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Energy storage systems – current status and outlook

Summary

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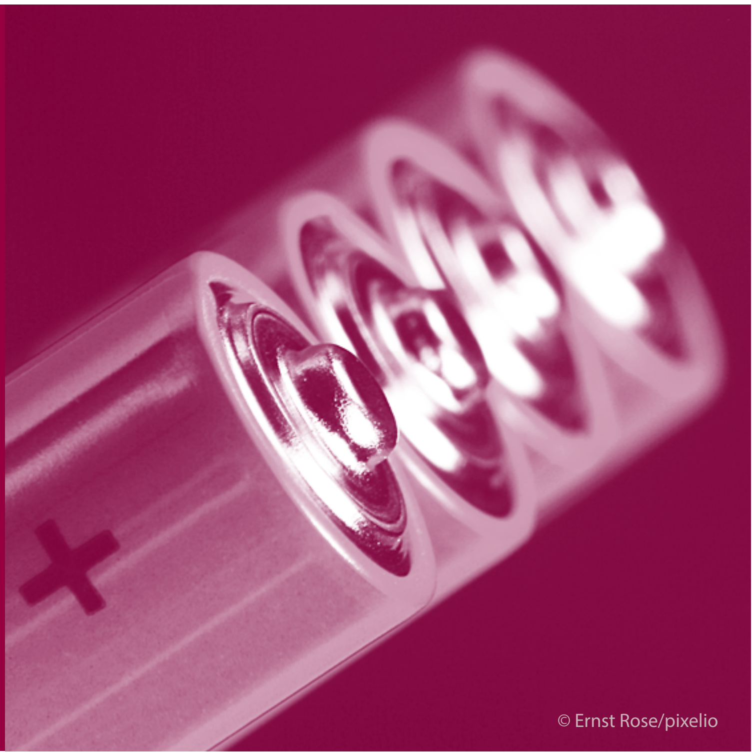

SUMMARY

Energy supply is facing a series of new challenges. The increasing liberalisation and globalisation of the energy markets not only creates new overall conditions but also places new demands on the energy supply systems of the future. A central feature here is maintaining a secure supply of electrical energy, above all with increasing proportions of fluctuating energy sources as well as altered terms of purchase for natural fossil resources. Other factors which play an important role are the avoidance of further climate changes and the environmental damage caused by energy supply. Energy storage facilities are a permanent feature of our energy supply system today. Nevertheless, their role is hardly noticed at all – except at the technical level. Against this background, the TAB report provides an overview of the current technological status of available energy storage systems and innovative storage concepts in both the stationary and mobile areas.

Energy storage is an area of research and knowledge that can look back on a relatively long tradition, as the basic concepts were discovered back at the end of the nineteenth century. However, there have been no breakthroughs in storage research in the past few decades, which means that not much spectacular has happened – apart from the hype seen a few years ago with regard to the storage density of hydrogen possible on carbon nanotubes, which has since been relativised. This observation, however, conceals a host of development steps – some of them using effects on the nanoscale – which have led to significant progress in energy storage facilities in the past few years.

The search for efficient energy storage facilities has emerged in the past few years, particularly in the traffic sector, as a critical factor for future mobility concepts. Work on storing hydrogen and electrical energy have a high priority here for new impulses. On the other hand, the need for new or further developed energy storage devices in the stationary sector in Germany was not very clearly distinguished for a long time. One reason for this is that the density of power plants is equally as high as the supply guarantee resulting from it – including the grids. In addition, the combined European grid ensures compensation to a certain extent in the supply and demand for electricity. Another reason is that »superfluous energy« was stored intermediately up to now on a large-scale, e.g., in pumped-storage plants. And up to now, this was sufficient. However, in Germany too, there could be larger amounts of energy available in the future which it would make sense to store temporarily.

THE NEW REQUIREMENT

For some time, the proportions of fluctuating energy sources (solar, wind) have been increasing, whereby – in line with the stipulations of the German government – these should still further increase significantly until 2020. The amounts of electricity achievable in this way have now reached a size which mean situations could arise in the future in which the »planned proportions« of these energy sources are either not available or available in excessive amounts in our energy supply. For example, wind energy would not be available in a wind-calm period or during storm shut-downs, but in favourable offshore locations there would be an oversupply at times. When a certain volume of energy is reached, this is relevant for load balancing in the supply grids. Because then in the case of a wind-calm period a corresponding level of normal power output must be available in the electricity grid. To this end, power plants with so-called »spinning reserve«, which are today mostly conventional type plants, must operate at less than full capacity over longer time periods. This is rather unfavourable from the perspective of emissions and efficiency. Any oversupply arising would first have to be fed into the local grid, whereby a portion of it could also be distributed throughout Europe. However, this is only technically possible to a certain extent in order to maintain the balance of feeding and extraction from the electricity grid which is necessary for reasons of grid stability for the maintenance of frequency and voltage.

One option for solving this dilemma and for dealing with the periodic surplus of electrical energy in a sensible way would be storage. For this, however, larger amounts of storage capacity would be required at certain locations than have been available up to now – with the exception of pumped-storage plants. The construction of pumped-storage plants, however, represents a considerable encroachment into the environment. Experience with other storage technologies has to date been mostly restricted to smaller dimensions, e.g., for guaranteeing the interruption-free electricity supply for sensitive consumers such as hospitals.

THE TECHNICAL OPTIONS

The range of technical storage options is wide. However, although it is possible to cover the whole spectrum of required capacity in principle, there are still no »universal storage devices« which can satisfy a large proportion of storage requirements. Since the direct storage of electrical energy is only possible in capacitors and coils, an indirect path is usually chosen. First the energy is transformed into a different form and subsequently stored in order to produce electrical energy again when required. This is always bound up with extra energy costs and losses through transformation.

The laws of natural science limit the energy density which can be achieved. Even if there are no new storage concepts in sight, there are a number of possible further developments, for instance in terms of materials engineering components. Thus established concepts re-enter the field of vision. Many further developments visibly perform a balancing act between the intended high density of performance and high level of efficiency on the one hand, and requirements on handling, robustness, and cyclical consistency on the other. Improvements in individual features usually go hand in hand with »regression« in other features. For instance, the higher performance density of lithium ion capacitors stands against their decreasing robustness and higher costs.

In the following, an overview is given – with no claims of covering all aspects – of the technical options of energy storage.

MECHANICAL STORAGE FACILITIES

Probably the most well-known, large-scale storage systems include *pumped storage plants*, i.e., hydroelectric plants with a storage reserve of water which is pumped up into a reservoir lying at a higher level during electrical surplus. Pumped-storage plants can make their whole capacity available in peak load periods in about one minute and this at an efficiency factor of between 70 % and 80 %. The focus of future developments is on technically improving existing plants. One future option for building new pumped-storage plants could possibly consist in installing underground plants, which would work with the lower reservoir. Alternatively, salt-water locations could be envisaged as well as freshwater ones. In Japan, there is already a salt-water plant to be used to investigate technical and environmentally relevant aspects.

In *compressed-air energy storage plants* the electrical energy to be stored is used to compress (surrounding) air which is stored in underground caverns. The energy is retrieved through combustion of the compressed air together with gas in a gas turbine. One favourable aspect here too is that the plants can make the stored energy available in a relatively short time; however, the efficiency factor is comparatively moderate at around 50 %. To improve efficiency, adiabatic compressed-air storage devices are being developed. Here the loss of efficiency is avoided by storing the compressed air without heat exchange with the surroundings. To achieve this, the heat arising during air compression is temporarily stored and then used again later to warm the air. The aim is to achieve an overall efficiency factor of about 70 %. From a technical perspective, however, the realisation of an adiabatic compressed-air storage device still requires the development of corresponding system components. Compressed-air energy storage plants have increasingly been the focus of attention recently because they are an option for decentralised, offshore-near storage of wind energy. Along the coast of northern Germany there are numerous salt formations which could be used for compressed-air storage for wind-energy plants. This could mean competition arising for their use with underground gas storage, but probably not with underground CO_2 storage since this is stored at deeper levels (around 800 m and more).

Flywheels – i.e., rotating bodies – also have the advantage of extremely short access times, which are in the millisecond range. For short storage, the efficiency factor attained is 90 % to 95 %, but the losses at rest are relatively high. Their use is under discussion for load levelling in feeding wind energy into the power grid. To stabilise grids, the installation of systems in the megawatt range is being considered, with several flywheels positioned in transportable containers. So far there is one demonstration plant. Flywheel stores are also attractive for space applications (small satellites, space vehicles). Their use in electric vehicles is also gaining new impulses with the development of lighter flywheel stores made of composite materials.

One method which has long been established is the direct storage of *material energy sources* such as natural gas, liquid fuel, and hydrogen. In the case of natural gas, depleted gas or oil reservoirs, aquifers, and artificially desalinated caverns in salt domes are used. Disused mines, however, are also a possible option. The use of underground natural gas reservoirs is being extended. For fuels, *mobile storage facilities* are customary. The most well-known are liquid fuel tanks for petroleum and diesel fuel but also for alternative fuels such as biodiesel. Here the trend is towards emission-dense synthetic models with special coatings. Natural gas tanks on vehicles (steel bottles designed to withstand a pressure of up to 600 bar) should become up to 75 % lighter with the use of aluminium or fibre-reinforced plastic cores, although these new materials are relatively expensive. Gaseous hydrogen can be compressed at high pressure and stored in traditional pressurised gas bottles (max. 200 bar). To reduce the weight, lighter high-pressure containers made of carbon-fibre composite materials are being used increasingly here too instead of steel. However, compression is relatively costly in terms of energy. The alternative – cryostorage of cryogenic, liquefied hydrogen at –253°C – demonstrates a much higher energy density than pressurised gas storage, but the low temperatures present an enormous challenge to storage facility construction, tanking and insulation. The amount of energy required for this corresponds to about one-third of the energy stored.

THERMAL ENERGY STORAGE FACILITIES

For storing heat and cold so-called sensitive heat stores have become established in which the storage medium changes its »felt temperature« when heat is supplied. Sensitive heat stores are »classics«, particularly where water is used as the storage medium in the building area. *Steam accumulators* – loaded with overheated water steam – are used as short-term stores for process heat in industry. In addition they can also be implemented in the supply of electrical energy in the form of buffer stores to copy with power peaks. In addition to pressurised water, thermal oils or molten salts are used to provided industrial process heat (so-called *fluid or solid stores*). Molten salts can be used at over 300°C in solar thermal power plants. While there is extensive experience with operating fluid stores in the industrial area and in solar power plants, solid stores are not yet commercially available but are currently being tested in practical terms.

If the heat is to be stored in long-term hot water stores over a longer period, significantly larger storage capacities are required (several thousand cubic metres). The colder part of the store here is partly submerged below ground level; using special concrete. Gravel-water heat stores can be described as pits in the form of truncated pyramids which are waterproofed with plastic foil and filled with a mixture of gravel and water. The heat exchange is either directly through water or indirectly via tube coils. They represent a cheaper alternative to the relatively costly concrete constructions needed for hot-water heat stores. In *borehole heat stores* too, the heat is stored directly in the ground or in rock layers. These are used in solar installations in buildings to balance out seasonal differences in heating requirements. Their advantages are minimal construction costs and the option of simple extension according to the size of the settlement. However, the steady state in the soil required for economic operation is only reached after three to five years. After the steady-state phase has been reached, it is calculated that about 60 % to 70 % of the stored heat can be made available for use.

In *latent heat storage units*, the stored heat is absorbed by a material by means of the latter changing its phase. These storage media, known as phase change material, PCM, allow the absorption of relatively large amounts of heat or cold and high levels of energy density – and this can be done at a generally constant operating temperature. In comparison to sensitive storage units, it is thus possible to achieve a 10 to 20 times higher density of heat storage. Due to the relatively low heat conductance of the storage medium, however, very large specific surfaces are required, which for instance it is thought will become possible through microencapsulation of the storage media or by means of new composite materials. With latent heat storage units, changes in temperature within a system can be levelled out, temperature peaks avoided and industrial process heat supplied. In the past few years, numerous PCM products have become marketable. In the future, phase change slurries – PCS – will be implementable, which store even higher amounts of energy per volume and thus make more compact storage units realisable.

CHEMICAL STORAGE SYSTEMS

Rechargeable batteries are one of the most familiar energy storage units. The most well-known are lead-acid batteries, which are technically perfected, reliable and cheap. Despite their comparatively low energy density, these are still widely used today. They have a relatively low level of loss of charge and no memory effect, but they are not suitable for fast charging and do not tolerate deep discharging. Lead-acid batteries have a serviceable life of 10 to 12 years today. The sizes used range from small batteries for storing solar energy in a stand-alone operation to large plants for maintaining stable frequency and voltage with an installed performance of 17 MW.

The much lighter *nickel-cadmium batteries* (Ni-Cd batteries) are just as technically perfected today, as well as efficient and robust, and they no longer have any memory effect. Although they have a higher energy density in comparison with lead-acid batteries, taken over the whole spectrum of storage units, this is comparatively low. For this reason, they are increasingly being supplanted by *nickel-metal hydride (NiMH)* batteries. These achieve energy densities that are 30 % to 50 % higher than Ni-Cd systems, are cadmium-free and can be charged and discharged quickly, but they do react more sensitively to overcharging and overheating. In addition, the loss of charge level is higher (50 % and above). They have so far been implemented in electric and hybrid vehicles.

A further development is the *nickel-zinc battery* which, compared with the Ni-Cd battery has higher densities of performance and energy, lower costs and has no toxic components. These will soon be introduced onto the market. The first areas of use are intended for small electronic devices and for interruption-free energy supply in the telecommunications sector. In addition, their use is planned for the future in electric vehicles and in the military sector.

Lithium ion batteries have the highest energy densities, although they are significantly less robust than the above-mentioned battery types. In comparison to the sophisticated concepts of lead acid or Ni-Cd batteries, lithium ion batteries are at an early stage from the perspective of engineering development. They are currently at the focus of international battery research, whereby significant progress could be achieved with the aid of nanotechnology. The *high-performance nano-phosphate lithium ion batteries* can be charged more frequently and within 5 minutes, according to the American manufacturer, and thus would be an attractive option in the future for electric vehicles. A further development is the *lithium ion polymer battery*, which has only been able to establish itself in certain niches despite its somewhat higher energy density. Its use as a prototype together with an electric motor is currently being tested in electric and hybrid vehicles. Another further development is the *lithium titanate battery*.

HIGH-TEMPERATURE BATTERIES

The marked difference between high-temperature batteries and those mentioned above consists in the fact that their high temperatures of over 300°C lead to the electrodes being liquid and the electrolyte solid. This means there are hardly any side reactions, which in turn leads to a comparatively high efficiency factor and negligible electrochemical aging. However, in dormant operation, heating is also necessary which means the requirements on temperature regulation have to be classified as relatively high. The most well-known example is the sodium nickel chloride battery (or ZEBRA battery). These were first developed for traction applications but are also suitable for stationary uses.

The first prototypes of sodium sulphur batteries (NaS batteries) exist, which are currently only used in stationary applications but in principle are also suitable for mobile use. They have a comparatively high energy density but also require an operating temperature of approx. 350°C. NaS batteries are suited for use in power generating plants for load levelling with renewable energy sources. In addition, they an be implemented to reduce power peaks (peak shaving), to ensure uninterrupted power supply and for emergency power supplies. There is a 6 MW plant in Japan. Basically NaS technology offers the potential of lower costs (not yet achieved today) coupled with a high life-expectancy.

The advantage of redox flow batteries lies in the fact that the energy-storing material – a chemical compound – is stored outside the cell. This makes the amount of energy stored independent of the size of the cell and in addition capacity can be increased at any time. The external electrolyte tanks can be filled manually by a tanker. The attraction of this concept lies in doing away with »modular limits« in storage since the amount stored is mainly dependent on the tank content of the electrolytes. Further advantages are offered by the lack of memory effect, no appreciable loss of charge and lack of sensitivity to deep discharge. One particularly interesting version are the vanadium redox flow batteries which are relatively well-developed, implemented in a variety of stationary environments and the most widespread of all redox flow batteries. Stationary plants for load levelling have been realised mainly in Japan, but also in the USA. Overall, the technology is regarded as not yet mature.

Metals with a high energy density such as zinc, aluminium or magnesium can be used in *metal-air batteries*. Their high energy densities make them competitive with lithium ion batteries. In addition, they are compact and can be produced cheaply. On the other hand, their performance is relatively moderate, and they are very sensitive to extremes of temperature and high air humidity. The most well-known example is the zinc-air battery, which will initially become available on the market as a mechanically rechargeable version. Planned are again rechargeable »high-power batteries« for traction applications and stand-by generators.

CHEMICAL STORAGE UNITS FOR HYDROGEN

Hydrogen is the subject of discussion as an option for providing stability in the context of grid stability problems caused by feeding in fluctuating energy sources. It would be produced via electrolysis when there is surplus energy and could flow back in peak periods via fuel cells, gas turbines or combustion engines. In comparison with directly forwarding electricity over short distances and with battery systems, this option has, however, a significantly poorer efficiency factor. Furthermore, storage of hydrogen in compressed or liquid form leads to a further loss of energy.

Alternatively, hydrogen can be stored chemically in a storage medium – i.e., special metal alloys, carbon nanostructures, or salts. This is interesting primarily for traction applications and for portable ones since neither pressure nor cryogenic storage can hold a sufficient quantity of hydrogen at acceptable levels of weight, cost and tank volume. Metal hydride storage units for hydrogen have already been produced, but these are mainly only used for special purposes (e.g., forklift trucks, submarines) on account of the high costs and low gravimetric energy density. There are also prototypes for the automotive sector. The advantages lie in the »freely« selectable, relatively low storage pressure and the high volumetric energy density. The disadvantages have so far been the high weight of the storage medium metal, the relatively low weight-related energy density and the long duration usually required for charging.

Nanotechnology continues to play an important role in hydrogen storage. One new storage unit for hydrogen are so-called nanocubes. This does not refer to the well-known nanostructured carbons (carbon nanotubes) but to an organometallic compound. The material demonstrates an enormous internal surface. Applications envisaged are memory cartridges for mobile devices but also miniature fuel cells in order to be able to produce the desired structures specifically at the atomic level.

THERMOCHEMICAL STORAGE UNITS

For the purposes of heating as well as cooling, *sorption storage units* can be used, with which comparatively high energy densities can be reached. One application are heating appliances for single-family homes. They are also under discussion for use as mobile heat storage units, in order to , e.g., transport waste heat from block-type thermal power stations or waste incineration plants to the user. Sorption materials used in practice are zeolites (alumosilicates) and silica gels (porous form of silicon dioxide) but metal hydrides are also suitable.

ELECTROCHEMICAL AND ELECTROMAGNETIC STORAGE UNITS

Electrochemical capacitors are high-performance energy storage units; they have an energy efficiency factor of over 90 %. The high density of performance and the capacity for rapid charging stand opposed to low energy density and loss of charge. The capacity can be increased if the pore size is reduced to less than one nanometre. Thus in *bilayer condensers* (so-called supercondensers), highly porous carbon nanofibres, aerogels, nanotubes or fullerenes are used. The metal oxides, ceramics or conducting polymers used in ultracondensers lead to even higher specific capacities but also to a lower serviceable life. Here too, ceramics are used which are manufactured from nanopowders. One special type are hybrid condensers, where the overall capacity and thus the energy and performance density can be significantly increased through the use of a battery-like electrode. A classic area of application for electrochemical condensers is the automobile industry in the area of drive systems as well as for on-board systems and operating systems. The first electric vehicles now exist in which the electrical energy is exclusively stored in electrochemical condensers. There is also potential for use in electrically driven locomotives, trams and underground railways. Furthermore, these can play a supporting role in balancing fluctuations in performance. They are also suited to short-term storage of photovoltaic feeding into low-voltage grids. To bridge short-term outages, above all in industry and telecommunication, electrochemical condensers can be used alone or in combination with other energy storage units. Widening the market for these condensers would require further reductions in costs.

In *superconducting magnetic energy storage* (SMES), the electromagnetic field of a superconducting coil is used. The effect of the superconductor lies in the fact that certain materials lose their electrical resistance below a certain temperature and then conduct electric power at zero loss. They can then reach efficiency factors of 90 % to 95 %. The extremely low temperatures, however, make a high degree of cooling performance necessary. Thus in contrast to low-temperature superconductors, so-called high-temperature superconductors are being developed which can be cooled with liquid nitrogen. To what extent these will be successful on a broad scale depends strongly on how costs develop.

OPTIONS FOR GRID SUPPORT

As the German government continues to strive towards a significant increase in the proportion of renewable energies in electricity consumption, the use of wind energy will provide a significant contribution, for instance through the extension of offshore sites. This results in a concentration of available wind energy power in northern Germany which must be fed into the grid in a region with comparatively low electricity demand. Together with the temporal fluctuations which can only be forecast to a limited extent, this means new requirements on the whole power plant park and the supply grids in Germany. It may be that this means that greater storage capacity is wanted in certain locations than was previously available – with the exception of pumped-storage plants. In addition to fluctuations in the load, forecasting errors and power plant outages, fluctuations and forecasting errors in feeding in electricity on the basis of fluctuating energy sources must also be considered in planning power plant deployment and in feeding into the grid. Energy storage units could be of assistance here in reducing these requirements on the local power plant park as well as on grid management.

LARGE-SCALE BATTERIES

One option is the implementation of megabatteries. One of the forerunners here is Japan, where there is already a large-scale battery in operation which is run as a so-called high-temperature battery to compensate fluctuations in regenerative electricity production. The 6-MW plant operated by the Tokyo Electric Power Company is charged with cheap power at night and feeds this back into the grid at peak load times (load-levelling operation). The further development of this type of battery will, however, depend, for instance, on the extent to which the technology improves and the commercialisation can progress with increasing demand. At the moment there are no such systems in Germany. A further possibility is offered by the so-called redox flow systems, i.e., once again rechargeable batteries in which the energy-storing material is stored outside the cell. This technology is a promising one for storing power from renewable energies as the storage capacity can be extended at any time by any amount. The external electrolyte tank can in addition be filled manually by tankers. In Ireland, there are plans to install a first large-scale battery of this type.

COMPRESSED-AIR ENERGY STORAGE PLANT

In addition to the large-scale batteries, another alternative to the pumped-storage plants which is receiving a lot of attention are compressed-air energy storage plants. Commercially, however, there are currently only two plants in operation – one in Huntorf near Bremen (Germany) and one in Alabama (USA). Currently, there are plans for a further, modern compressed-air energy storage plant, also located in the region of Lower Saxony in Germany in order to address the problem of feeding in fluctuating wind energy. This plant is initially intended – as in Huntorf – to operate with gas firing and in a second phase is to be upgraded adiabatically. The new plant should go into operation in 2011, but there are still a number of technical problems to be solved. The location and size of the whole power plant also still have to be settled (probably between 150 and 600 MW). To what extent compressed-air energy storage plants represent a technology that can be implemented on a broad scale is still undecided at present.

VIRTUAL POWER PLANT

The term »virtual power plant« designates a collectively run cluster of regionally distributed (decentralised) small plants such as wind, photovoltaic and biogas plants, small hydroelectric plants, fuel cells, block-type thermal power stations, which are controlled centrally. Storage facilities can also be a part of a virtual power plant. Up to now, this option has been used relatively little and mostly without any link to the competitive electricity market. Concepts envisaged today for virtual power plants aim to allow the operators to participate in the economic success of the decentralised production plants. In order to unite several individual plants into a single virtual power plant, it is necessary to have the most modern information and communication technology. Virtual power plants can provide an important contribution to the stability of the system and cover peak loads.

SHIFTING CAPACITY

A further option for supporting the grid consists in significantly reducing the demands on standard supply by shifting the load peaks to load troughs. This option assumes that the storage of electrical energy is costly in comparison to the storage of thermal energy. It thus seems obvious to give preference to thermal energy storage rather than to electrical energy storage in all cases where the electric load can be shifted. Such options for providing load flexibility consists in distributing existing electric loads to non-electric storage facilities that are already present. These could be decentralised storage facilities such as (night-) storage heaters, refrigeration units, or warm water heaters, which could then be charged with wind energy, not at night but at some time in the course of the day, e.g., where there is a surplus of electricity. These technical systems pay for themselves after a certain time. For example, the electricity supply for cold stores could be regulated such that cheap electricity phases are used without the goods defrosting. This may increase the cost in terms of technical regulation, but it does open up storage potentials which are not inconsiderable when taken overall. This would also apply to energy-heat coupling where electricity and heat are simultaneously generated, whereby the use of the two products could be temporally split by using thermal storage facilities. Load shifting is an innovative field of possibilities which, despite not being new, has gained new dynamics from the perspective of increased integration of fluctuation energy sources. A central feature here is a sophisticated information and communication system to manage loads. There is still a need for research, e.g., with regard to various design types and environmental and cost restrictions.

ELECTRICITY PRODUCTION IN THE »SUN BELT«

The highest amount of solar radiation is found in countries near the equation – in the so-called »sun belt«. It therefore seems obvious to regularly reconsider the storage and transport of solar power produced there to Europe or Germany. There are now new concepts on this topic currently under discussion. Of the options considered, the transfer of solar-produced electrical energy using high-voltage, direct current transfer incurs the lowest costs, both in terms of transport and overall. The costs of transporting liquid hydrogen are higher, and as a result of the necessary conversion steps there is a resulting lower overall efficiency factor (approx. 30 %). However, liquid hydrogen would also be usable in a future traffic sector. The transport costs where zinc-air batteries are carried by ship turned out to be the highest in this comparison (3.16 Euro/kWh) although the transport efficiency factor is high (90 %). Both high-voltage direct current transfer and liquid hydrogen transport have the short-term or medium-term potential to be considered for energy transfer, since they can be regarded by and large as technically well-developed.

STORAGE IN VEHICLES

As a reaction to the changing situation with raw materials, various strategies are pursued in considering how the available classic engine concepts and the development of alternative fuels can be optimised. A further direction is the development of alternative vehicle concepts such as hybrid or purely electric vehicles which rely on (electrical) energy storage facilities. For vehicle operation, batteries are usually used, but also double-layer condensers.

BATTERIES

Electric storage units are used for the operating electric motors for electric or hybrid vehicles, both in the on-board power supply as well as in starter batteries. While nickel metal hydride batteries have already proved their worth when used in hybrid vehicles, their implementation in electric vehicles is only possible with some restrictions. The use of lithium ion or lithium polymer batteries depends on further development of safety features, robustness and costs. They may be suitable for hybrid and electric vehicles but they are still at the prototype stage. Lead accumulators are available as a mass-produced product, also robust and in principle can be used in electric vehicles too, but on account of their weight, they are not the preferred choice in implementation. Driving forces for the development of new storage systems or the further development of existing systems are higher specific energy densities, an increase in the specific performance, and a necessary reduction in costs.

THE PLUG-IN CONCEPT

Electric or hybrid vehicles can be fitted with a bidirectional storage unit and a power adaptor so that they can be recharged via a plug socket when parked. So-called plug-in hybrid vehicles mostly draw their energy from the electric grid. The hybrid design (battery and combustion engine) guarantees functionality, even when the battery is not charged. A fully hybrid vehicle, however, cannot be charged externally but only via the combustion engine. The storage unit in plug-in hybrid vehicles may serve primarily to allow mobile provision of electrical energy, but during the charging periods, the storage units built into the vehicle can be used as stationary storage units in the electrical grid. Since there is usually more time available for charging than is actually necessary for the purpose, the vehicle storage units that are plugged into the grid can be used as a controllable load. Thus a fleet of plug-in hybrid vehicles at rest represents a »larger storage unit« – basically a virtual energy storage power plant – which could be exploited in times of increased energy demand from the grid. The plan is to make this possible using appropriate regulations and controls. This also represents an enormous challenge from the perspective of information and communication. The result would be a relatively large »sector of regulatable consumers« which could be of a size that is attractive to energy supply businesses, too. To exploit this potential, appropriate infrastructural measures are required in addition to the introduction of plug-in hybrid or electric vehicles on a large scale.

CONCLUSIONS AND OUTLOOK

Energy storage facilities hold a key position in energy supply systems. They facilitate the task of matching a temporally and spatially variable energy supply with a temporally and spatially variable energy demand and permit interruption-free electricity supply. It is thus necessary, not only for the integration of higher proportions of fluctuating energy sources to concern oneself more with optimised storage techniques. In the future a higher priority will probably be given to a sophisticated energy storage system – not only in terms of increased integration of fluctuating energy sources – coupled with an efficient information management to coordinate supply and demand and with the use of information and communication technologies than is the case today. In this way, on a technical level too, the normal energy requirement can partly be controlled in the grid.

In energy storage research, the priority is on full exploitation of technical possibilities – with high storage densities and low losses. For today's requirements, e.g., for large storage facilities in the stationary area, there are, however, hardly any pilot plants. Many of the storage techniques named are still at the development stage. Even if there are no new breakthroughs to be seen, there are, however, a range of possibilities for giving the new requirements on storage facilities a new status in the research and development area, too:

> In basic research, proceed on a very broad thematic basis but direct the focus in terms of concrete applications strategically;
> Develop aspects of materials technology, particularly including nanotechnology;
> Systematically analyse grid support (ensuring stability) with energy storage facilities and concretise the corresponding storage requirements;
> Analyse experience with the use of large storage facilities and transfer this to local situation;
> Give more emphasis to heat stores;
> Analyse options for shifting capacity;
> Follow-up international developments.

In an international comparison, the superordinated strategies for action in energy and research politics is ranged around the triad of supply guarantee, environmental compatibility and competitive capacity. They are, however to some extent pursued with different concepts, which has repercussions for the requirements on energy storage facilities. In the USA, the emphasis is on more use of hydrogen while in Europe the focus is primarily on energy efficiency and renewable energies. In the *mobility area*, research is conducted on hydrogen storage facilities and batteries with mostly congruent aims. In the context of *electricity grids*, by contrast there are visible differences in setting the focus. For instance, the use of storage facilities in the USA focuses more on improving the quality of supply overall, while in Europe and Japan storage technologies are investigated in the context of systems – integration of renewable and decentral energy sources. Heat-cold storage is the subject of extensive research activities in Europe and Germany (building sector and local heat systems), while this field of research is no longer funded at the national level in the USA. Overall, at an international level, it can be seen that, within energy research, energy storage systems mainly represent a marginal topic.

The altered situation on the energy market requires a new glance at the options for energy storage. In overall energy concepts to be expected in the future with high proportions of fluctuating energy sources, the demands on temporary storage of energy will tend to become intensified. Energy storage facilities thus deserve increasing attention from society, economics and politics.

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