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Fuel cell technology

Summary

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SUMMARY

Fuel cell technology is in a decisive phase. Important decisions can be expected on the directions that innovation will take. Worldwide development efforts by major companies and extensive state promotional programmes document the expectation that their use will tap major market potential and produce solutions to encountered problems in the transport and energy sectors. Fuel cell technology also holds out prospects of significantly more eco-friendly propulsion systems for road traffic and more efficient and ecologically sound power plants and heating systems. This medium-term prospect is supplemented by the plausible vision of the use of fuel cells as a bridge in a (future solar) hydrogen economy and as its central element.

Technically, such ideas of successively replacing conventional technologies are not unjustified, and particularly in ecological terms they are solidly based. Fuel cell systems are highly-efficient energy conversion systems, in most cases with advantages in terms of efficiency, fuel consumption and greenhouse gases balance sheets. Finally, fuel cell technology could also supply a far-reaching stimulus to innovation.

Progress in achieving the potential of fuel cell technology varies, depending on the fuel, the process and the area of application. In most cases, numerous technical obstacles remain to be overcome, and competitive cost structures in production have yet to be achieved. A general consideration is that fuel cell technology has to contend with established conventional and competing new technologies in the transport sector and in the field of power generation and supply.

GOAL AND KEY AREAS OF THE REPORT

The present final report attempts to give a realistic, comprehensive and nuanced picture of the state of development and future prospects for widespread use of fuel cell systems and the possible consequences. For this purpose, technical peculiarities of fuel cells and the different systems are described, and an overview presented of the essentially usable energy sources and fuels. The report focuses on a nuanced analysis of the state of the art of and prospects for fuel cell technologies in three areas of application: transport, energy economy and portable small electronic devices. For each of these areas the relevant systems and their state of development are described and the necessary supply of energy sources reviewed. A scenario approach using the life cycle analysis, or eco-balance sheet methodology is used to make a primarily ecological assessment (differentiated according to the fields of application), supplemented by a review of relevant technical aspects and economic dimensions, in each case in comparison with conventional systems. The period under consideration extends to 2010, and the geographical basis is Germany.

MOBILE APPLICATIONS

For some time the automotive industry has been making significantly greater (and, in part, major) efforts to optimise the propulsion technologies used in road transport, and particularly to reduce specific fuel consumption and improve the emission balance. Besides conventional options, there is growing interest in alternative concepts for propulsion systems and fuels. The focus here is increasingly on the fuel cell (using both conventional and renewable fuels).

Fuel cells for mobile use are currently being discussed and developed to power road vehicles (passenger cars, coaches). In addition, other uses have been proposed, such as fuel cells as powerful energy sources (battery substitutes) in vehicles with conventional internal combustion engines or as propulsion systems for electric railways or ships, and some of these have also been pursued. The present report focuses on use in passenger cars.

Attractive potential

The reasons for the numerous activities are rooted in the fuel cell's potential (although this has yet to be technically and economically accessed in many areas) in terms of efficiency, reducing fuel consumption and emissions and for innovations in vehicle technology, together with the possibility of achieving diversification and regional differentiation of the fuels used for transport. Compared to internal combustion engines, the following aspects (among others) deserve favourable emphasis:

- High levels of efficiency under part load result in higher overall efficiency and lower consumption. Fuel cell propulsion systems have the potential of matching or improving on the low level of specific fuel consumption of future diesel engine passenger cars.
- Used in fuel cell vehicles, hydrogen as a fuel releases no emissions and methanol or other hydrocarbons only minimal amounts, compared with internal combustion engines. Depending on the fuel used and the fuel cell concept,

there are clear advantages in the greenhouse gases balance sheet and other parameters of ecological relevance.
> The extensive reduction in moving parts in the propulsion system leads to mechanical simplicity, low vibration and noise, and lower maintenance, although under certain circumstances this may be offset by additional costs and maintenance for the peripherals of the fuel cell system, depending on the system concept In addition the technology makes possible a powerful on-board energy supply and much greater freedom in vehicle design.

For vehicles, the technology regarded as most likely to achieve this potential is the membrane fuel cell (PEMFC).

Ecological aspeacts

Virtually all traffic forecasts assume that vehicle-miles driven will continue to rise up to 2010. A reduction in CO_2 emissions could be achieved by reducing specific fuel consumption of vehicles or by using new fuels with lower specific CO_2 emissions. Widespread introduction of low-consumption vehicles, available on the market in growing numbers, could make a rapid contribution here. Another approach which has already been commercially implemented is the use of natural gas in particularly low-emission engines, generating 20–30% less CO_2 emissions than petrol-fuelled engines.

Fuel cell vehicles can also help reduce emissions, provided they are introduced in sufficiently large numbers. However, this does not apply to all systems, as the use of fuels from fossil sources means that – compared to conventional internal combustion engines – the advantages of fuel cells in terms of energy and emissions are offset by energy losses and emissions in fuel production and processing. This also applies to alternative fuels made from renewable energy sources – although limited to emissions – but not to hydrogen production based on emission-free electricity from renewables. In assessing fuel cell technology, one consideration for each option is whether and how far energy losses and emissions are simply shifted from vehicle operation to fuel production and manufacture. This has political relevance in particular because of the fact that individual industries and associations (not least under covenants or voluntary commitments) also have goals for reducing greenhouse gases.

Fuel cell passenger cars using hydrogen as a fuel are zero-emission vehicles. Fuel cell passenger cars with methanol and largely also those with hydrocarbons as fuel will meet and in some cases fall significantly within Euro4, the future European emission standards (from 2005), and also the stringent Californian emission standards.

However, new, consumption-optimised vehicles with internal combustion engines also make possible operation with almost zero local emissions. To this extent we can argue that traffic-related environmental pollution can be reduced by optimising the internal combustion engine to a sufficient extent and, above all, with lower financial investment, so that the development of alternative propulsion technologies – such as the fuel cell vehicle – is not a matter of urgency. Against this, however, it should be said that in the medium and longer term and in the context of broader consideration, further reduction in the direct exhaust emissions of the passenger car may be necessary, particularly if the general increase in traffic results in new growth in pollutant emission as the potential for optimising the internal combustion engine is increasingly exhausted. In addition, if zero-emission vehicles become a competitive option, consumer demand for these could then increase, or politicians or environmental associations could call for their use. Current technical developments and the emerging tightening of emission standards for vehicles with conventional internal combustion engines prompt intensive consideration of the introduction of fuel cell vehicles

The analysis of the use of fuel cells in vehicles makes it essential to include the fuel supply system and the energy source used: Hydrogen as a direct fuel for fuel cell propulsion systems is a long-term prospect from our present position, although the industry is currently investigating the feasibility of a basic hydrogen infrastructure in Germany from around 2005. However, for the energy market as a whole, the next 20–30 years are likely to see priority for other fuels, from both renewable and fossil energy sources – primarily liquid alcohol fuels (methanol) or hydrocarbons (petrol). In both cases the fuel must be stored in the vehicle and converted to hydrogen there. Methanol permits a simpler and more effective systems design for the propulsion systems, but there is currently no adequate methanol infrastructure. Petrol on the other hand requires elaborate fuel cell systems, but could build on an established fuel production and distribution system, although the fuel quality is currently inadequate for fuel cells.

A life cycle analysis shows positive features depending on the fuel used.

> Fuel cell vehicles powered by hydrogen generated using electricity from renewable fuels have clear advantages over conventional propulsion systems for all impact categories.
> In the impact categories acidification, eutrophication and photosmog fuel cell vehicles powered by fossil fuels generally show significantly better figures than

conventionally-powered vehicles, but bio-fuels based on energy plants show significantly worse ones.

> In the category carcinogenicity fuel cell propulsion systems are all significantly better than conventional systems.
> Contributions to the greenhouse effect are lower for hydrogen-powered fuel cell vehicles (except for liquid hydrogen won from fossil sources) and for all bio-fuels than for passenger cars with Otto cycle internal combustion engines, while the contributions from fuel cell vehicles with methanol, dimethyl ether (DME) and petrol as fuel are roughly comparable.
> In terms of consumption of non-regenerative energy resources all options with renewable fuels and vehicles powered by centrally-compressed hydrogen from fossil sources have advantages. For fuel cell vehicles with methanol, dimethyl ether (DME) and petrol as fuel, however, the figures are rather less favourable than for conventional propulsion systems.

As the important potential fuel cell fuels hydrogen and methanol can be manufactured from a range of different primary fuels, corresponding propulsion systems will permit regional differentiation and diversification of fuels for transport. In addition the technical basis could be created for using renewable fuels in transport, with a smooth transition from petroleum-based fuel supplies to renewable fuel supplies. This is another reason why fuel cell vehicles are an option for the near future which should be pursued further.

In the medium and long term options for the use of renewable fuels in transport (and other areas) should be opened up. This is necessary not only because of emissions and climate protection but also because of the limited availability of fossil fuels. Resources of fossil fuels are limited, and it would be irresponsible to transfer the concept of a mobile society based on petroleum to the largely unmotorised parts of the world.

Economic aspects

Generally speaking, the development of fuel cells for mobile use is shaped by the debate over the »right« fuel, the need to demonstrate the functionality of the technology in practical use (particularly in long-term operation), the massive cost reductions required from today’s standpoint, and the question of market entry. For acceptance by the market, a number of technical and economic barriers need to be overcome, and the benefits to users and investors made more apparent than is so far the case. Currently there are no reliable data on the costs (and prices) to be expected for vehicles with fuel cell propulsion systems. A rough estimate shows that the additional price for purchase and operation will probably be around DEM 30–50/kW for a medium-sized car (in absolute terms between DEM 1,500–2,500) for expected petrol prices around DEM 2.25/l. According to information from the car manufacturers, the price of a fuel cell vehicle is intended to »be in line with that of a comparable model with a diesel engine and automatic transmission«. This would mean a mark-up of DEM 2,000 over a diesel model and DEM 5,000 over a comparable petrol model. To achieve this goal (which in current terms is extremely ambitious) would require annual production of several tens of thousands of cars.

Framework conditions

Widespread introduction of new fuels in the transport sector would require – largely independent of the propulsion system – coordination and support from politicians in approving these substances as fuels and in the pan-European harmonisation of approval regulations. Unless the automotive and petroleum industries agree on a joint strategy, the creation of suitable infrastructures also seems to require greater involvement on the political front. Both processes must take place upstream to the introduction of such fuels and corresponding new propulsion systems (for fuel cell vehicles with methanol, 2004 is scheduled) so that a largely self-sustaining market can evolve.

Research and development

The focus in R&D in the next few years is likely to be on the fuel cell propulsion system itself. Key issues in this area include:

> developing efficient and dynamic propulsion systems,
> developing compact units and miniaturising components and systems generally,
> developing storage systems,
> increasing operating safety and improving practicality.

In addition, work is needed on the total system comprising fuel cells and vehicles. The focus here is likely to be on reducing costs. Approaches for this – besides corresponding economies from high volume in production – lie primarily in the production process itself, for example through the use of new materials or reduction in use of noble metals.

In addition, answers are needed to the questions about the »right« fuel and supplying the necessary infrastructure. Key areas for research here are likely to include the changes to be expected in the fuel production process, processes for the economic and ecologically acceptable supply of renewable fuels, definition of globally comparable fuel specifications, handling potential fuel hazards, requirements for establishing new fuel infrastructures, and the definition of practical criteria for comparison.

STATIONARY ENERGY SUPPLY

Stationary energy supply is in a state of flux. The increasing liberalisation of energy markets is resulting in rapid changes in the technologies and fuels used. A major trend is the decentralisation of power and heat supply, so that not only manufacturers of classic heating plants but also supraregional electricity supply utilities are taking an interest in alternative technologies such as the fuel cell. In addition, there is also a continuing need in power and heat supply for more efficient energy conversion technologies which reduce the high proportion of climatically-relevant pollutants from power plants, combined district heating and power plants and small boilers.

Attractive potential

An initial reticence in the early-to-mid 90s has now given way to a favourable attitude towards fuel cell technology. This is documented by the substantial growth in development efforts and numerous strategic alliances. The reason for these activities is the expected potential, although this still has to be technically and commercially developed.

> High efficiencies under part load result in high overall efficiency, e.g. in the combination of high-temperature fuel cells with a gas turbine, which reaches levels unavailable to conventional technologies alone. This is combined with a decrease in specific need for primary fuels and specific pollutant emissions.
> A possible fossil fuel is natural gas, which has the advantage of having a broad-based existing infrastructure. In the medium to long term there is the possibility of building up a hydrogen infrastructure (based on renewable fuel), analogously to the transport sector.
> A new feature is the prospect of using the fuel cell in a technically attractive implementation for widespread use of combined heat and power generation in domestic energy supply. This also creates the additional possibility of feeding surplus electricity into the local distribution system.
> The elimination of mechanically moving parts means a significant reduction in maintenance inputs.

Fuel cells for stationary use are currently being discussed for almost all areas of stationary energy supply. As the entire range of fuel cell types is under consideration, this includes fuel cell types which are more robust in terms of the gas composition. This would make a wider range of gases (e. g. sewage and industrial gases) available for energy use.

DOMESTIC ENERGY SUPPLY, SMALL-SCALE CONSUMPTION

Development efforts for energy supplies to households and housing developments show that currently PEMFC is the primary contender, followed, with some limitations, by the phosphoric acid fuel cell (PAFC) and solid oxide fuel cell (SOFC). In a technical comparison with conventional heating plants these fuel cell systems can be regarded as equivalent. The main handicap is their excessive price (for the moment). In addition, technical and cost optimisation of the fuel cell systems still remains to be done. The most ambitious goal is likely to be achieving a useful lifespan of around 40,000 operating hours.

Besides hydrogen, the fuels for fuel cell systems to supply energy to buildings currently being tested are primarily natural gas, but also fuel oil, petrol and methanol. Conventional fuels like natural gas or fuel oil have the advantage of an existing infrastructure and are familiar to users. As the energy balance sheet for the reformer improves with the cleanness and hydrogen content of the feedstock, hydrocarbon mixtures (fuel oil, petrol etc) are less suitable in terms of process technology, but would have strategic importance for the transitional period before a hydrogen infrastructure is established.

Ecological aspects

As the fuel cell itself only emits steam into the environment, a direct local hydrogen supply means a less complex unit without pollutant emissions, which could make a contribution towards reducing local emissions.

Emissions are, however, released during production of hydrogen using fossil routes. To this extent production of hydrogen using renewable fuels is more effective in environmental terms. With fossil fuels, natural gas is more favourable than fuel oil as a source. Despite the higher efficiency of methanol compared to fuel oil in fuel cell cogeneration plants, this is not enough to compensate for the higher emission levels in methanol production. The situation is more favourable for methanol from renewable sources. Consequently, climate protection considerations rule out the use of methanol from fossil sources as a fuel, and make the use of natural gas more logical. An associated increased consumption of natural gas – exacerbated by growth in other areas (e.g. vehicles, power plants) – does, however, involve some problems for strategic reasons (e.g. dependence on imports, depletion of fossil resources).

Economic aspects

An analysis of the economic aspects of fuel cell systems in domestic energy supply shows inter alia that it is still some way short of cost effectiveness, but that this point should be easier to reach than in mobile application. One of the reasons for this is that specific investment in conventional stationary plants is significantly higher compared to mobile applications. Plausible investment for a fuel cell cogeneration plant with a rating of 1–10 kW (el) is accordingly around DEM 2–4,000/kW (el) for a fuel cell system comprising gas processing, cell stack and converter, which is roughly the order of magnitude of manufacturer figures. For larger plants (e.g. central installations for housing developments), economies of scale should make possible a figure around DEM 2,000/kW (el).

Due to the current comparatively high purchase prices, new financing models should be considered for financing fuel cell systems. These consist of a leasing model and the use of energy service packages.

Prospects for widespread use

With their modularity, fuel cells have broad potential for use. The variant which currently appear interesting are individual house supply (fuel cell and reformer in the basement) and housing development supply with a local heat distribution network (reformer and fuel cell installed centrally). Central supply of hydrogen on a significant scale is only possible in the medium to long term (infrastructure construction).

With regard to widespread implementation of fuel cells in homes and for small-scale consumption, different substitution variants and their effects in 2010 were analysed (reference: trend outline by Prognos). Assuming a 10% rate of substitution by fuel cell plants (PEMFC reference system with peak load boiler) for conventional domestic heating plants, the consequences would be a change in fuel structure (and demand for electricity, district heating, natural gas and fuel oil) and hence a reduction in the emission of gasses with climatic relevance. Roughly summarised, there would be a shift towards natural gas (up to 18% increase in consumption), with corresponding reductions in fuel oil, district heating and electricity.

For the emission of gases with climatic relevance this would mean for CO_2 that even a 10% substitution of conventional heating systems would cut up to 2.3% of CO_2 emissions from domestic energy use for the four fuels cited. A separate point worth mentioning is the favourable effect on the local emission situation, where natural-gas-fuelled fuel cell cogeneration plants have the lowest emissions.

Research and development

There is need for R&D on optimising fuel cell systems in terms of improved long-term stability to achieve a useful life of 40,000 operating hours while significantly reducing costs. For this, synergetic effects with mobile uses could be exploited with PEMFC systems in particular. In addition, modification of classic gas treatment for the scale required for building energy supply has proved considerably more difficult than originally assumed. There is accordingly need for R&D on miniaturising current standard reformer processes to use fossil fuels (natural gas, fuel oil etc).

The commercial availability of hydrogen storage media with the expected storage densities (roughly comparable with those of hydrocarbon nanofibres) could make decentralised hydrogen-based energy supply of even thinly-populated regions more profitable, and also considerably simplify the technical aspects of market launch. However, as the available options for hydrogen storage currently do not offer any practical alternative, there is need for research here.

INDUSTRIAL ENERGY SUPPLY, PUBLIC ELECTRICITY SUPPLY

For applications in industrial heat-power cogeneration and public electricity supply, high-temperature fuel cells (SOFC, molten carbonate fuel cells [MCFC]) are most suitable. Both systems are still in an early stage of development, but permit the use of a wide range of fuels.

Such fuel cell systems compete in the lower rating range with gas turbines and motor cogeneration plants, and in the upper rating range with combined gas/steam turbine power plants. Conventional plants have a clear advantage in practical experience and comparatively low costs compared with fuel cell plants. In addition, conventional plants also still have various possibilities for development. Besides covering a broad range of requirements, fuel cells have the following advantages:

> Higher power coefficients of high-temperature fuel cells in cogeneration systems are in line with the tendency towards growing electricity consumption in industry. They are accordingly optimal for use by industrial consumers with high electricity intensity.
> High part-load efficiency is valuable in explicit part-load needs, such as part-load power plants, or for specific startup and shutdown of heat or electricity loads at cogeneration plants. Together with their rapid load change performance this could be an advantage for high-temperature fuel cells in a liberalised energy market, as cost considerations could mean increasing importance for decentral part-load power plants.
> Total waste heat is made available flexibly at a high temperature level. This means that both district heating networks and combined gas/steam turbine power plants can be served.

In the long term, the potential for further improvement in the electrical efficiency means that the combination of fuel cells and gas/steam turbine power technology is attractive for high-efficiency gas and coal-fired power plants. Specifically, this combination can further reduce the $CO2$ disadvantage of coal as a fuel, as comparable increases in efficiency are not expected with conventional coal-fired power plants.

Ecological aspects

Overall, fuel cells are superior to conventional systems in almost all areas in terms of their environmental impacts. They can in particular make a significant contribution to reducing greenhouse gas emissions. However, in considering the significance of these positive contributions, it must be borne in mind that conventional energy conversion technologies still have considerable potential for reducing emissions. Although fuel cells have the advantage of »zero emissions« of pollutants at the local level, upstream fuel chains have an effect on the overall balance. High emission levels in some fuel chains are an »ecological backpack« for fuel cells. There is potential for reductions in primary energy consumption, greenhouse gases, acidification and NOx emissions. In terms of primary energy savings and reduction in greenhouse gas emissions, fuel cells are logical candidates for use in both pure electricity generation and in cogeneration plants. In detail, the following can be said:

> Fuel cells are superior in industrial heat-power cogeneration to the conventional systems studied in terms of the observed environmental impacts (with the exception of NMVOC emissions).

> The reduction in greenhouse gases and consumption of exhaustible fossil resources is particularly marked in a transition from a fossil fuel to a renewable one. With regard to the greenhouse effect and consumption of exhaustible fossil resources, the fuel is more important than the energy conversion technology.
> The advantages of biogenic fuels with respect to the greenhouse effect and consumption of resources can be efficiently linked in environmental terms with those of fuel cells. Overall – and given further exploitation of the potential of renewable fuels – fuel cells can make a significant contribution to climate protection, even allowing for upstream chains.
> Where high-temperature fuel cells are integrated into lignite-fired power plants, the increase in efficiency compared to future steam turbine power plants can be assumed to deliver primary fuel savings as well.
> In fuel cells, the ecologically-acceptable use of gasified or fermented (residual) biomass (almost neutral CO_2 balance, no consumption of exhaustible resources) is possible without any significant deterioration in other environmental categories.

Economic aspects

In use in industrial heat-power cogeneration the »permissible« (feasible) investment in a hybrid system (high-temperature fuel cell combined with a gas turbine) is around 15–20% above that of a comparable gas turbine system, and in central power generation up to 30% above a combined gas/steam turbine power system.

The comparatively high electrical efficiency of fuel cells in all rating classes has a favourable overall trend on fuel costs. However, it is necessary to distinguish between the use of conventional fuels and alternatives (e.g. hydrogen) for which there is currently no infrastructure. The useful lifespan of fuel cell stacks is currently well below that of conventional technologies. The resulting need for a stack change after c. five operating years has an adverse impact on electricity generating costs. In the current environment, and assuming constant statutory emission requirements for (conventional) energy conversion plants, no economic advantage is apparent for potential operators of fuel cell systems. This could change in the event of more stringent emission standards.

POTENTIAL FOR USE OF HIGH-TEMPERATURE FUEL CELLS

The use of high-temperature fuel cells in stationary energy supply will probably appear first in decentralised, low-rating plants in the short to medium term. Use of high-temperature fuel cells in power plants is more likely in the long term.

Market launch will require prior demonstration of the maturity of the technology. For the present, advance work is still needed to bridge the current gap between the market price and the existing high production costs.

Combining high-temperature fuel cells with gas turbines opens up an attractive market segment, as this gives further improvement in the overall efficiency, and hence a reduction in emissions. This also applies to integration in coal gas fired combined gas/steam turbine power plants, which are expected to appear on the market in the medium term. Coal gasification could result in more efficient use of domestic raw materials, which could under some circumstances create export potential (China, India).

The »classic« decentral cogeneration market will probably shrink as a result of liberalisation, which inter alia will also adversely affect the market potential of fuel cells. On the other hand, the EU is seeking to expand the share of cogeneration plants, which could lead to growth in corresponding markets in Europe. Falling electricity prices and growing uncertainty in planning are reflected in the target short amortisation periods for new plants in order to limit the investment risk. This favours new plants with minimal initial investment. Efficient energy conversion concepts such as fuel cells, which require relatively high initial investment and which have comparatively long amortization periods through fuel savings, are at an according disadvantage.

It is also assumed that instead of large plants there will probably be several geographically distributed smaller plants, which will (inter alia) reduce the investment risk. Besides fuel cells, motors or gas turbines are also suitable candidates (among others) for the operation of such plants. This makes market integration of fuel cells dependent on whether they can meet the new requirements flexibly and at competitive prices. Energy and environment policy measures could possibly assist this process.

Research and development

Fuel cells for larger plants are still essentially in the development stage. Before major pilot plants can be built, there is still enormous need for development, including in the field of material technology. Specifically, materials are needed which can withstand high temperatures without corroding, are easy to process and are available at low cost. A major contribution to this – and also to reducing the problems of insulation and comparatively long cold startup times – is promised by efforts to reduce operating temperatures of high-temperature fuel cells, although these efforts need to be intensified. In addition there is also the question of optimising overall systems with respect to their long-term stability.

Framework conditions

Currently, the widespread introduction of fuel cells in stationary energy supplies is not significantly dependent on the introduction of new fuels (as in mobile use). Primarily, the industry is backing natural gas for an expected market launch. It is presently assumed that fuel cell systems are not yet »self-starters« in the market, as their economic appeal is limited by the relatively high investment still needed. As, however, ecological advantages are apparent in widespread use of fuel cells in stationary applications, the process of introducing and establishing them in the market could be assisted by policy-making (e.g. through suitable market launch programmes).

In the longer term, the use of new fuels (e.g. hydrogen) is an expedient concept in stationary applications as well. The creation of corresponding infrastructures should be coordinated with the development of infrastructure in mobile applications.

FUEL CELLS IN PORTABLE SMALL APPLIANCES

In another rapidly growing market (small appliances), fuel cells have good prospects of acquiring substantial market shares. For portable small electrical appliances low-temperature fuel cells such as PEMFC and DMFC are particularly suitable. For so-called CCC applications (computers, cellular phones, camcorders), membrane fuel cells (PEMFC) are likely to achieve market maturity first. Direct methanol fuel cells (DMFC) also have good prospects, but are still currently in the laboratory stage.

Attractive potential

Energy consumption of new small appliances is increasing faster than the energy density of new batteries, with resulting shorter operating times. Here the use of fuel cells is becoming attractive, also because it is expected that the market for small appliances will continue to grow. This demand could be covered by mini-fuel cell systems (e.g. with metal hydride storage).

The advantages of fuel cells over batteries and accumulators is in their significantly longer mains-free operating times with effective use of limited space, favourable weight ratios, flexible load dynamics and relatively low operating temperatures. As fuel cells on the laboratory scale are candidates here, no further upsizing is required.

Based on the relatively short useful lifespan of batteries and accumulators and the resulting relatively rapid potential for substitution by fuel cells, the market segment of portable small appliances should offer the fastest potential development.

Ecological aspects

Pure hydrogen should be preferred as the fuel for portable electrical appliances with a PEMFC because of the handiness of such systems. Considerations of fuel cell logistics also favour carbon-based fuels which are typical for households. These require mini-reformers, and work is already in progress on these. Direct use of methanol in DMFC systems is more favourable in energy terms than reformation to hydrogen.

PEMFCs generate only water locally, while DMFCs generate not only water but also small quantities of CO2. Hydrogen can be generated through a mini-electrolysis unit, which can also use electricity from renewable sources. The emission contribution of mini-fuel cells is not determined significantly by the fuel pathway but (a relatively favourable consideration) by the long useful life of the fuel cell system. For this reason, and because of the partial recycling capability, fuel cells could make an important contribution to reducing refuse if they are substituted for accumulators on a significant scale.

Economic aspects

The competing technology here is conventional batteries and accumulators (primary and secondary cells). The »yardstick« is the lithium ion accumulator, which in the current state of technology has the highest energy density (although also the highest price of all the accumulators).

The advantages of batteries and accumulators is their current availability at market prices. The drawback are the small number of recharging cycles and resulting disposal problem for batteries. Other problems arise in terms of cycle stability, self-discharging and the memory effect. In principle, there are no new accumulator systems on the horizon.

In terms of cost, fuel cells have the relevant advantage of a significantly longer useful life. Due to the spatial separation of cell and fuel storage, no self-discharge is possible. In addition the metal hydride storage available for use can be recharged up to one thousand times.

Research and development

Besides increasing the power density of fuel cells, R&D efforts generally are also concentrating on improving the reliability of the whole fuel cell system. With respect to the use of hydrogen for professional and home use, fuel cell peripherals need optimising in terms of safety. Besides developing concepts for water management within the fuel cell, the development of mini-reformers is also relevant.

Of the known storage variants for hydrogen, the primary candidate for use at present is metal hydride storage. The use of compressed hydrogen storage involves unresolved safety issues, for example in the transport of small appliances in aircraft. Nanostorage units would be ideal, but are not yet available. Besides the lack of technical standards, a key disadvantage of mini-fuel cells (assuming the use of PEMFCs) is the lack of a »global« hydrogen supply.

OUTLOOK

Generally, we can say that in the current situation energy conversion systems with fuel cells can be competitive in the future, even if achieving corresponding cost goals (particularly for the fuel cell systems themselves, but also for new fuels) is still very much an ambitious goal for development. For this purpose fuel cell types which are suitable for both mobile and stationary energy supply use offer possible synergetic effects, even if there are differences to be taken into account in development. Use in vehicles is characterised primarily by short useful lifespan with relatively low cost targets and weight goals, whereas stationary plants are distinguished by a significantly longer useful lifespan with comparatively moderate cost and weight goals.

The development of fuel cell systems promises leaps in innovation, both for fuel cells themselves in terms of material technologies and manufacturing procedures and for the various peripheral units. An efficient hydrogen storage system which can be integrated in all applications (vehicles, decentralised energy supply, portable small appliances) is increasingly emerging as a key factor.

The fuel used must be integrated into evaluations of the potential of fuel cell technology and in comparisons with conventional systems. In this process it is clear (inter alia for ecological reasons) that fossil-based fuels at least involve additional energy inputs in the upstream energy chain. From the strategic aspect, it must be considered that in the short and medium term the widespread use of fuel cells would significantly enhance the already apparent trend to increased use of natural gas. Other possible fuels for fuel cell systems (such as electricity from renewable sources and hydrogen generated from this) also involve competitive uses whose scale and relevance for cost are currently difficult to assess.

A decisive question for further diffusion of fuel cell technology will be the framework conditions in terms of energy, environment and transport.

The innovation process has meanwhile acquired considerable momentum, but much of the potential of the fuel cell will only take on its full value within the framework of a reorientation of the transport system and energy industry towards energy supplies based on renewable fuels. Here, there would be potential scope for political action, in order to create suitable framework conditions and use suitable instruments to intensify the market momentum of fuel cell technology and provide stimuli in a way that makes its ecological benefits available earlier and on a broader scale.

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