move from technological potential to practical applications. For example, because of the progressive miniaturization of electrical devices, fuel cells also have to become smaller. Further efforts are necessary in order to achieve largely passive heat and water management. Moreover, appropriate energy management, for example for voltage control, has to be integrated into systems. For certain applications, a hybrid system comprising a fuel cell with battery or capacitor would appear advisable.

Hydrogen or methanol?

The choice of fuel is dictated by volume and weight constraints, the electrical efficiency of the system and the power characteristics of the particular fuel cell type. In the low power range hydrogen and methanol are primarily being considered, but chemical hydrides and even the use of hydrocarbons with microreformers are also being examined.

Hydrogen fuel cells have a higher power density than methanol fuel cells, i.e. they provide higher power output per unit volume and weight. Methanol fuel cells, however, supply more total energy per unit volume and weight than hydrogen in metal hydride storage units. When higher capacity is needed, a hydrogen fuel cell is at an advantage; when more energy output is the priority, a methanol system is advantageous.

### Cost and time forecast

The cost of the fuel-cell systems will one day probably be comparable to that of batteries – provided that they are mass-produced. Decisive prerequisites are the reduction of the catalyst material, the economical production of system and peripheral elements and automated assembly.

Currently all the signs indicate that niche applications under special conditions will be the first uses for fuel-cell technologies. Some examples are applications in sensors, data archives or signal systems, security cameras, backup systems and medical and military applications. Here a market launch is expected in 2003 to 2005. Parallel to that, fuel cells will become established as external power supplies and/or as mobile charging units, probably before they will become available on the market integrated into devices. Fuel-cell powered laptops could become available in about 2006. Reliable, country-wide supply will be a factor in customer acceptance and commercial success.
Fuel cells in small applications
Klaus Borkhoff, Ballard Power Systems AG

Today, PEM fuel cells are developed for power ranges from a few watts up to several hundred kilowatts. They can be used to power vehicles, in systems for power and heat generation, and in compact or portable power sources. The first products, about to be launched on the market, are primarily fuel cells in small applications with a power of approximately 1 kilowatt.

In the power range of up to a few kilowatts, fuel cells compete well with small internal combustion engines and batteries. Unlike petrol or diesel engines for example, fuel cells do not emit any pollutants. PEM systems operated on hydrogen release only water, and therefore can readily be used in indoor environments. Moreover, fuel cells are quiet and do not require long recharging times.

Portable energy source
On the basis of compact fuel-cell systems such as Ballard’s Nexa™ power module, products for a wide range of applications can now be developed. The Nexa™ module is produced in relatively large numbers, which significantly reduces cost.

Fuel-cell systems are ideal for integration into uninterruptible power supply systems or emergency generators. In addition, they are ideally suited as energy supply systems in mobile applications. It takes approximately one standard cubic meter of hydrogen per hour to operate a PEM fuel-cell product with a power of about 1 kW. With compressed gas storage (200 bar), metal hydride storage, or lead-acid batteries, this can be reduced to approximately 2.5 l.

For commercial introduction of fuel cells, the consumables must be available everywhere. This is not yet the case. Cartridge systems are planned which, like propane cylinders, will be available at replacement stations. Concepts have already been developed to the stage of field testing. In contrast to batteries, in a fuel cell, power output (a function of fuel cell size) and run time (a function of the size of the hydrogen storage unit) are decoupled. For an application which must ensure a power supply of approx. 1 kW over several hours, the fuel-cell system will be considerably smaller and lighter than a battery with a comparable capacity.

Energy for mains-independent systems
Manfred Stähler, SFC Smart Fuel Cell AG

SFC Smart Fuel Cell AG develops, produces and markets miniaturized fuel-cell systems in mobile, independent energy sources. The product has since been used as an optimal power supply for traffic equipment, monitoring and surveillance systems, environmental engineering and in the caravan, mobile home and leisure field.

Fuel cartridge logistics set up
Successful marketing of the Smart Fuel Cell depends mainly on setting up an infrastructure for supplying the fuel cartridges. SFC has established a cartridge logistics system which in future will make it possible to obtain cartridges in every supermarket and at every service station. The safety and reliability of the products and of the production processes are the No. 1 priority here. Necessary approvals for the shipment of filled methanol cartridges even on board aircraft have been obtained. Moreover, responsible authorities have approved the original SFC tank cartridge M2500 with 2.5 l of methanol and the patented safety connection for distribution to customers and partners.
In May 2001, the world’s first high-temperature fuel-cell power plant was put into operation in a hospital owned by Rhön-Klinikum AG. It is a natural gas-powered molten carbonate fuel cell with a carbonate melt as the ion conductor. In this system, the natural gas is converted, via an internal reforming process, into a mixture of hydrogen, CO and CO₂ gas that drives the fuel cell.

High efficiency
The fuel cell used at the Rhön-Klinikum has an electric rated capacity of 250 kW and can meet about 20% of the hospital’s power requirements. The system achieves an electrical efficiency of almost 50%, better than that of conventional plants of this capacity class. Moreover, the 400 °C waste air from the plant is utilized – first to generate process steam for sterilization and then to heat service water.

Besides very high efficiencies and minimal emissions, fuel cells offer further advantages, particularly for hospitals. They are virtually noiseless and require little servicing and maintenance. Complicated and expensive licensing procedures are not required because the waste air, though it contains CO₂, is non-polluting. During the first year of operation, an effective running time of 8,300 hours was achieved, some unscheduled shutdowns being caused by disruptions in the conventional plant periphery.

Uninterrupted emergency power supply
The operating results so far are encouraging. Therefore, planning to ensure an uninterrupted emergency power supply from the fuel-cell plant is under way. This would be advantageous not only for the large number of DP applications in hospitals, but also for data processing in any large organization. The high efficiency and high percentage of useful energy associated with high-temperature fuel cells are expected to lead to a variety of other potential uses – for example, optimized refrigeration processes.
The virtual power plant – united on a decentralized basis

Nina Konda, Vaillant GmbH

Nowadays large power plants supply most of the electricity society requires. This centrally organized generation is increasingly being supplemented by small distributed generation units such as wind power plants, unit-type distinct heat power stations and, in future, fuel-cell heaters (FCHA). A potential solution to the integration of numerous small distribution generation units is the “virtual power plant”.

In a virtual power plant an automatic computing system handles the collection of selected data from the distributed generation units (DGU), evaluates them in the interest of efficiency optimization and feeds back the required generation profiles to the DGU. Among the DGU known at present, fuel-cell heaters are currently being most intensely discussed. FCHAs not only generate electricity, but also heat for domestic water and central heating.

The Vaillant fuel-cell heater provides combined heat and power generation for buildings that are supplied with heat using natural gas and to some extent on hydrogen produced from renewable energy sources.

How much control is needed?

Companies currently working on virtual power plants feel that only a modicum of central control over FCHAs will be necessary. The internal FCHA controller could be adapted to the network so that power is only generated when it is needed in the network. In order to estimate generation and consumption, it could be sufficient to extrapolate from the empirical values of a transformer district. On the other hand, one could also actively switch FCHAs on or off in order to cushion peaks in the network.

Supply reliability

An advantage of distributed generation systems as compared with large power plants is the higher security from failure of the overall system, since as a rule the failure of individual FCHAs has only a minor impact on the overall system, since as a rule the failure of individual FCHAs has only a slight effect on the distribution network.

The virtual power plant – a comparison

Ulli Arndt, Forschungsstelle für Energiewirtschaft e.V.
Dierk Köhler, enwikon Energiewirtschaftliche Konzepte GmbH

The concept of the “virtual fuel-cell power plant” has been debated in professional circles for some time now. For this reason, the Bavarian Hydrogen Initiative (Wasserstoff-Initiative Bayern) has examined the energy industry-related aspects of this issue.

In cooperation with the Research Institute for Energy Economics (Forschungsinstitut für Energiewirtschaft e.V.) and enwikon GmbH, the study “The virtual fuel-cell power plant – technical and energy economical assessment” has been conducted. In the study, the power supply of a model housing estate with a virtual power plant is analyzed in comparison with conventional and energy-optimized technologies.

A simulation program calculates the electricity and gas consumption as well as the emissions of these power-supply variants. Likewise, the energy-related expenditure for the provision of the energy carriers electricity and natural gas were taken into account.

The following supply variants were compared:

- conventional heating technology and present-day power plant mix for electricity generation,
- condensing boiler and GuD® power plant (gas and steam turbines)
- virtual fuel-cell power plant.

Electricity purchase reduced and smoothed

The calculations show (see illustration) that with fuel-cell systems in the domestic energy supply infrastructure, the estate’s power consumption peaks on the public grid could be reduced by up to 60%. Moreover, the maximum demand is smoothed over the year. The virtual power plant thus depends on the public grid to a minimal extent.

The study also analyzed whether a central control system has any advantage over a local, building-optimized control system for the fuel-cell power plants. Here, however, hardly any differences were found – in the case of both control systems, about 80% of the electricity demand of the estate would be met by the fuel-cell plants.

Comparison of energy consumption

A primary energy saving of approximately 23% was realized relative to conventional heating technology and current from the present-day power plant mix (see table). The virtual power plant (whether controlled centrally or building-optimized) shows almost the same consumption of primary energy in the model as the variant with condensing boiler technology and the GuD® power plant.

The virtual power plant as a form of decentralized generation of power and heat thus has an efficiency that is similar to the central supply of electricity using modern power plants and optimal systems for the supply of heating energy.

Using fuel-cells, however, opens up additional applications for cogeneration. Advantages, in this case, are the possible downsizing as far as to miniature capacities below 1 kWel and the high electricity-to-heat generation ratio.
Hydrogen in the energy industry – prospects for an energy supplier

Hans Reiner, E.ON Energie AG

Technical developments for the utilization of hydrogen as a secondary energy carrier in the energy industry concern both the generation of hydrogen and its conversion into electricity – especially with the help of fuel-cell technology. The current interest shown by E.ON Energie is in particular directed toward the generation of hydrogen from renewable energy sources and the coupled electricity and heat supply to households, commercial and industrial businesses.

Currently hydrogen is produced from renewable energy sources using the following methods: gasification and fermentation (in a mundane way via the methane produced) of biomass and the electrolysis of water with electricity from renewable energy sources. Processes using biomass are restricted to decentralized conversion plants, as long transport distances are counterproductive for biomass because of its low energy density. These processes have a potential for the disposal of organic waste as a fuel available at low cost. Decentralized hydrogen supply from biomass makes environmental sense and can be cost effective under suitable conditions.

Hydrogen as an energy storage medium

With increasing generation of electricity from renewable energy sources, a generation of energy that is not always in step with demand, storage is gaining in importance. The production of hydrogen by electrolysis of water is an innovative use of electric current in times of low consumption and surplus generation. Converting electricity into hydrogen, however, involves high costs, leads to losses and converts high-quality electrical energy – unable energy – back to the energetically lower valued fuel level. Energy storage by means of hydrogen hence competes with the proven technology of pumped storage.

Decentralized power supply

Fuel-cell technology makes possible small, decentralized plants for cogeneration of heat and electricity for households, businesses and industries. For the time being, natural gas will be used as the main source of hydrogen for fuel cells. Economic efficiency can be achieved only if heat and electricity are simultaneously consumed for many hours each year and the purchase prices for fuel-cell plants drop drastically. The cost of connection to the grid will be incurred in any case and has to be taken into account in considering economic viability. If the decentralized generation of electricity and heat by fuel cells increases as strongly as some experts are predicting today, new forms of supply structure could be created in which the advantages of large power plants and small plants complement each other.

New technologies undergoing testing

Since 1990, E.ON Energie has gained considerable project experience with the generation, storage and use of hydrogen as well as with fuel cells. One focus is the viability of new equipment in everyday use. As innovative technologies are evaluated in field tests, valuable operating experience is gained and contributions are made to the further development and optimization of the components and systems that are valuable from an environmental and cost perspective. Today, new forms of supply structure could be created in which the advantages of large power plants and small plants complement each other.

Larger systems in the capacity range between 200 and 500 kW electric could be ready for market introduction at an earlier point in time. In order to promote development and to gain experience, E.ON Energie is running several pilot projects in this capacity range as well.

Knowledge of hydrogen as an energy carrier and of the fuel cell is available at E.ON Energie. What is needed now is to widen the experience with new concepts, so that widespread implementation can proceed when the technology is sufficiently developed for the market requirements.