VDE-Study

Energy storage in power supply systems with a high share of renewable energy sources

Significance, state of the art, need for action

ETG Energy Storage Task Force

VDE

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Imprint

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Cover picture: Siemens
Design: Michael Kellermann, Graphic Design, Schwielowsee-Caputh

December 2008

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Contents

Key results

1) Part of the planned massive expansion of renewable energies to reach 40% of Germany‘s total power generation by 2020 includes providing large-scale storage capacities as one of the measures necessary to safeguard stable grid operation. Otherwise it would be necessary to reduce power generation from renewable energies at times, in the interests of a stable power supply.

2) In principle, storage technologies are available for all tasks in a power supply system with a large share of renewable energies. However, in many cases great efforts will still be required until these technologies are ready to be launched on the market. This will only be possible with immediate intensive investment in the research, development and demonstration of storage systems, with the creation of a suitable industrial basis.

3) The storage of electrical energy generates significant costs with minimum rates at the best of 3 €ct/kWh for hourly storage and 10 €ct/kWh for long-term storage („weekly storage“). The demand for stationary electrical storage should therefore be minimized as far as possible by exploiting alternative lower cost measures such as load management, participation of all power generators (including wind and PV) in grid control, generation management (particularly of CHP plants), use of thermal storage, grid expansion and specific shared use of storage facilities in applications that need storage anyway (particularly e.g. in electric vehicles). The possible contributions of these alternative measures are to be quantified with regard to economic efficiency in a pan-European approach.

4) Electrochemical storage systems (batteries) have relatively short amortization periods, are quick and flexible to erect and therefore constitute one possible solution for covering storage demand over the next few years, particularly in the context of decentralized energy supply concepts. A whole number of battery technologies offer the potential of being successful on the market.

5) Batteries are also deemed to be technology that will play the key role in the success of electric vehicles. If electric mobility should arrive on a large scale (plug-in hybrids and fully electric vehicles), then the batteries installed in the vehicles and integrated in an intelligent load management and billing system could make a considerable contribu-

tion to grid control and to the provision of spare power on a time scale from milli-seconds to a whole day.

6) Economically efficient long-term storage with less than one cycle per week for balancing out general weather conditions and seasonal fluctuations seems scarcely conceivable based on current criteria. However, only this kind of long-term storage has the potential of being a sustainable replacement for thermal power stations when it comes to the provision of reserve power. By comparison, hydrogen storage systems or the conversion of today‘s large reservoirs into pumped storage systems are the most cost-effective technology options.

7) Central large-scale storage systems (pumped storage, compressed air, hydrogen) involve technologies that still demand intensive investment, resulting in very long amortization periods. There is a correspondingly high commercial risk because it is difficult to estimate the demand, as well as the role of competing technologies. Investment reticence must therefore be expected here, which can only be countered by stable general political conditions. Synergetic effects are anticipated from using hydrogen as fuel and in the long-term storage of „central“ offshore wind energy.

8) In the long term, it will be necessary to stipulate the general conditions for operating energy storage facilities in terms of statutory regulations and with regard to energy management. Here there is an urgent need for start-up grants or incentive systems in the initial phase.

9) There is an urgent need to expand university and non-university research, also with regard to training and qualifying the necessary manpower.

10) Altogether Germany and Europe only offer inadequate infrastructure conditions for the research, development, demonstration and industrial production of storage systems. North America, Japan and Australia show far more advanced levels of development.

1. Introduction

Storage systems for electrical energy are used in many different applications and dimensions. These extend from micro-systems for use in the home and on the transport sector through to large-scale facilities as part of the energy supply.

This study concentrates essentially on the use of storage facilities in electrical energy supply systems. There is an urgent need to act here on account of two major challenges facing society: a) to achieve greater independence from imports of primary energy sources, and b) to comply with the contractual obligations ensuing from the Kyoto Protocol for drastic reductions in carbon emissions. Together with improving the efficiency of power generation and consumption, this results in particular in the need to make greater use of the country‘s own renewable energy sources.

When power is fed into the electricity grids from regenerative sources that are subject to seasonal and meteorological influences, such as solar and wind power, there are inevitably great deviations between the fluctuating input power and the demand for power resulting from the working and living patterns of the consumers. On-going expansion of resource-dependent power generation technologies that cannot be planned exactly in advance and are not always going to be available exactly in line with load demand, results in an increasing need for short-term flexibility. Deviations are also inevitable in the forecasts between the anticipated power and the actual power coming from renewable sources. Only rarely do combined heat and power systems (CHP) see a coincidence in time between the demand for power and heat. But in this case, preference should be given to power-led operation with local heat storage to minimize the need for electrical storage as far as possible.

In other words, corresponding control and balancing will be necessary to stabilize the grid; this task is performed today mainly by the remaining thermal power stations. However, they become less efficient as the demand for control increases (partial load operation) with an increase in their specific emissions, accompanied by an increase in wear while the life cycle decreases. This results in growth in the specific power generation costs. Consideration should be given here to the fact that many of these power stations have already reached the end of their life cycle and investment in new power stations is being reviewed from the point of view of long-term economic efficiency under these changed general conditions.

In principle, energy storage facilities are a suitable means of decoupling the supply and demand for electrical energy. Measures are also possible here on the load side (load management), but this would entail rethinking the current concept of always having power available on demand in practically any required quantity. Suitable grid expansion can also help balancing on a national scale in the framework of the corresponding possibilities. In terms of finding a solution that is tenable for the national economy as a whole, it is necessary to strive for the best possible combination of grid expansion, load management, the use of storage facilities and the possibility of making fast adjustments to power station output.

In the context of further expansion of renewable energy sources, the question arises as to how to cope in future with longer term fluctuations in the supply with surplus and deficit situations lasting several days to weeks. Here again, storage facilities used on a large scale could help to solve the problems.

The challenges mentioned at the beginning will also make it necessary to rethink the energy situation on the transport sector, i.e. moving away from fossil fuels. A growing share of vehicles driven by electric power will also increase the demand for mobile energy storage systems. In principle this means batteries – and/or hydrogen – used in fuel cells. Depending on the rate at which electric mobility expands, this will open up considerable potential for separating power generation and power demand, also resulting in synergetic effects for the power grid.

The task of this study was to provide an overview of the currently foreseeable possibilities for storing energy for the supply of electricity and to evaluate their technical and commercial significance with regard to various use scenarios. The intention is to provide the general public and the political sector with balanced information and recommendations as to how to solve the increasing problem of aligning the load demand and generation of electrical energy that arises from expanding the use of renewable energy sources, with an indication of the research and development initiatives that should support this approach.

2 Description of the problem and the role of energy storage facilities in systems with an increased share of renewable energies

2.1 Challenges from fluctuating input

In a power supply grid, the overall generated power must correspond to the demand at every moment in time. Deviations could be detrimental to supply reliability, or even cause the grid to collapse. Local imbalances change the load flows in the grids and can result in an overload on the power lines.

The energy stored in the rotating masses of the power station generators (mass inertia) dictates the permissible delay in load distribution. Today as a rule, inputs made via power inverters (photovoltaic (PV) systems and many wind turbines) do not have any such characteristics, thus making greater demands of power supply stability.

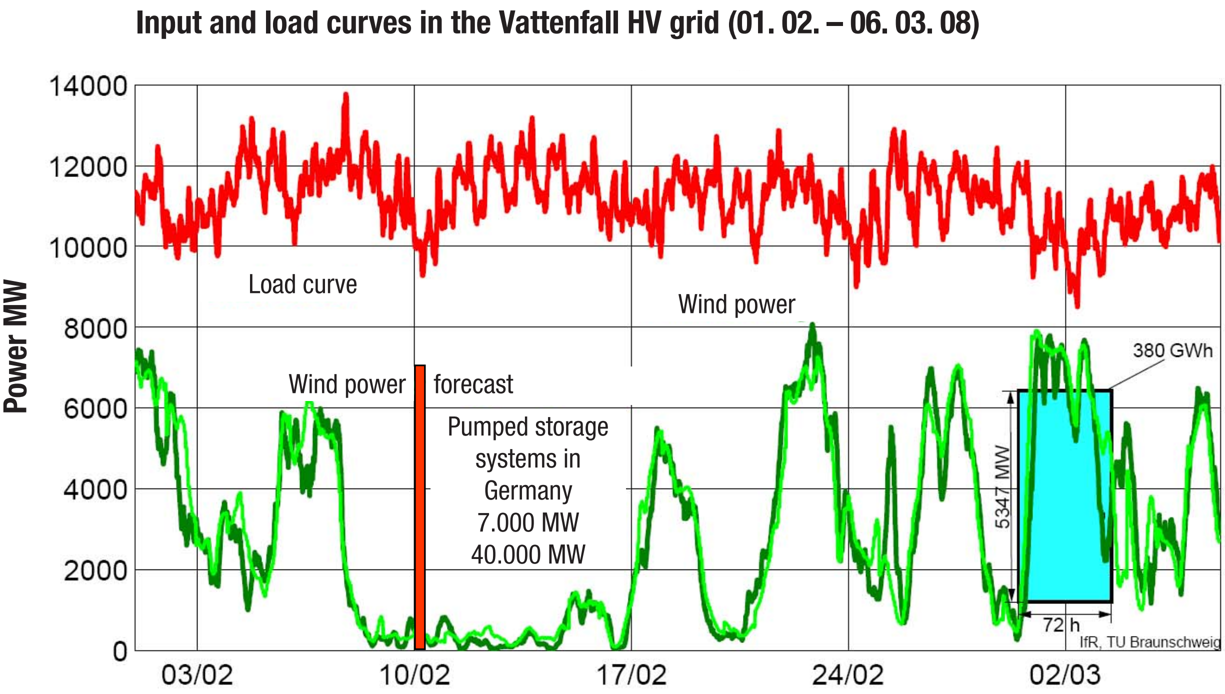


Fig. 1: Wind energy input and load curves in a control zone

In the case of most renewable energy sources (wind, sun, running water), no storage is formed: on the contrary, electricity is obtained from the current supply of power (wind speed, sunshine intensity, water current) which naturally fluctuates and does not coincide with the corresponding demand (see Fig. 1). When there is not enough energy supply, the deficit has to be made up by the remaining thermal power stations. In turn, a surplus of renewable energy has to be compensated by throttling or shutting down thermal power stations, on account of the priority given to renewable energies as a carbon-free energy source. Today already, situations emerge where the power generated by wind energy exceeds the load demand (in times of low load). If there is no possibility of exporting power, the consequence would then be that no thermal power stations should then be on the grid, and even so it would be necessary to throttle power generation from renewable energies and CHP.

At the moment the scope to which renewable energy sources are currently used means that it is still possible to compensate these fluctuations with the existing conventional regular power stations (mainly thermal power stations based on fossil energy sources). But these become less efficient in partial load operation where greater control is required, with an increase in the specific emissions from these power stations. At the same time there is an increase in wear and thus in costs for maintenance and servicing, while the life cycle decreases. Moreover, the number of full-load hours operated by these power stations is reduced. Altogether, this causes an increase in the specific power generation costs. Here it must be borne in mind that the old power stations are generally less efficient and not rated for load follower operation.

Any further increase in the generation of power from renewable energy sources will mean that the available control capacities are no longer sufficient. What's more, some of the thermal power stations will have to be closed down in the foreseeable future for age reasons. Consideration must be given to the changing general conditions when renewing the power station fleet, as this kind of investment has to be made with a long-term perspective.

For a long time now, pumped storage hydroelectric power stations have been used to help with grid control. But the corresponding storage facilities available in Germany (about 7,000 MW with a capacity rated as a rule only for 4 to 8 hours use) are by no means sufficient for this to be the sole means of compensating for fluctuations. The Vattenfall control zone would need the entire available storage capacity, and this for more than 10 days and not just a few hours (see Fig. 1). Consequently, great storage capacities will be needed in future to permit a transfer in time of energy from high-supply periods to low-supply periods.

The geographical restrictions of sites for new pumped storage hydroelectric power stations and their low level of acceptance in the population at large demand new approaches to aligning generation and load and thus also to storing energy. Together with long-term storage facilities with large storage capacities, this also includes new methods of load or generation management.

Without adequate storage capacities, in future power generation from fluctuating renewable sources will also have to be integrated in grid control in the short-term context. In the interests of stable grid operation, this would then also entail operating a wind turbine for example in throttled mode in order to supply positive and negative control power, even if this causes a slight decrease in proceeds for the operator. This is already in practice in other countries, e.g. in Ireland. According to the previous EEG (Renewable Energies Law), this is currently only permitted in Germany in cases of grid-related bottleneck situations.

But according to the new EEG, from 2009 the operators of wind turbines can receive an additional system service bonus if they participate for example in holding the frequency. Bio energy offers a limited scope for controlling energy generation from stored stocks, but consistent use is not yet made of this possibility. Together with more flexible input remuneration, this would also entail forming clusters of the small plants so that they can operate on the various markets as a virtual power station. However, the possible share of power that can be produced with this kind of system is controversial as they must be seen in part to compete with food production and with the transport sector. Up to now and probably in future too, wind turbine power generation is Central Europe's prime technology for generating power from renewable energy sources. In future, offshore systems will be the main option for expanding regenerative energies. The DENA grid study provides concrete figures for the related consequences. Costs exceeding €1 billion are named for necessary grid expansion through to 2015. In addition, the demand for control power is calculated at 14.5 GW for coping with transient generation surplus (Fig. 2). The corresponding costs will be far higher than for expanding the grid. While the DENA grid study presumes that alignment will be possible in the presumed period without additional storage facilities, it is foreseeable this will no longer be feasible without storage in subsequent expansion phases (40% share of renewable energies by 2020).

Initially it would seem appropriate for energy storage systems to be located as near as possible to the point of generation in order to limit the necessary grid expansion, e.g. on the coast in order to absorb wind energy from the offshore wind farms.

But as the following chapters will show, under certain general conditions grid expansion can constitute a commercially interesting alternative to storage facilities. The aim therefore is to find the best possible technical and commercial solution between the scope of grid expansion which will be necessary in any case, and the use of storage facilities. This will also have to give due consideration to the possibilities of exchanging energy with neighbouring countries running similar expansion programmes for wind energy.

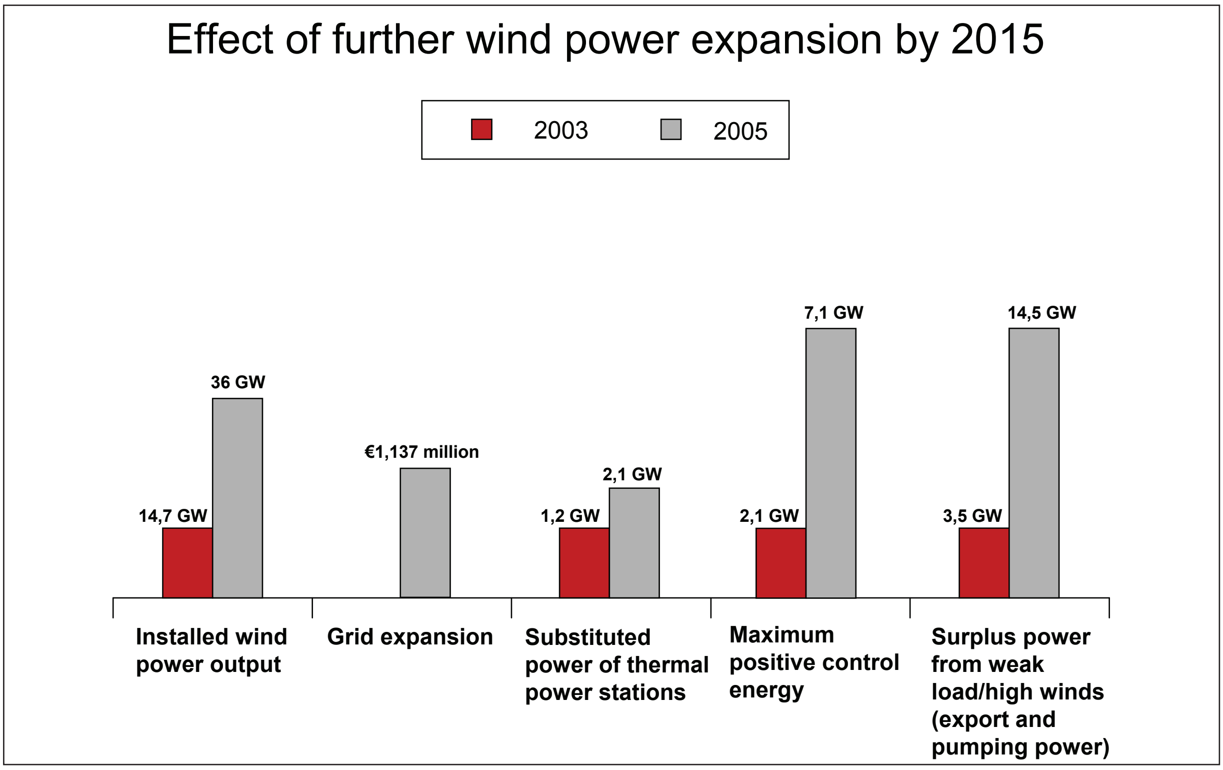


Fig. 2: Results of the DENA grid study

2.2 Infrastructure development

The possible use of energy storage systems depends to a great extent on the structural circumstances. This is why this particular study looks in particular at various aspects pertaining to the very special situation in Germany.

The electricity supply is part of a country's infrastructure. It depends primarily on the industrial development of the country and on the geographical circumstances.

Germany is integrated in the UCTE grid which covers almost all of Europe. Widespread compensation even of large power fluctuations is therefore conceivable as an alternative or supplementary measure to storing energy. But here consideration has to be given to the fact that all European countries are pursuing similar concepts for the expansion of regenerative energy sources, so that surplus or deficit situations can be expected to occur on a large scale. We must therefore expect that in future, ever increasing distances have to be bridged to connect regions with unrelated meteorological conditions and possibly differing load behaviour. Various studies show that many critical fluctuations, particularly in wind energy, can be compensated extensively on a European scale. However, for a long time now the general public has objected to any further expansion in overhead transmission networks, which means that any fast provision of the necessary transmission capacities will not be possible without corresponding political support. High voltage direct current transmission (HVDC) constitutes a possible technical alternative to the current three-phase systems when it comes to transmitting large quantities of electricity over large distances with the lowest possible losses.

2.3 Energy management aspects

The electricity supply has to fulfil differing and partly contradicting optimization targets. As a rule, low-cost energy is to be provided. On a free market, this is warranted by free access for the largest possible number of participants, together with a high level of liquidity. In physical terms, the electricity supply must be highly reliable. The safety- and security-related significance of the electricity supply demands availability of nearly 100%. This is supported by the use of control energy and reserve power.

Scheduled energy and fluctuating input
Scheduled energy constitutes the normal electricity supply for the public provision of energy. It faces strict competition through public trading. Today energy storage systems derive their financial proceeds from fluctuating price spreads by taking up energy at low prices and discharging it into the grid again when the prices are on a high level. Following conclusion of the trading transactions, scheduled energy is used to plan system operations. It is superimposed with the input from fluctuating power generators, such as wind energy, which input can deviate from the forecast. This can constitute a considerable complication or impediment to system management.

Control power
Even without fluctuating input, control power has to be available on various time scales in order to balance out the system. While the expansion of the UCTE network resulted in a decrease in the specific demand for control power, this development has been reversed again by the increase in fluctuating input. Energy storage systems can generate a possible profit contribution on the markets for control energy. On the other hand, this puts them in competition to the rotating reserves from the entire power station park which currently still has very high capacity, together with favourable expenditure levels.

Backup power
In addition to the continuous demand for control energy by the minute, reserve energy is only needed in rare emergency situations, although such situations are meanwhile apparently occurring with greater frequency. As a rule, this entails providing high power for a limited period of time (hours to days). As a rule, systems with specific low power costs (gas turbines) are used for this purpose.

3 Possible uses for energy storage systems: how they work and possible strategies

Storage technologies are used as a central feature in the transmission network, on a decentralized basis in the distribution networks and also independently of the grid, depending on the various powers, storage capacities and tasks.

3.1 Applications in transmission networks

In the large power range of medium to long-term storage, there are basically three main areas for using stationary storage technologies in the grid system.

3.1.1 Central large-scale storage facilities for energy trading and control tasks

A central storage facility is used for shifting low-cost off-peak generation from power stations with low variable power generation costs (also including wind turbines) to peak times of day with high consumption and high electricity prices. The investment costs of the storage system are recouped by the differences in price between the storage price (taking into storage) and the sales price (releasing from storage), after deducting the efficiency losses and operating costs.
Fig. 3 shows the typical use of a storage facility on the basis of the wholesale market as illustrated by the EEX prices from 14 July 2002 (Sunday) to 20 July 2002 (Saturday). The low price level on Sunday and during the night are used to take energy into storage, while it is then released again at the high-price times during the working week.

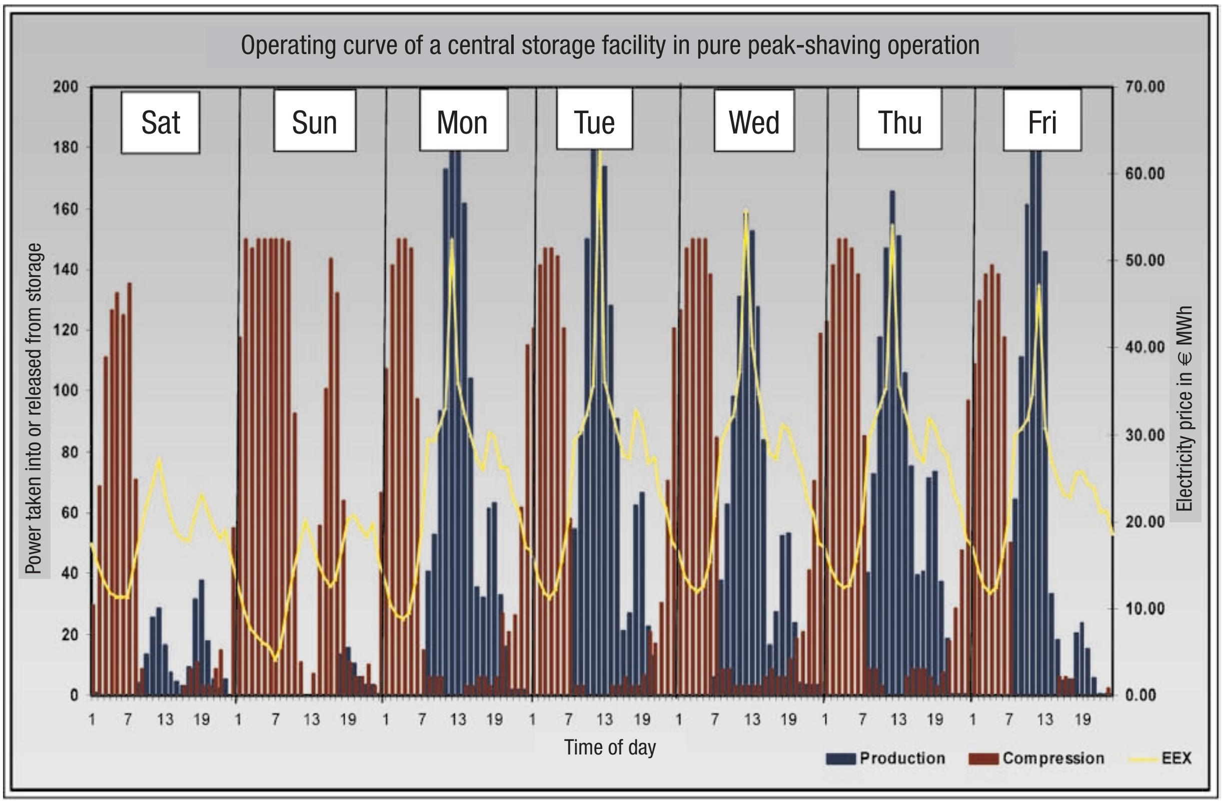


Fig. 3: Typical curve of a storage facility on the wholesale market, illustrated by a compressed-air storage system (source: EWI). “Compression” refers to periods when energy is taken into storage and “production” refers to periods when it is released into the grid again.

The storage facility tends to smooth out price fluctuations occurring actually during the day, as it increases the demand for electricity at low-price times and provides the market with additional quantities of electricity during the high-price times. This indicates that increasing storage capacity will reduce the price difference, so that in the end these storage facilities could lose their financial justification. This is offset by the increasing need for compensation resulting from the growth in the share of fluctuating electricity producers. It is important to keep an eye on the overall development, particularly in the case of long-term investments in storage projects.

If a storage facility can satisfy the corresponding requirements, the operator can offer both control energy and other system services on the relevant markets. Storage facilities are in a position to provide the following system services:

- Positive and negative primary control (provision within 30 s for a period of up to 15 min)
- Positive and negative secondary control (provision within 5 min for a period of up to 1 h)
- Positive and negative minute reserves (provision within 15 min for a period of up to 4 x 15 min)
- Reactive power compensation (possibly also without active power supply – phase-shifting operation) and
- Black start of grids or parts of grids following grid failure

At the moment, only battery storage systems are capable of providing primary control reserves in view of the required dynamics. Pumped storage systems are frequently used to provide secondary control power. While other storage technologies such as compressed-air storage systems are more flexible than other thermal power stations, they take about 15 minutes to provide their full power and are therefore only suitable for minute reserve supply.

Reactive power control is always possible with active power output or intake (charging or discharging). But it is also frequently worth looking at an operating mode where reactive power can be supplied or taken up even without active power (phase-shifting operation). At the moment, this is only possible in pumped storage hydroelectric power stations or in systems with a full power converter. To this end, in compressed-air storage power stations the turbine would have to be decoupled from the generator. Black start capability applies to almost all storage technologies. These profit contributions for storage facilities are almost negligible as these services are in very great supply in extensive grids.

3.1.2 Central large-scale storage system for bridging longer slack periods and for seasonal compensation

Any further expansion of renewable energy sources gives rise to the question as to how to cope with the seasonal fluctuations in supply, surplus and deficit in future. Storage facilities erected for this exclusive purpose would have to be very large (discharge periods lasting several days to a few weeks with a power demand for Germany of altogether several 10 GW), but would only be used for a few charging/discharging cycles each year. Given the generally high investment costs, energy storage is more profitable when the systems are used more frequently, so that here the best solution could consist of combined storage utilization. This could consist of simultaneous involvement in daily recurring control tasks (or, in the case of hydrogen cavern storage, co-utilization of the energy source for other purposes). Storage concepts where a clear increase in capacity only entails a relatively low level of additional costs are predestined for this purpose.

3.1.3 Buffer storage and grid input management

Another approach that has frequently been discussed but not yet implemented in practice consists of using storage facilities that have been attributed directly to a generation unit as buffers (power station or wind farm). However, in an extensive grid it is more appropriate to install large-scale storage facilities in the grid in view of scaling and compensating effects.

The concentrated expansion of power generation from offshore wind energy along the North Sea and Baltic coasts will in future increase the need for transmission capacities from the coast to the consumption centres (central and southern Germany) and entail expansion of the grid. Even though necessary grid expansion may be delayed by the elaborate permit procedures, this would presumably only result in temporary financial advantages for local buffer storage systems which would probably be less than their financial life cycle.

3.2 Decentralized applications

In the context of the on-going structural transformation of the electricity supply, in future, energy storage systems boosted by the development of new storage technologies are expected to fulfil a wide range of applications, particularly also when it comes to the distribution networks.

Future energy supply concepts will be characterized by an increasing share of electricity producers using regenerative energy sources and decentralized CHP systems supplying an input of power into the medium and low voltage grids. The grids and the associated system services have to take account of these change processes. This is in particular also an issue in the EU’s “Smart Grids” strategic research agenda that describes research in this field. Accordingly, a growing demand for storage facilities can be expected in distribution networks parallel to the growth in decentralized energy supply. This applies in particular to systems based on regenerative energies such as the sun and the wind, which only supply heat or power when this energy happens to be available. Storage facilities are also advisable for CHP systems to decouple the quantities of power and heat simultaneously generated in these processes in order to adapt the supply to the corresponding demand.

There are many possible uses for energy storage facilities, extending from harmonizing the supply of energy through to bridging short-term supply interruptions with sensitive customers. It goes without saying that in addition to local control tasks, decentralized storage facilities distributed in the grid can also be grouped together in clusters ("virtual large storage facilities") for use in overriding tasks in the transmission network so that they are also involved in the provision of system services. Fig. 4 shows the range of possible uses.

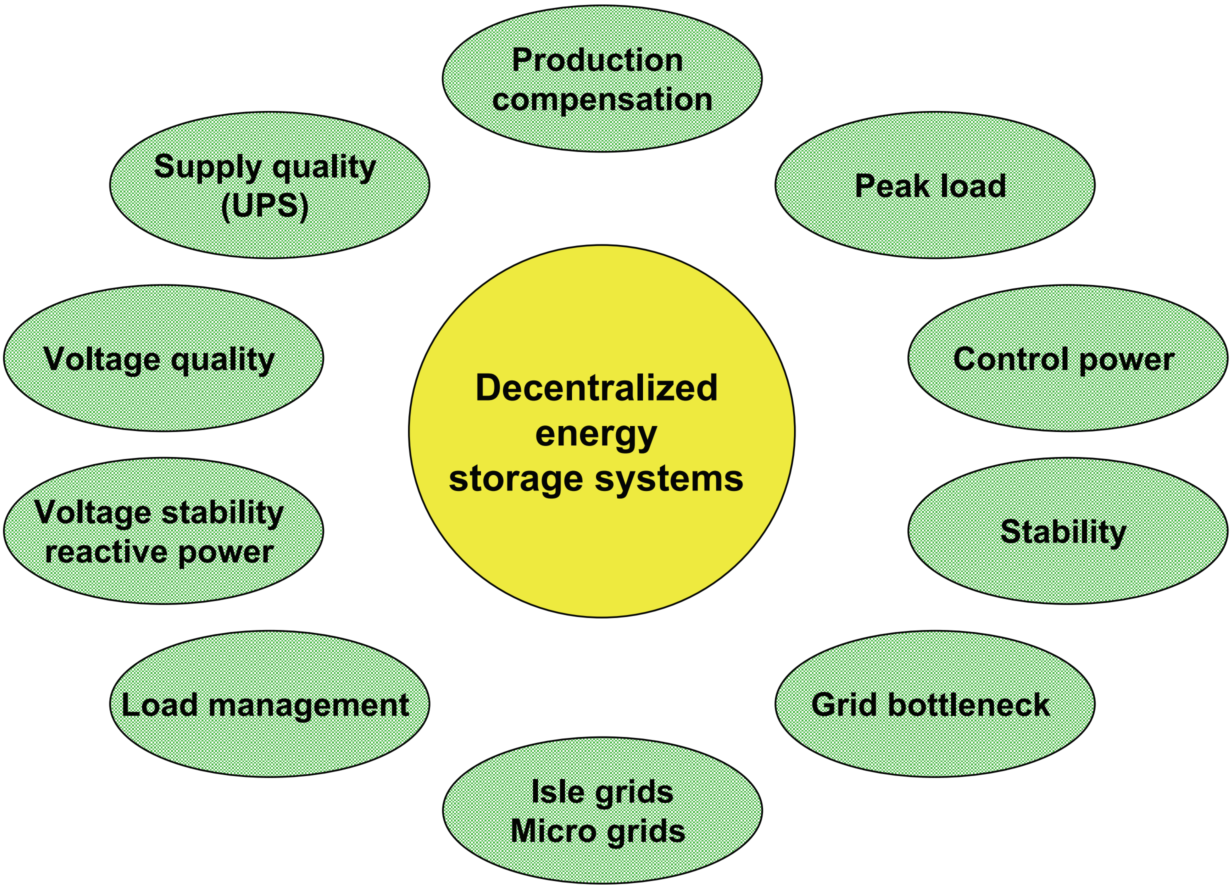


Fig. 4: Possible uses of decentralized energy storage systems.

Multifunctional storage systems

In many cases it will be possible to use a storage facility for not just one but several of the above applications. For example, an uninterrupted power supply system (UPS) that is only needed extremely rarely in the case of grid disruptions could be used for the rest of the time to reduce grid repercussions or also be involved in the provision of system services in the scope of the facility' possibilities, integrated in a virtual power station. Using one single storage system for several tasks naturally makes high demands of storage management so that e.g. the primary UPS task can be fulfilled when there is an interruption in supply. It may therefore be quite appropriate to opt for a somewhat larger storage capacity as this kind of multifunctional use can clearly improve economic efficiency. The choice of a suitable storage system depends in particular on the differing application scenarios. This category of storage system also includes batteries in future electric vehicles. Their prime task is to drive the vehicle. But while they are connected up to the grid for recharging, they can also perform a wide range of other tasks (see section 4.6).

4 Storage technologies: state of the art and potential for development

In the context of expanding the use of renewable sources of energy, various forms of energy or storage technologies can be considered in order to store energy:

- Potential energy with water storage
- Mechanical energy with compressed-air storage
- Electrochemical energy with batteries and
- Chemical energy, e.g. with hydrogen (compounds)

This study will be looking primarily only at electrically reversible storage, i.e. technologies where electrical energy can be added and later removed again as required after deducting the losses, even if the energy is stored in another form, e.g. pumped storage or batteries. In other storage systems, energy is used for non-electrical demand, e.g. for heating (electrical night storage heaters) or for operating refrigerated warehouses.
The full version of the study describes the technologies in detail. In addition, it also looks at other storage possibilities.

4.1 Pumped storage hydroelectricity power stations

Pumped storage hydroelectricity power stations are used today above all in the grid to make use of hydroelectric power during peak load periods, to guarantee the balance between demand and production at any moment in time, and to ensure that there is a steady flow of energy being generated in the thermal power stations.
Over the last two decades, the original tasks of pumped storage hydroelectricity power stations have been transformed increasingly from daily energy processing and covering peak loads to fulfilling the role of controlling power frequency, i.e. providing secondary control power.
The power levels and storage capacities currently available in Germany are by no means sufficient to cover longer-term compensation for fluctuating wind energy. At present, pumped storage systems operate with about 7,000 MW and discharging periods of a few hours, used for the most part in a daily cycle for frequency regulation and power trading. The total storage capacity amounts to about 40,000 MWh.

Large pumped storage systems can be found in particular in the alpine regions of neighbouring countries. At present, consideration is being given to the possibility of adding a pumping function to the large seasonal storage facilities located there.
Pumped storage systems are capable of achieving cycle efficiency levels in the range of 75 – 80%. Start-up times amount to a few minutes. For example, Goldisthal pumped storage hydroelectricity power station takes 75 s until it produces full turbine power and 185 s for full pump power (from a standstill in each case).
Pumped storage hydroelectricity power stations operate with well developed technology on high efficiency levels, offering high availability and a long service life, with only little potential for further technical development.
Developments in pumped storage hydroelectricity power stations are moving towards greater drop heights or heads and larger power station powers. Even so, the capital expenditure involved still requires investment on a very high level, given the small quantities and high share of construction costs. Today, modern pumped storage systems with converter-fed machines also offer the possibility of control in pumping operations.
Pumped storage hydroelectricity power stations are tied to topographic requirements which are difficult to fulfil and entail major interventions in the landscape, as the upper and lower reservoirs usually have to be man-made. Permit procedures can therefore consume great amounts of time and money, and will be subject to extensive conditions. Possible sites are also far removed (> 500 km) from areas with a high potential for wind energy.
Given the limited geographical availability of suitable sites in Germany and the current lack of acceptance in the population at large, no notable increase can be expected when it comes to pumped storage hydroelectricity power stations. Should there be any necessity here for additional storage power and capacity, it will be up to the political sector to create the required general conditions, similar to the permit procedures for new transmission lines.

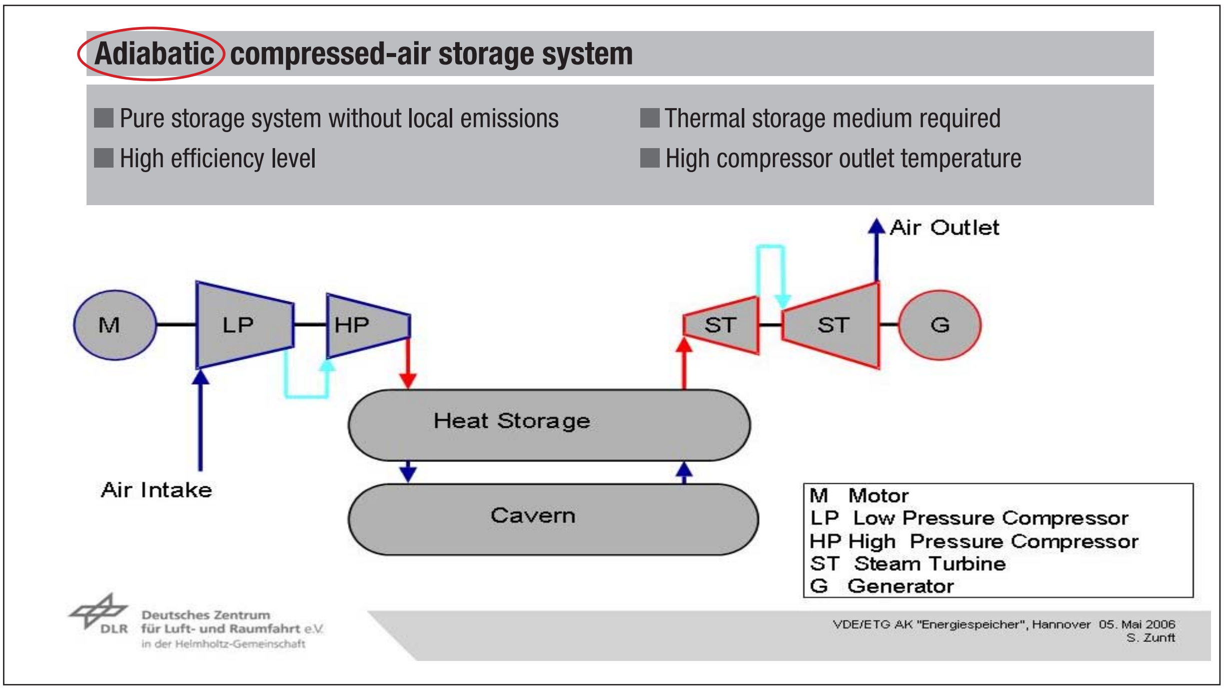
4.2 Compressed-air storage power stations

Compressed-air storage power stations – also referred to as CAES power stations (compressed-air energy storage) work in a similar power range and with similar operating characteristics to pumped storage hydroelectricity power stations. The target applications for this kind of storage technology are therefore also similar.
In the case of CAES power stations, compressors are used to store the energy in an air reservoir, preferably man-made salt caverns, by

bringing the air in the reservoir up to an increased pressure level. The energy is released from this kind of storage in suitable turbines that release the pressure from the compressed air. There are two different kinds of CAES: “diabatic” and “adiabatic” CAES.

With diabatic CAES, the compression heat generated during the charging process is discharged into the atmosphere by inter coolers and therefore lost for the process. During the expansion phase, air thus has to be heated up again in additional gas-fired burners. Taking account of the additional fuel required, the efficiency levels of corresponding storage systems are limited by process criteria to the range 42 – 54%, depending on whether the waste heat from the gas turbine is used to pre-heat the air.

By contrast, adiabatic compressed-air storage power stations (ACAES) use an additional thermal storage medium for heat management. In this case, the compression waste heat is coupled back into the discharging process so that there is no need for an additional supply of heat. Corresponding storage systems therefore operate without any local emissions and can achieve overall efficiency levels of up to 70%.



Adiabatic compressed-air storage system

- Pure storage system without local emissions
- High efficiency level
- Thermal storage medium required
- High compressor outlet temperature

M	Motor
LP	Low Pressure Compressor
HP	High Pressure Compressor
ST	Steam Turbine
G	Generator

DLR Deutsches Zentrum für Luft- und Raumfahrt e.V. in der Helmholtz-Gemeinschaft

VDE/ETG AK "Energiespeicher", Hannover 05. Mai 2006
S. Zunft

Fig. 5: Schematic diagram of an adiabatic compressed-air storage power station.

The nominal power of a unit ranges between 100 and 400 MW. In the concept featured here (Fig. 5), the motor/compressor power can be chosen regardless of the turbine/generator power. The storage capacity is defined by the size or number of underground caverns. Storage caverns can be generated in underground salt domes without mining by chemical leaching. The additional thermal storage medium required in the adiabatic power station type is rated according to the quantity of heat required for expansion. In principle, liquid or solid storage media are chosen for this purpose.

The fast starting capability of 15 minutes required for participation on the control energy market (minute reserves, tertiary control) can be achieved by both types of power station.

Up to now, two diabatic CAES power stations have been built worldwide and have been operating successfully for many years. Adiabatic compressed-air storage technology is currently in an advanced concept stage and can be expected to be implemented in the long-term. In principle, the technology required for the individual components is available, but high demands are made of the actual design in concrete terms. It can be presumed that clear preference will be given to the adiabatic version when CAES power stations are to be erected in Europe in future, which is why this study also only gave closer attention to this version.

The potential use of this technology depends essentially on the availability of suitable salt formations for producing the storage caverns, with areas such as Europe’s north-western coasts in particular offering favourable conditions in accordance with previous study results. However, it should be noted that availability is restricted by the competing use of these caverns for natural gas storage.

4.3 Hydrogen storage systems

Although hydrogen is used in great quantities as an energy medium in industrial settings, up to now it has not played any notable role in currently established energy systems – neither as final energy medium for the user, nor as an energy storage system. But this could change in future.

The further expansion of renewable energy sources will necessitate large storage facilities that can store energy for a longer period of time (several days to weeks during periods without wind and to compensate for seasonal differences in generated power) while still offering high power levels. Corresponding storage systems must offer power levels in the GW range and capacities of several 100 GWh, i.e. with a discharging period ranging from several days to weeks. While these power levels can also be achieved with conventional pumped storage and compressed-air storage power stations, these cannot offer the required storage capacities.

Hydrogen would appear to be particularly suitable for being stored under pressure in underground salt caverns, on account of its relatively high energy density. Hydrogen can be used to extract about 60 times more effective energy (electrical energy) from comparable storage caverns than compressed air systems (CAES) (see Fig. 6). Hydrogen caverns are state of the art in the petrochemical industry; in addition, extensive experience is available from the construction of natural gas caverns. In principle it would appear possible to use current natural gas caverns to store hydrogen in future after certain modifications.

Hydrogen can be generated from electrical energy by means of electrolyzers. The use of high-pressure electrolyzers is conceivable where hydrogen leaves the electrolyzer at a pressure of 5 MPa or more, thus considerably reducing the compression workload. There is a need for further development here to bring the high-pressure electrolyzers up to the required power levels. Compression to a cavern pressure of approx. 15 MPa and above can be achieved with conventional compressors. There is currently controversial discussion about how flexible electrolyzers will be in reacting to supply fluctuations in the context of load management in order to contribute to providing control.

Gas-fired engines, gas turbines, gas and steam power stations and in principle fuel cells can be used to convert the hydrogen back into electricity. When hydrogen is used in today’s turbines that were developed for natural gas, it is still necessary to add quantities of natural gas. Further development work is already in progress on converting these turbines into pure hydrogen turbines.

Initial approximations estimate an efficiency level of 65% for electrolysis, 97% for compression and 60% for gas and steam power stations, resulting in an overall efficiency level of just about 40%.

The low specific costs for the actual storage medium (hydrogen, cavern volume) mean that together with seasonal water storage facilities retrofitted with pumping functions, this is the only technology suitable for use in situations where the energy is not used on a daily basis but on average less than once a week.

Such storage facilities can become increasingly significant for balancing out general weather conditions. In addition, hydrogen can also be put to direct use, for example in the transport sector or in other industrial processes. And so it is not always necessary to convert the hydrogen back into electrical energy. This means that financial synergetic effects are therefore expected from the direct use of hydrogen as fuel.

4.4 Comparison of storage capacities

Comparison of the corresponding suitability of the various storage technologies with the high geometric storage volume for various use scenarios looks at the specific storage capacity, including the efficiency level. The table shows the net storage densities referred to volume. The far greater capacity of hydrogen storage results from the chemical binding energy.

Comparison of the volumetric storage capacities

	Specific net storage capacity	Efficiency level
Pumped storage power station	0,7 kWh/m³	80%
Adiabatic compressed-air storage power station	2,9 kWh/m³	70%
Hydrogen storage (electrolysis storage reconversion)	187 kWh/m³	40%

Presumptions

Pumped storage power station	Drop height (head)	300 m
Adiabatic compressed-air storage power station	Pressure cycle	2 MPa
Wasserstoff-Speicher	Pressure cycle	11 MPa

A storage facility with the same geometric total volume of 8 million m³, which corresponds to the largest natural gas cavern storage facility currently available in North Germany, would therefore the storage capacities indicated in Fig. 6. By comparison, Germany's largest pumped storage hydroelectricity power station Goldisthal offers a storage capacity of 12 million m³. This example demonstrates the finite capacity of future large storage facilities. Storage caverns of this capacity cannot be added at will. In addition to the cost factor, the limits also result from the availability of suitable geological formations. Fig. 6 also illustrates the magnitude of the featured storage capacities for the presumed storage volume of 8 million m³ compared to the wind power input over a period of about three weeks in the transmission grid of E.ON Netz AG in early 2007. It clearly shows that the use of pumped storage and compressed-air storage power stations will be restricted first and foremost to compensating for short-term forecast deviations respectively for providing control energy.

These capacities are not sufficient for any longer-term compensation of fluctuating wind energy production. By contrast, underground hydrogen storage facilities allow the same geometric volume to be used for compensation over far longer periods of time. This indicates that only hydrogen storage systems offer the possibility at least in technical terms of making predictable use of fluctuating wind energy over longer periods of time.

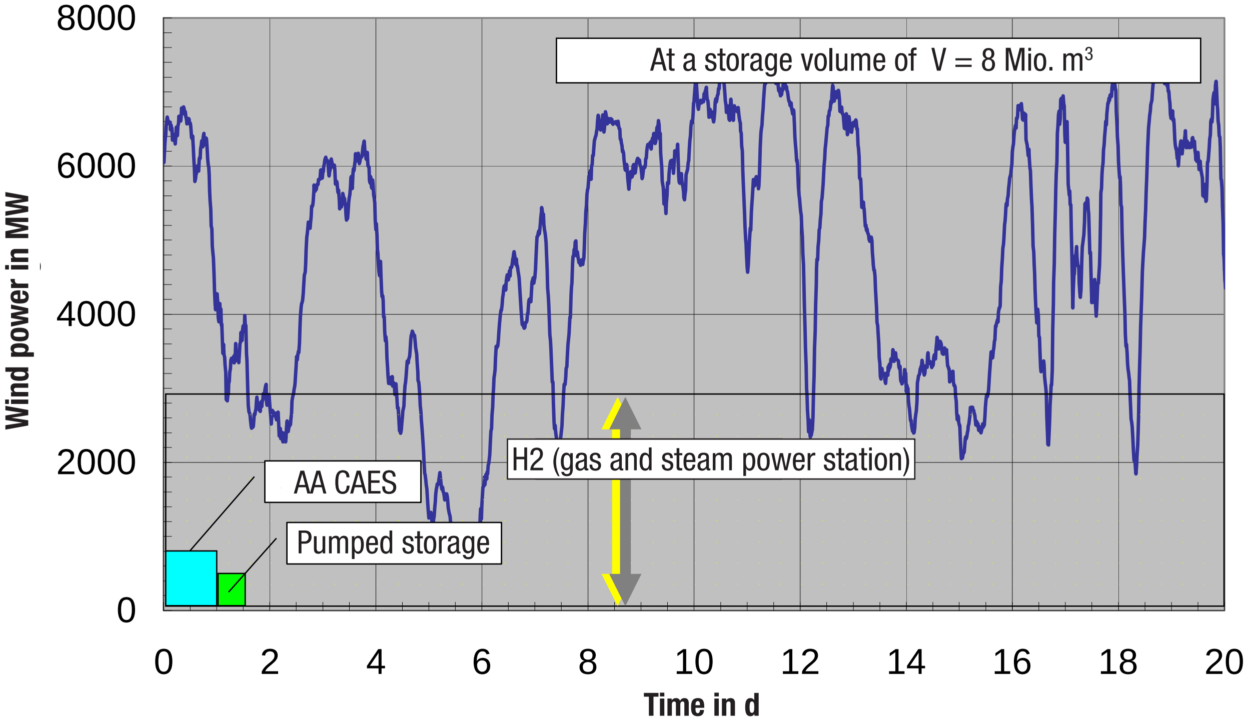


Fig. 6: Comparison of different storage media with a storage volume of 8 million m³ in relation to the input of wind energy into the grid of E.ON Netz AG in early 2007.

4.5 Electrochemical storage systems

Electrochemical storage systems can be classified as shown in Fig. 7. The main differentiation is made with regard to integration of the actual energy storage medium. In systems with internal storage, electrochemical energy conversion and energy storage cannot be separated in physical terms. The storable quantity of energy is linked directly with the charging or discharging capacity. Greater demand for power increases the size of the energy storage medium, and vice versa. This class includes all classic accumulator systems, which in turn are differentiated into those that work at room temperature and those that work at a higher temperature. In systems with external storage, the storage medium can be separated and kept independently of the energy conversion units. This means the energy conversion units for the charging and discharging process can be dimensioned completely independently from the size of the energy storage medium.

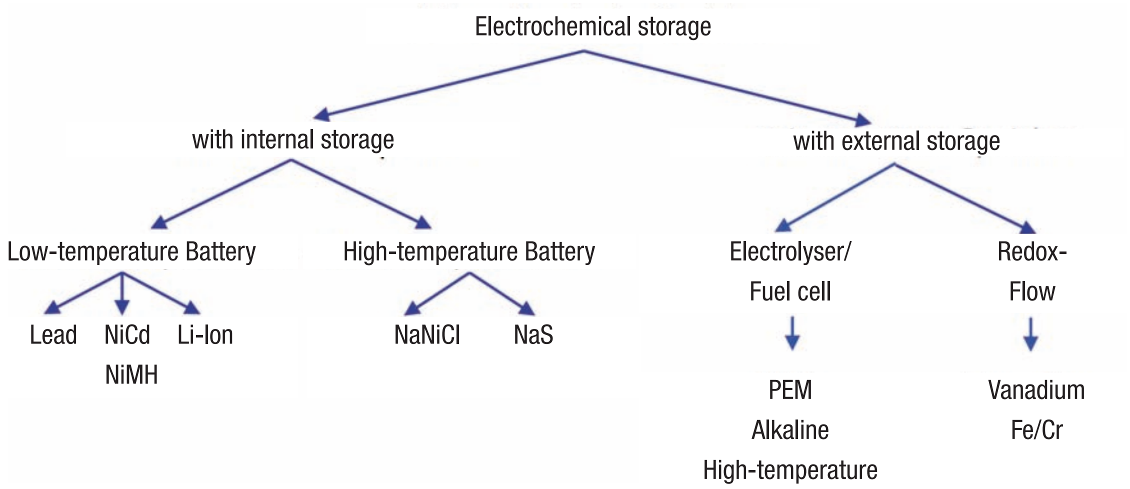


Fig. 7: Classification of electrochemical storage technologies

There are very many material combinations that can be used for electrochemical batteries or accumulators with internal storage. At present, only lead and NiCd batteries are available on a commercial scale for use in power grids as discussed here. Lithium ion and NiMH systems offer interesting technical potential, together with NaS and NaNiCl high-temperature batteries. The characteristic data of the various battery types are shown in Fig. 8 in the form of a Ragone diagram.

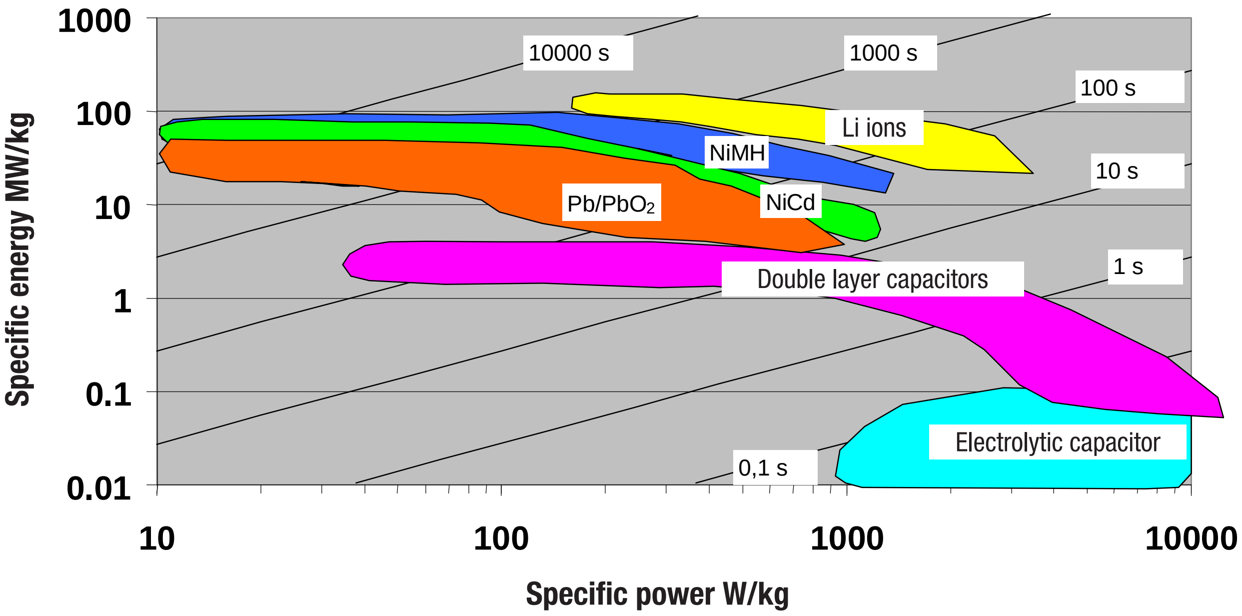


Fig. 8: Ragone diagram to show specific power and specific energy referred to weight

In electrochemical energy storage systems with external storage, the converter for electrical to chemical energy, the energy storage and the converter for chemical to electrical energy are units all independent of each other. They can therefore be dimensioned regardless of each other and also separated in physical terms. This results in additional degrees of freedom for storing large quantities of energy and additional possibilities for using the stored energy. Such systems include redox flow batteries and also hydrogen storage systems.

4.5.1 Lead acid batteries

Stationary lead batteries offer a far higher standard of quality compared to starter batteries. They can be presumed to have a service life of 6 to 12 years with a cycle life of 2,000 cycles at 80% discharge depth, and they achieve cycle efficiency levels of around 80 – 90%. While the costs for such batteries are currently far higher than for starter batteries, mass production offers clear potential for bringing the costs down to a lower level.
One drawback of lead batteries is their low capacity utilization at high currents. If a battery is discharged within one hour, this releases only about 50 – 70% of the capacity available when discharged over 10 hours. Battery storage systems in networks of lead batteries were and are used all over the world to solve local problems in the energy

supply. This includes power supply away from the grids, stabilizing line taps and also sustaining steady frequency and voltage. These batteries are also used for emergency power supplies in power stations and grid installations.

4.5.2 Lithium ion batteries

Within just a few years, lithium ion batteries have become one of the most important power storage systems for portable mobile applications (e.g. laptops, mobile phones). They stand out with a very high gravimetric energy density, offering considerable competition advantages on this market segment. Mass production has meanwhile brought about a considerable reduction in costs. The currently still high costs for top quality batteries and the safety issues involved with lithium ion batteries are currently still preventing any further widespread introduction in stationary and automotive applications. But in 2009 Daimler Benz will be making delivery of the first series-production vehicle with a lithium ion battery.

The high cell voltage (up to 3.6 V/cell) makes it easier to establish high voltage storage systems. Standard cells with 5,000 full cycles can be obtained on the market at short notice; higher cycle rates are deemed possible. Another advantage of lithium ion batteries is their high cycle efficiency level, ranging from 90 – 95%. However, further development is necessary before they can be used in large storage systems as necessary for grid or electrotraction applications, where it is above all the price and the service life that play a crucial role.

While lithium ion batteries are currently still too expensive for stationary use so that they can only compete with lead batteries for example in individual applications with short discharge times (e.g. as primary control backup), the battery industry is concentrating its efforts on applications in the vehicle sector. Here there is great interest in using batteries in plug-in hybrid or fully electric vehicles, or also in terms of storing electricity for the gird (see section 4.6).

4.5.3 Nickel metal hydride and nickel cadmium batteries

Nickel metal hydride (NiMH) were developed initially to replace nickel cadmium batteries (NiCd). Indeed, NiMH batteries have been shown to offer all the positive properties of NiCd batteries. Furthermore, NiMH batteries can achieve far better gravimetric energy densities. In portable mobile applications, NiMH batteries have meanwhile been replaced extensively by lithium ion batteries. On the other hand, hybrid vehicles currently available on today’s market operate almost exclusively with NiMH batteries, as these are robust and far safer to use than lithium batteries.

The cycle efficiency level of NiCd and NiMH is only about 70% because of the low cell voltage of only 1.2 V.

NiMH batteries currently cost about the same as lithium ion batteries, whereby lithium batteries are said to offer greater potential for cost reduction. Economical use in stationary systems demands an excellent cycle service life.

From a technical point of view, nickel cadmium batteries are a very successful battery product; in particular, these are the only batteries still capable of performing well even at temperatures in the range from -20 to -40°C. Large battery systems using NiCd batteries operate on a similar scale to lead batteries. Recently a battery storage system was commissioned for example in Alaska (40 MW for 7 min, 26 MW for 15 min). However, the costs are two to three times higher than for lead batteries.

The use of cadmium is a critical factor so that the technology is under review by the EU.

4.5.4 NaNiCl and NaS high-temperature batteries

Sodium nickel chloride batteries (NaNiCl, also called ZEBRA batteries – Zero Emission Battery Research) and sodium sulphur batteries (NaS) differ from the batteries featured above in that it is the active masses and not the electrolyte that is present in liquid form. Instead, NaNiCl and NaS batteries have a solid electrolyte. Typically these consist of ion-conducting ceramic. Operating temperatures of 270 – 350°C are necessary to achieve adequate ion conductivity and render the active masses liquid. When used on a daily basis with suitably dimensioned insulation, the battery temperature can be sustained by its own reaction heat. These batteries therefore qualify for applications with daily cyclization. Basically both technologies offer the potential for low costs and a high cycle service life.

NaNiCl batteries tend to become low resistant when faults occur. And so cell faults in serial connections only result in the loss of the voltage from one cell, instead of premature failure of the complete system. This technology is therefore also suitable for use in applications with high system voltage.

Fig. 9: Sodium sulphur high-temperature battery for load-levelling operation (Tokyo Electric Power Company, Tsunashima – 6 MW, 48 MWh).

In Japan in particular, intensive research is being pursued into using the NaS battery for grid storage. For several years now, the Tokyo Electric Power Company has been operating a system with 48 MWh energy storage and 6 MW power (Fig. 9).

4.5.5 Redox flow batteries

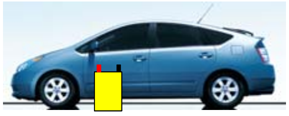
In redox flow batteries, the active material consists of salts dissolved in a liquid electrolyte. The electrolyte is stored in tanks and pumped to a central reaction unit for the charging or discharging process as required. As the solubility of the salts in the electrolyte is normally not very high, these systems offer energy densities in the same range as lead batteries. The central charging/discharging unit usually consists of a membrane fitted with catalysts and closely resembles a hydrogen fuel cell or electrolyzer in how it works. The tank size defines the energy content of the battery, while the charging/discharging unit defines the power. In redox flow batteries, each electrode has its own electrolyte tank. The charging and discharging process changes the valency of the ions in the salt. Various combinations of salts have already been tested.

Fundamentally this battery technology is ideal for large-scale technical use, as the construction of large tanks is very easy and can be very efficient. However, large-scale implementation has not happened up to now because of material problems. There is therefore scarcely any authoritative information about the properties of this kind of system. System efficiency levels are presumed to be around 75%, including the necessary auxiliary units.

4.6 Energy storage on the transport sector

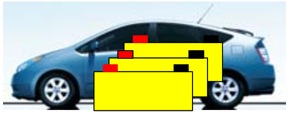
In the medium term, solutions will have to be found for mobile energy storage that also permit the use of renewable energy sources on the transport sector. Together with bio fuels, which only have a limited and controversial availability and which in particular are already included in the plans for many other applications, solutions are especially available on the basis of electricity, generated from renewable wind and solar energy. Referred to the space required, these solutions offer improved energy yield which is more than one magnitude better than bio fuels. Furthermore, a highly efficient electric drive also has an additional contribution to make compared to a combustion engine.

Purely electric vehicles that run on batteries will be suitable above all as second vehicle for urban traffic, given their limited range. On the other hand, so-called plug-in hybrid vehicles with the possibility of connecting up to the grid offer universal, swiftly implemented solutions. Fig. 10 shows a comparison of the various concepts.



Hybrid vehicle (HEV)
Battery approx. 1 kWh
Recharged only while the vehicle is moving
Fuel savings max. 20%

Plug-in hybrid (PHEV)
Battery 5 – 10 kWh
Recharged from the grid
Range 30 – 70 km without fuel
Full range, full performance



Electric vehicle (EV)
Battery 15 – 40 kWh
Recharged from the grid
Range 100 – 300 km without fuel

Fig. 10: Various concepts and their battery requirements.

A plug-in hybrid can still operate just with its electric system in urban traffic in spite of the limited range of the battery. On longer journeys, the driver can revert to conventional drive systems thanks to the widespread supply of petrol, diesel, natural gas or bio fuels.

In order to meet the demands in urban traffic, it is currently presumed that the range of a battery charge does not have to exceed 50 km. Energy content of approx. 7 – 8 kWh would be sufficient here. There is sufficient time to recharge the battery during the day, for example while at work or during the night hours, so that a charging capacity of 3 kW would be sufficient. This is less than the connected wattage of an electric stove so that even a relatively high level of market penetration is deemed to be compatible with the grid, as long as intelligent load management prevents high simultaneous demand. The battery can thus be fully recharged at a normal house connection in less than 3 hours. And so a widespread infrastructure for recharging the batteries is already available on launching this solution. At the moment, lithium ion batteries are the preferred technology, with their high energy density making them predestined for mobile use.

On the one hand, clever load management can adapt the "green" periods for recharging batteries to the corresponding supply of renewable energy; on the other hand, a very high level of market penetration can prevent local overloads on the grid. Furthermore, this kind of energy storage system can also be used for grid control tasks (primary or secondary regulation) or also for providing minute reserves. In the long term, a larger fleet of such vehicles, grouped together as "virtual large-scale energy storage systems" could even eliminate the need for additional expansion of central large-scale storage systems on the level of an integrated grid for the stated application (of up to a few hours), at least some of the time. This is just one of the reasons why great interest is being shown in this topic by energy utilities and grid operators. It can therefore be presumed that these general conditions will lead to the offer of a lower electricity price. Even on the basis of today's electricity prices, the specific energy costs for an electric vehicle are far lower than when using fossil fuels, even when taxation and duties are taken out of the equation. The aim is for Germany to have at least 1 million cars operating as plug-in hybrid or fully electric vehicles by 2020.

Another possibility for using renewable energy on the traffic sector respectively for decoupling supply and demand on the electricity sector consists of the hydrogen solution. Discussions about reducing the carbon footprint and the availability of fossil energy have led to increasing efforts by the automotive industry in terms of hydrogen vehicles, particularly with electric drive and fuel cells. The first vehicles are expected to appear in 2010, followed by a widespread market launch after 2015.

However, in contrast to the stationary hydrogen solution described in chapter 4.3, a higher energy density is required for mobile use in vehicles. But the processing this involves is detrimental to the overall energy efficiency. Today, attention is focused in particular on concepts with high-pressure storage (approx. 70 MPa) which fare much better in this respect compared to a solution with cryogenic liquid hydrogen. However, batteries are a far more efficient form of storing energy (by a factor of 2 – 3) when it comes to using electricity generated from renewable energy sources.

It is generally agreed that there is currently no battery technology on the market or in the development phase with foreseeable commercialization offering a range of 200 or more kilometres with one battery charge. Fuel cells with hydrogen are therefore an option for longer routes, whereby here again it makes sense to equip these vehicles with a larger battery along the lines of a plug-in hybrid with a range of 30 to 50 km to benefit from the far higher efficiency level that can be achieved by making direct use of electricity from the battery in predominant short-distance traffic (urban traffic). And so in the end, the actual competition is not between battery and fuel cell: instead, the fuel cell must be seen in competition with the combustion engine, a competition which the fuel cell will win if fuel costs continue to rise respectively in view of the prohibitive aspect of using fossil fuels on account of the carbon problem. In the long term, it will be the fuel cell vehicles, and probably as a plug-in concept, that will offer the only remaining alternative for satisfying the high general demands made of universal mobility arising from environment compatibility, range, vehicle performance, payload, low costs and fast refuelling.

Together with the use of pure battery vehicles for short distances, this development constitutes a fundamental change in technology, and opens up new sales markets for electricity utilities. The infrastructure required to keep vehicles supplied with hydrogen on a widespread scale is currently not available. A transitional period will therefore need a balanced and well coordinated approach that includes energy utilities, fuel providers, the automotive industry and the political sector. The focus will have to be on strategic planning for the widespread supply of hydrogen, based on fleet applications in the conurbation areas, in order to achieve high sales figures for the corresponding vehicles as quickly as possible so that in turn the infrastructure itself will quickly become profitable.

The provision of hydrogen as a fuel becomes particularly appropriate when electricity from renewable energy sources is available in such large quantities that it can no longer be put to direct use even in the integrated grid without some form of intermediate storage, and when the possibilities offered by load management have been extensively exhausted. And so the traffic sector is not competing with classic electricity generating activities: on the contrary, they can both supplement each other. The additional demand for road transport will even help to accelerate the rate of expansion in the use of renewable energies, as the resulting storage capacities will permit a higher level of penetration.

The intelligent integration of this additional energy path thus enhances the economic implementation of hydrogen storage systems while at the same time reducing the necessary capacity of stationary storage facilities.
Intelligent use of regenerative energy sources on the transport sector will contribute to a further increase in the quota for this kind of energy, as this approach permits the development of further sales markets, while at the same time decoupling supply and demand. The long version of this study therefore dedicates a detailed chapter to the issue of energy storage on the transport sector, with a comparison of the technologies involved.

4.7 Other storage technologies

Other storage technologies are suitable in particular for very short discharging periods:

- Static electricity storage (SES): storage in the electrical field of condensers
- Electrodynamic storage, storage in the magnetic field of soils, in particular superconducting magnetic energy storage (SMES)
- Kinetic storage, storage of rotation energy in flywheels using electromechanical converters, e.g. electric motors and generators

This kind of storage is interesting particularly for applications where supply and voltage quality are significant. Technical details are described in the long version of this study. However, these storage systems are not used on the basis of energy efficiency aspects, but primarily in the context of the consequential costs of power supply interruptions, so that this study dispenses with any further comparison of these technologies and their energy efficiency aspects.

5 Evaluation of the storage technologies

5.1 Evaluation according to scenario

This current study compares various storage technologies on the basis of simplified cost accounting. To this end, reference application cases are defined and the corresponding accrued costs are referred to the energy taken from the storage system. Consideration is given to all essential aspects, such as service life, efficiency levels and investment costs for the actual storage system itself and for the power interfaces.

Table 1 summarizes the reference cases defined in this study.

Table 1: Overview of the reference cases.

Case	Designation	Brief description	Power	Energy	Cycles per day
1	Long-term storage	Storage energy from renewable sources over a period of weeks (no seasonal compensation)	500 MW	100 GWh	0.06
2	Load levelling in the transmission grid (high voltage)	Typical rating of a large pumped storage hydroelectricity power station	1 GW	8 GWh	1
3	Peak shaving in the medium voltage grid	Storage system on the municipal utility level, particularly for peak shaving	10 MW	40 MWh	2
4	Peak shaving in the low voltage grid	Storage system in a low voltage grid for peak shaving and load levelling	100 kW	250 kWh	2

Table 2 shows the reference cases with the corresponding powers and discharge periods together with the specific response times required from the storage systems. Reference case 2 looks at both fast systems with response times of less than one second (in principle also suited for use in the primary control context) and also slower systems which can be used in particular for use in the context of the minute reserves; depending on capability, these can also be used in part for secondary control. However, only one application is considered in each case when evaluating the reference cases. Possible multiple use, e.g. for electricity trading on the stock exchange and provision of primary control power, has not been discussed in the interests of clarity.

The evaluation also states which storage systems were viewed as the principle technologies for the various reference cases. As far as CAES is concerned, only adiabatic systems were examined on account of their far higher efficiency.

The life cycle costs were analyzed for the reference cases for the various storage technologies. The reference cases are defined by the required charging and discharging capacity, the net available energy, the number of cycles per day and the required total operating period of the storage facility. In the various scenarios, components could be replaced as often as necessary during the service life; the corresponding costs were included in the evaluation. The gross size of the storage system results from the net size, taking into account the permitted discharging depth and the efficiency level when discharged.

Calculating the life cycle costs included taking account of the investment costs for the actual storage system, the necessary auxiliary units and the power converters respectively interfaces to the grid. Consideration is given to the service life of the components – in some storage systems such as batteries, this depends on the cycle depth – and also to the electricity price that has to be paid to cover losses in efficiency. This price is required to put a figure on the surplus energy (losses) which can be absorbed by the storage system, but not released again.

Table 2: Technical characteristics and examined storage technologies for the various reference cases.

Case	Power	Discharging time	Response time	Examined storage technologies
1	500 MW	200 h	1 – 15 min.	Pumped storage, CAES, hydrogen
2a	1 GW	8 h	90 – 120 sec.	Pumped storage Longer response times for CAES (15 min) and hydrogen (15 min)
2b	1 GW	8 g	< 1 sec	Lead acid, NiCd, Li ion, NaS/NaNiCl, redox flow (vanadium), zinc bromine
3	10 MW	4 h	< 1 sec	Lead acid, NiCd, Li ion, NaS/NaNiCl, redox flow (vanadium), zinc bromine
4	100 kW	2.5 h	< 1 sec	Lead acid, NiCd, Li ion, NaS/NaNiCl, redox flow (vanadium), zinc bromine

5.2 Results

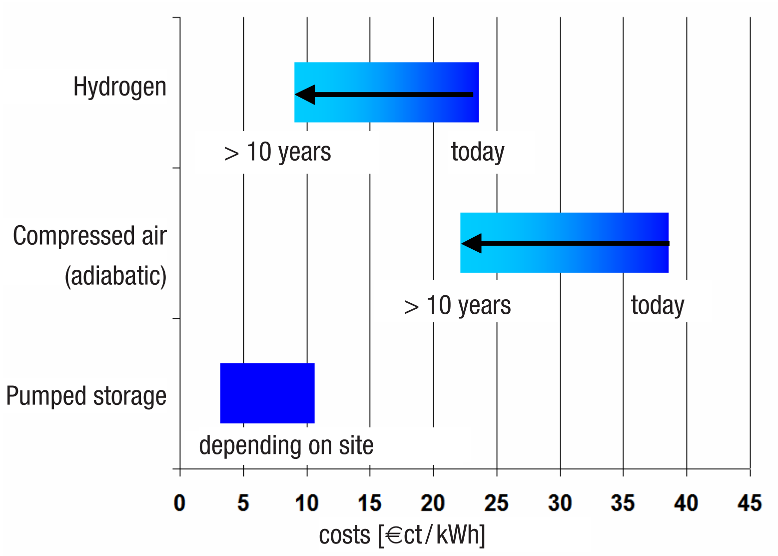
This short version of the study only provides excerpts of the results obtained in the scenario calculations. Further results together with a sensitivity analysis of the input parameters can be found in the long version.

All calculations are based on an interest rate of 8% on capital. The costs discussed below consist of the income that has to be earned with every kWh released again to the grid for the construction, operation and financing of the storage facility in order to cover the costs of operation. And so the corresponding purchasing costs incurred during the charging process have to be added to the calculation of the overall costs of the energy supplied by the storage systems. This systematic approach offers the advantage of depicting the differing service lives, efficiency levels and permitted discharge depths as a single monetary value in order to permit a direct comparison of the technologies. An investment decision is naturally also influenced by other factors that are not included in a value, such as the geological availability of suitable locations or restrictions on the space available.

The width of the cost bars in the following figures therefore represents the range resulting from the “state of the art” (higher value) and the costs attainable over the next 5 to 10 years for corresponding large-scale production (lower value). The relatively large spread for pumped storage results among others from the presumably differing geological general conditions for construction of the storage reservoirs. The costs have been calculated on the basis of data obtained from technical literature, studies and experts. Batteries in particular offer considerable potential for cost reduction when manufactured in large quantities on automated production lines. The range for established technologies is slighter than for technologies not yet established on the market.

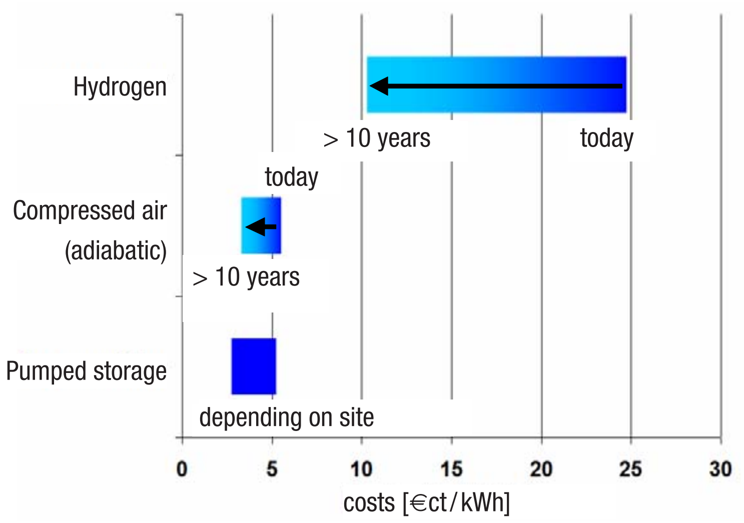
Reference case 1 “Weekly storage” (Fig. 11) results in extremely high electricity production costs for all storage technologies. While pumped storage hydroelectricity power stations would normally be the lowest cost option, there is practically no potential for expanding the necessary storage volume here in Germany. Hydrogen storage in caverns is therefore the feasible option at the lowest costs. In this particular case, the capacity-specific costs are lower because the energy storage density is greater by about two magnitudes compared to compressed air, so that it would be possible to make effective use of even limited cavern capacity.

Fig. 11: Comparison of the full costs of storage systems for long-term storage (reference case 1)



Reference case 2a "Hourly storage" (Fig. 12) shows the classical application and rating of large pumped storage hydroelectricity power stations, such as those in operation in Vianden or Goldisthal, for example. Adiabatic compressed air storage facilities are comparable in terms of costs, but have a lesser impact on the environment as there is no need to build reservoirs. These storage facilities thus constitute a promising option for further expansion. Hydrogen storage systems cannot keep pace in this reference class in terms of operational profitability, as the low efficiency level results in high operating costs, especially in compensating for the energy losses.

Fig. 12: Comparison of the full costs of storage systems for load levelling tasks (corresponds to today's rating of major pumped storage hydroelectricity power stations) (reference case 2a)



This class can include battery systems when a highly modular structure is used (reference case 2b – Fig. 13). The lowest possible costs per kWh range from 8 to 12 €ct/kWh. Battery storage systems with

50 MWh have been established in various cases; in principle, a 1 GWh storage system consists of 20 such units working in parallel. However, the size of the system means that there are no scaling effects in the costs. These storage facilities can therefore also be arranged in decentralized locations in various places and used as virtual large-scale storage when the need arises. Batteries offer advantages when the geological conditions are not suitable for pumped storage hydroelectricity power stations or compressed-air storage systems, or when the planned operating period is less than 20 years. Here there is not sufficient time for amortization of the high investment costs involved in compressed-air or pumped storage hydroelectricity power stations with their service lives of 30 to 50 years. Batteries can be put to central or decentralized use and also supply both primary and secondary backup, as the full power is available within about 10 ms.

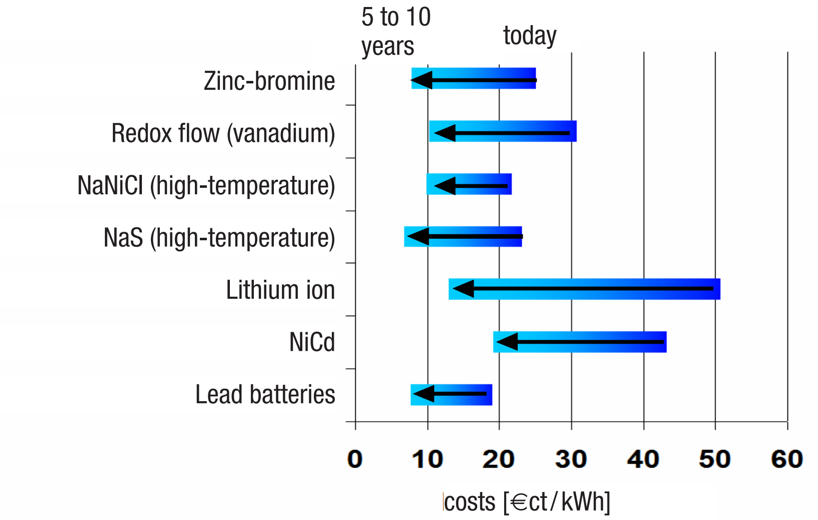
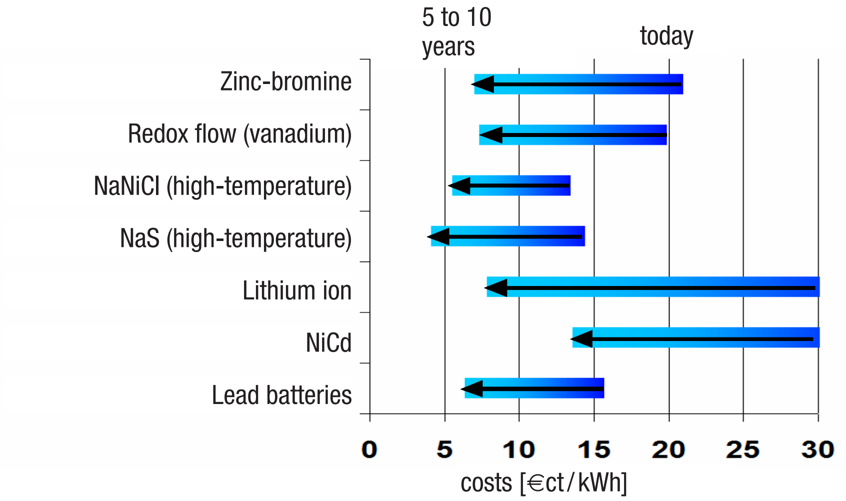


Fig. 13: Comparison of the full costs of storage systems for load levelling tasks (reference case 2b) (as reference case 2a, but in this case with battery systems and a response time < 1 s)

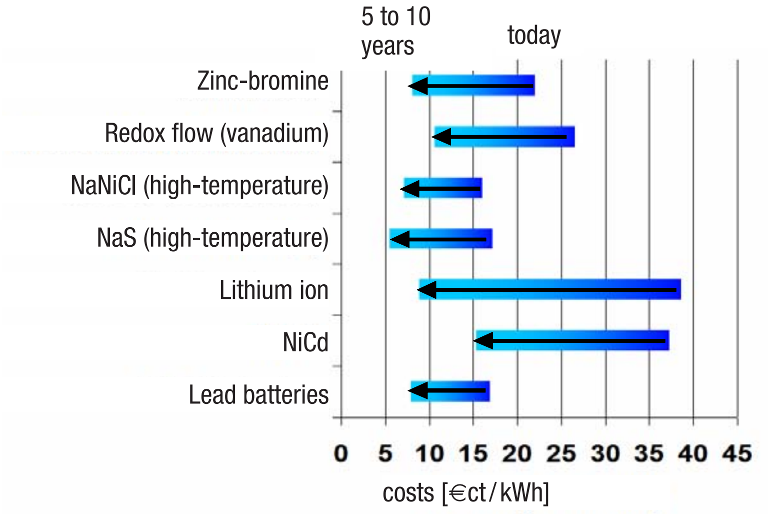
Reference case 3 (Fig. 14) includes a number of different electrochemical storage technologies in the context of smart grids and virtual power stations/storage systems. In terms of the medium-term cost targets, NaS technology offers the greatest potential with regard to costs per implemented kWh. Japan has already implemented several storage facilities with up to 50 MWh based on this technology. In economic terms, lead batteries with liquid electrolyte are still a very interesting option, particularly in view of the fact that cell standardization and mass production will reliably move the costs a long way along the scale towards the presumed best case. But it must be said that all the featured technologies have the potential of being launched on the market, so that further research and development in all technologies is appropriate and justified. Competition is a major motor behind the ongoing development of the technologies.

Fig. 14: Comparison of the full costs of storage systems for peak shaving applications in the medium-voltage grid (reference case 3)



In principle, various electrochemical storage technologies can also be considered for reference case 4 (Fig. 15). Here again, NaS technology seems to offer the best potential in terms of costs per implemented kWh, with regard to the medium-term cost objectives. In particular, the load levelling required for the operation of micro grids makes such storage facilities a necessity. Today batteries are used in the low voltage grid above all in UPS systems, but are also put to other use. However, when grouped together as virtual power stations or virtual large-scale storage facilities, they can also be used for other tasks, as the short-term UPS use results in oversized battery capacity.

Fig. 15: Comparison of the full costs of storage systems for peak shaving and load levelling applications in the low-voltage grid (reference case 4)



5.3 Alternatives to energy storage

In a liberalized electricity market, energy storage systems have to face up to competition from alternative possibilities, as investment decisions are taken on the basis of business management aspects. Alternatives include for example grid expansion, generating units that can be started up and controlled quickly (gas turbines), load management and in the end also negative control of electricity generators using renewable energy sources. But as a rule, it is not always possible to put a value on all the advantages or drawbacks of the various possibilities. In addition to a comparison on pure business management terms, it is also necessary to consider general economical and ecological aspects, with possible support from suitable incentive programmes where necessary.

The following sections describe typical applications where storage systems face competition from other technologies. In each case, it is presumed that ideal storage conditions prevail with regard to the regularity and duration of use. Calculating the costs for the storage systems is based on the systematic approach described above together with the corresponding statistics.

5.3.1 Connection of a 10 MW wind farm (power line 10 km in length) Grid expansion vs. storage facility

Alternative 1: Grid expansion to the full capacity of 10 MW (construction of a new power line including control panel, replacement of transformers and proportional expansion in the HV grid).

Working on the basis of a service life of 40 years for the grid operating equipment, this results in relative costs amounting to 1.05 €ct/kWh.

Alternative 2: Storage facility for 10 MW and 80 MWh (8 hours full load).

Working on the basis of existing grid capacity of 2.5 MW.

Note: on days with lots of wind with more than 8 hours full load, it will not be possible to absorb all the energy in the storage facility so that the surplus is lost: this is not featured in the calculation.

Resulting costs per kWh (on the basis of an NaS battery): 5.4 – 19.1 €ct/kWh

Even under the positive general conditions presumed here for operation of the storage facility, it does not offer an economic alternative to expanding the grid when it is presumed that the wind site can be used in the long term.

5.3.2 Long-distance transmission or delayed use of the wind energy (displacement in place vs. displacement in time)

It is possible to make considerable reductions in storage demand if a large share of the generated electricity can be transmitted directly to consumers. This needs efficient transmission grids capable on the one hand of overcoming the long distances and on the other of relieving local bottlenecks on the grid.

In this context, it is possible to speak of competition between the specific expansion of grids for transmission of energy, e.g. from onshore and offshore wind farms in North Germany to high-consumption centres, and corresponding storage of the energy. Here it should be noted that grid capacities can often be required when using storage systems. The grid capacity should be at least in the range of 50% of the nominal power of the wind farms to permit dynamic reactions to demands for load, rather than just transporting permanent power via the storage facility according to the mean power of the wind turbines.

It is presumed that an HVDC transmission line with transmission capacity of 2 GW is available to absorb the entire wind farm power, and that this is constructed solely for forwarding the energy from offshore wind farms, transmitting the energy over large distances. This does not take account of the undersea cables which are always installed through to the coast.

Fig. 16 shows that the additional costs for transmission via an HVDC transmission line amount to 2 €ct/kWh for utilization of 25% of the line over a transmission distance of 2,100 km, and around 3 €ct/kWh for 3,800 km.

Even with this singular use of the line and a utilization rate of only 25%, it is possible for electricity to be transmitted from the German coast to practically any point in Europe for additional costs of 3 €ct/kWh. No storage facility can be constructed for these costs, so that the transmission of energy to centres with subsequent consumption offers a very favourable option in economic terms. This applies in particular when the same lines can be used to transmit energy in the opposite direction as well, depending on the varying supply situations. This then also provides low-cost access to more remote storage capacities. However, it is important not to lose track of the stability problems that can possibly result from the massive, long-distance transmission of energy. But this only applies to a limited extent when using special high voltage direct current (HVDC) transmission lines for this purpose. However, the grid must be capable of coping with the possible failure of such energy transmission lines.

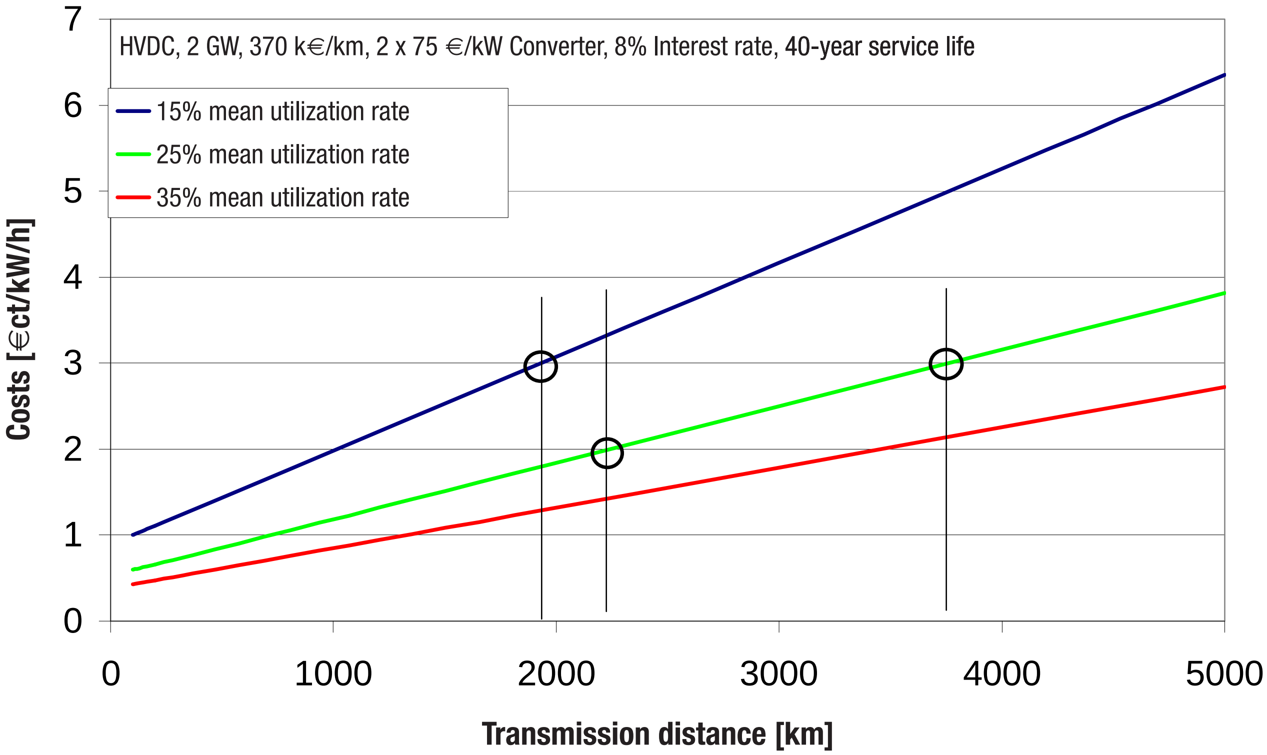


Fig. 16: Transmission costs for a 2 GW HVDC overhead power line as a function of the utilization rate

5.3.3 Shutdown of wind turbines for grid overload

The shutdown of wind turbines when there is an overload on the grid always constitutes a financial loss for the operators, as otherwise they would have been remunerated for the power fed into the grid under the EEG. Two cases have been looked at in this context.

Case 1: In this case, after viewing the current situation in the grids, it is presumed that the wind turbines are shutdown twice a month because of a surplus of energy in the grid. Each shutdown lasts 5 hours and affects 50% of the installed peak load. Referred to the installed power, this translates into lost income for 60 full-load hours which corresponds to three percent of the total income for a presumed 2,000 full-load hours.

In order to absorb this energy, it is presumed that a storage facility is required with a charge capacity (negative control energy) of 10 GW and a discharge capacity (positive control energy) of 2 GW for an installed wind turbine power of 20 GW. The storage capacity is therefore 50 GWh and the system operates 24 cycles a year.

The adiabatic CAES option would result here at best in costs of 40.7 €ct/kWh. In this case, the wind turbine operator would be remunerated for his power supply according to the EEG, so that the calculated costs are additional costs and constitute a financially unjustifiable amount, even if the storage system operator would not have to pay for the energy required to charge the system. Shutting down the wind turbine is therefore always the better solution, even if compensation has to be paid for lost EEG income.

Case 2: Here it is presumed that the wind turbine is shut down every 3 days for 5 hours at a time with 50% of the peak power. This leads to a shutdown of about 300 full-load hours or around 15% of the annual energy. Based on a storage system with asymmetrical charge and discharge capacity as above, this results at best in costs of at least 9 €ct/kWh for the adiabatic CAES and 16.2 €ct/kWh for hydrogen storage. In this case too, these are additional costs. But here we are approaching an area where the use of storage facilities could make general economic sense. Without suitable support, e.g. additional remuneration similar to the EEG, profitable operation of a storage facility is currently scarcely conceivable in view of the still high costs. However, the EEG or corresponding subsequent legislation could make it possible to integrate current instruments for subsidizing renewable energy in order to obtain a financially interesting business model. But here it is important once again to draw attention to the fact that with the rating conditions chosen here, the storage system would not be capable of covering any necessary shutdown periods in excess of 5 hours, which would be quite conceivable in reality, as by that point it would already be full.

By the way, this statement also applies to photovoltaic systems with higher EEG remuneration, as this does not impact on the additional costs incurred for the storage system.

5.3.4 Provision of control power (primary and secondary control, minute reserves). Power station fleet (thermal) vs. storage facility

Primary control power today is provided mainly by thermal power stations. In order to supply positive control power, the participating power stations are normally run in slightly unrestricted mode. The costs incurred for this by the power station operator result essentially from the resulting additional losses with correspondingly higher primary energy input. Primary control power as tendered in Germany amounts on average to + 650 MW, i.e. about 1% of total power. The primary control power is tendered on a monthly basis, whereby only the capacity charge is remunerated, but not the unit price. As primary control power always has to be activated fully within 30 seconds, only battery storage systems can be used for this purpose here.

The demand for positive secondary control power in Germany amounts to about 2,900 MW, and 2,400 MW for negative control power. The secondary control power is also tendered by the month, with a differentiation between positive and negative control power

and also between high-tariff (HT) and low-tariff (LT) times. A different capacity charge and unit price is paid in each case. Secondary control power today is provided from the rotating reserves of the entire power station fleet and from pumped storage hydroelectricity power stations. CAES are not suitable for providing secondary control power, as they cannot meet the required start-up times (< 5 minutes). Thermal power stations running in partial load could offer control power practically at marginal costs (i.e. essentially fuel costs), but attain far higher prices on the market. Battery storage systems could offer a particularly favourable combination of primary and secondary control power, as these are needed successively and not simultaneously, and batteries combine both attributes: fast standby availability and adequate discharge time. To this end, a very low unit price would have to be offered for secondary control power to put it right at the top of the ranking and ensure that it always comes into play as far as possible when the need arises. It is not possible to assess the economic efficiency of this kind of combined use using the simple model chosen here; instead a detailed study is required. But battery storage facilities could probably constitute an economically efficient solution for the corresponding control energy markets under the general conditions prevailing today.
The minute reserves are tendered on a daily basis. There are great fluctuations in the prices depending on the power demand and power station availability. A capacity charge is paid for provision of the reserves, together with a unit price according to the necessary use. As a rule, thermal power stations running in partial load can offer minute reserves at a very low price insofar as sufficient capacity is still available. On the market for minute reserves, storage systems also complete with gas turbines which can produce the full power within the required time of 15 minutes. Meanwhile emergency power systems grouped together to form a virtual power station also bid successfully on this market. Furthermore, thought is also being given to combining decentralized generators to form a kind of local virtual power station in order to offer control power on the market and, on the other hand, to support balancing group management. This is also seen as a possible way of getting away from inflexible input remuneration for electricity generated from renewable energies and CHP power stations so that these can be gradually integrated in the market. Decentralized storage facilities could be used as a supportive measuring in this kind of concept.

In order to provide negative control power from storage systems as well, storage management will have to ensure that sufficient free capacities are kept available.

Whereas generally high power prices are paid for control power which can be taken as secured income in the calculations, as far as the storage systems are concerned the unit prices have to be monitored closely to see which volumes are actually being traded on the market and at which prices the storage systems can be charged up.

Given that control power is awarded according to the rules of the game on the market, an increase in supply leads to falling prices, and vice versa. This must be taken into account particularly for those storage facilities whose investment is tied in with a high service life.

5.3.5 Provision of control power (primary and secondary control, minute reserves). Load management vs. storage (thermal) vs. storage facility

In principle, load management can make a contribution on all these markets. But the basis for successful load management consists of electricity prices that vary in time, to tempt the customer to shift his demand for power from times with a power shortage (high price) to times with an excess power supply (low price). In terms of control power, this could consist of refunds paid to the customer if part of his load can be interrupted in the short term. Here a load shutdown is the equivalent to feeding additional control power into the grid from a generating unit. As far as the profitability of load management is concerned, the investment costs for the corresponding infrastructure are also a significant element; this refers to the management system, ICT, switchgear and smart meters. The electricity prices or refunds are derived from the corresponding prices that can be obtained on the various markets, taking account of the necessary expenditure. Apart from compulsory measures, such as avoiding grid collapse, the decision for or against load management lies with the customer.

In the case of shutting down loads in the short term, systems generating heat and cold are predestined for such applications because of their thermal inertia. In future, even plug-in hybrid vehicles can be included in load management, as here again, short-term interruptions in the load process are possible practically without problems.

And so storage systems will probably have to share these markets with load management. While load management comes up against its limits relatively quickly in terms of utilization period (load interruptions of several hours are only possible with selected consumers for technical reasons), storage systems are generally rated for discharging periods lasting several hours and perform other tasks on a primary level. This is why combined usage in particular is advantageous with storage systems, but this cannot be included in a simple, clearly structured profitability analysis.

In accordance with the rules of the game on the market, it can be said that the appeal of load management also decreases with increasing demand, and vice versa.

5.3.6 Provision of reserve power. Peak load power station (gas turbine) vs. storage facility

Gas turbines are suitable for providing reserve power and thus constitute an alternative to storage systems. Such power stations are naturally not capable of absorbing generation surplus from the grid.

The electricity production costs with gas turbines depend greatly on the attainable full-load hours and on the gas price. Accordingly, future developments in gas prices are of particular interest. In addition, the kWh generated from natural gas also has to bear the additional costs for CO_2 certificates, where again it is not possible to predict the developments.

A comparison of costs has to take account of the systematic approach used for calculating the costs of storage systems. This entails calculating the specific costs resulting from the operation of a storage system including covering for losses in a certain scenario. This does not yet take account of the costs for purchasing the energy emitted by the storage system. These must be added to the specific storage costs ascertained here to obtain a comparison with the costs for electricity from a gas turbine.

On the one hand, storage systems offer more possibilities on the income side as they can also absorb negative control power so that there is no the need to reduce or shutdown power station output when there is a surplus supply, thus preventing uneconomical or volatile power station operation (with elevated emissions). On the other hand, there are practically no time limits on gas turbine availability, as long as the required natural gas is provided. They can thus be used to bridge longer periods without wind (several days to weeks), a situation where storage systems are usually not suitable. Hydrogen could prove the exception to this rule when used in gas turbines, currently still mixed with a small share of natural gas.

6 Summary, conclusions and need to act

Given the ever clearer symptoms of climate change, the foreseeable scarcity of fossil sources of energy and the increasing reliance of Germany – and most other EU states – on energy imports, the political sector has set a sign and initiated corresponding programmes.
In Germany in particular, these include subsidizing renewable energy sources through the EEG. These measures have taken effect in recent years particularly with regard to wind energy, so that Germany meanwhile has an installed wind turbine fleet with total output of more than 22 GW, of which about 40 TWh were fed into the grid in 2007. Referred to load peaks they therefore already contribute about 30%, but referred to gross electricity consumption this figure decreases to about 6.5%. Altogether the contribution of renewable energy sources to electricity generation is to exceed 30% by 2020. To this end, further wind turbines are being planned with about the same output again, and will be installed in particular in offshore wind farms. However, the supply of renewable energy sources, particularly from the wind and sun, is not geared to the demand for load. Accordingly, it is possible already today for situations to occur where at low load times, regional inputs into the grid from wind energy exceed the demand for load, or where wind turbines have to throttle their generation of electricity during periods of high winds because of inadequate grid capacities. Moreover, the highly fluctuating supply results in an additional need for control at thermal power stations with all the resulting consequences (deterioration in efficiency, elevated emissions, shorter maintenance intervals, shorter service life, fewer full-load hours), thus resulting in increased generation costs. And so there is an urgent need for action to integrate the fluctuating input compatibly into the grid in the planned scope while at the same time offering customers a high quality of supply at economically acceptable electricity prices.
The anticipated restrictions on output will also affect the second mainstay of Germany's energy policy, which is the decentralized cogeneration of heat and power (CHP). In many cases, the electricity generated in heat-run operation is not correlated with the corresponding demand. Although today EEG electricity does not take priority over CHP electricity, it can be presumed that when there is a surplus of renewable energy, it also makes sense to reduce or shut down gas-fired CHP systems. Here the political sector is required to set the course appropriately in plenty of time.

This study concentrates primarily on the use of storage systems in electrical energy supply systems, whereby these can be charged with electrical energy which they then make available again during their discharging phase.
Together with decoupling supply and demand in terms of time in a daily rhythm (load levelling), storage systems have also been examined with regard to their suitability for the following applications: long-term storage for several days, provision of peak load (peak shaving), control power, reserve power and bottleneck management.
To this end, the study looked at large-scale storage facilities for integration in the transmission network (pumped storage, CAES, hydrogen) and at various battery systems qualified by their modular structure particularly for use in distribution networks. But in principle, battery storage systems can also be pooled to form a large storage facility – either in real or virtual terms – and assume tasks in the transmission network.
As well as characterizing the various storage technologies that can be used for these purposes, the study has defined scenarios for analyzing the profitability of the various storage systems. One single monetary value was attributed to the differing storage characteristics to permit a very simple comparison of system profitability in a given application.

The cost calculations have produced the following systematic findings:

- Most storage technologies entail high initial investment and low operating costs. The profitability of storage systems therefore improves with the increasing annual number of cycles.
- Long-term storage systems with cycles of less than one a week are currently not profitable. While pumped storage hydroelectricity power stations are the most profitable alternative, Germany has practically no potential for further pumped storage hydroelectricity power stations in this magnitude. The only conceivable option for this application, in spite of the poor conversion efficiency rate, consists of hydrogen storage in salt caverns, a solution which offers a relatively high energy density. There are relatively good conditions for facilities of this kind in particular near to Germany’s coastal regions – an advantage when it comes to absorbing energy from offshore wind farms.
- With regard to large storage facilities with a daily cycle, similarly favourable results are obtained for compressed air storage and pumped storage hydroelectricity power stations. In future, various battery systems could also work at approximately comparable conditions, with the advantage that these can also be used on the market for primary and secondary control energy, thanks to their fast provision of power.

- Most of the battery storage technologies examined here offer comparable potential for reducing costs, so that dynamic market development can be expected from genuine competition between the various systems. Under certain circumstances, a low-cost battery with a shorter service life may be a better alternative than a more expensive one with a long service life. It is therefore currently much too soon to opt for just one specific technology.

Apart from making a comparative evaluation of the various storage systems, the study also views alternatives which could possibly compete with storage facilities.
For example, if a line bottleneck means that it is not possible to transfer all the energy from a wind farm into the grid, suitable grid expansion is conceivable instead of a local storage facility, making it possible to transfer all the output to a correspondingly high-powered grid node. This solutions cost far less than the storage alternative, so that a storage system erected solely for this purpose is out of the question for reasons of economic efficiency.
Sharing energy on an international level can also help to balance out supply and demand within the scope of the relevant possibilities. However, here it must be borne in mind that all European countries are pursuing similar expansion concepts for regenerative energies so that surplus or deficit solutions must be expected to occur on a large scale. The scenarios described in the various studies where a country simply transfers its surplus power to the neighbouring country or where the neighbouring country acts as power supplier in periods of power deficit have therefore not found much favour in the affected countries. In view of the similar energy policy objectives, in principle, international power sharing within Europe can only contribute to solving the problem of balancing supply and demand if there are clear regional differences in the generation load curves, resulting for example from the use of differing sources of primary energy, or from regional differences in climate.
This then entails bridging large distances. This study has therefore included long-distance power transmission in the comparative appraisals. As a result it can be said that overhead power lines with high voltage direct current (HVDC) transmission are a highly efficient, low-cost means of transmitting energy to even remote spots in Europe. No storage facility can be erected for the same costs. As well as connecting generation and load centres, such long-distance power lines can also then be used for accessing remote storage capacities at low cost. However, most projects for constructing such long-dis-

tance power lines are doomed because of a lack of acceptance in the population. Here the political sector has to create resilient general conditions to facilitate the implementation of power line construction projects as the most favourable alternative in general economic terms within a reasonable time frame; or the population will have to accept that alternative solutions are going to cost more.

Using storage facilities will not be able to avoid grid expansion completely. 24/7 transfer of the constant output from a wind farm requires transmission capacity amounting to at least 25-30% of the wind farm output. A far higher transmission capacity is required for load-oriented input respectively for the additional provision of control power.

On the markets for control and reserve power, storage systems currently compete with the thermal power stations which are still available in adequate quantity and which are able to provide power at low costs and quickly by releasing the throttling mechanisms, or in a less dynamic process from the rotating reserves. However, the available reserves will disintegrate quickly with the pending shutdown of power stations for reasons of age. This could result in generation bottlenecks above all in the case of widespread, long-lasting periods with no wind. In principle, the conditions for operating storage facilities would then improve, as new power stations have to work at full costs; this refers particularly to gas turbines which are suitable for short-term operation. Bottlenecks would then also have to be expected in the case of primary control power, as it is not possible to throttling mechanisms cannot be released arbitrarily in the case of a smaller thermal power station park. Wind turbines and photovoltaic systems should also be involved in primary and secondary control as the lowest cost alternative in general economic terms. Germany is now following this path at least for wind turbines with the new EEG, by paying an additional system service bonus for participation in holding the frequency. And in other countries, such as Ireland for example, the grid connection guidelines for wind turbines already stipulate integration in primary control as a requirement.

Battery storage systems can provide power very quickly; in principle, they are therefore also suitable for primary control. But the current market situation means that singular use of battery storage systems for this purpose is not yet economically efficient.

In contrast to a power station, storage facilities have more possibilities on the income side. For example, they can also absorb negative control power. In times of surplus supply, they can therefore avoid having to reduce or shut down power station output which always entails uneconomical or volatile power station operation (with increased emission levels). Storage facilities are particularly beneficial when fulfilling a combination of several functions.

There are practically no time restrictions on the availability of gas turbines, as long as the necessary natural gas is available. They can therefore be used to bridge even longer lasting periods without wind of several days or weeks: as a rule, storage systems are not suitable here. One exception to this rule is hydrogen, which can be stored in adequate quantity in underground caverns and used in gas turbines. However, far greater efforts must be made in research and development for this particular application to ensure that suitable solutions for these situations are available in good time.

In addition to the storage of energy, measures are also possible on the load side to achieve a partial decoupling of generation and demand. The aim here is to use as much energy as possible directly, i.e. without interim storage. But this kind of load management requires a change in approach from the current situation, where power is available on demand at any time and in practically any quantity.

Electricity tariffs with a variable time component respectively remuneration models for the provision of grid services will be needed as prerequisites for making load management acceptable. In view of the emerging generation situation with a high share of renewable energy, consideration should be given to whether under these changing general conditions it is still appropriate to do away with electricity night storage heaters and service water tanks, as these systems are ideal for load management while working on an outstanding efficiency level.

It should be noted here too that contracts for control power are awarded according to the rules of the game on the market: favourable conditions boost business; but subsequent increases in supply bring the prices down. Therefore it cannot be presumed that conditions which may appear favourable today will still apply unchanged in the future. This must be taken into account both for storage systems and for the mentioned alternatives, particularly where corresponding investments are linked to a long service life.

The challenge of an environment-friendly energy supply that is essentially independent of imports will have to bring about a change in approach on the transport sector as well, with the need to move away from fossil fuels and inefficient combustion engines. An increasing number of vehicles with electric drive systems will also boost the demand for mobile energy storage systems. This refers primarily to batteries, or to hydrogen in the form of fuel cells. Compared to hydrogen systems, batteries offer the great advantage that the electricity generated from renewable energy sources is far more efficient in use than hydrogen (by a factor of 2 – 3). In addition, refuelling from the electricity grid brings clear advantages when it comes to the necessary infrastructure, which is essentially already in existence. Given the limited range possible with one battery charge, systems with hydrogen in combination with fuel cells could be an appropriate addition to the storage concept. Both together open up huge potential for decoupling power generation and demand, and thus also facilitate synergetic effects for the grid as well. As with the introduction of the EEG, it is up to the political sector to work together with the automotive industry, utility companies, grid operators and local authorities in order to create the corresponding general conditions for a corresponding market launch.

Following the introduction of the EEG, the political sector now follows a course which makes it possible to bring new technologies onto the energy market for a sustainable reduction in emissions and in the current dependence on energy imports. By creating reliable conditions, renewable energy sources are thus given a chance to acquire notable shares of the market without being exposed to the rules of the game. But the aim in the long term is to generate electricity also from renewable energy sources under competitive market conditions. Meanwhile energy generated from renewable sources, particularly wind turbines, has reached such a high level that corresponding integration in the existing infrastructure already comes up against its limits, as it was not conceived for this purpose. Following this course consistently is therefore a political necessity, also with regard to grid integration, adaptation of the power station fleet and consumer behaviour. This also applies to creating the general conditions required for setting up the necessary storage capacities which will permit investment in infrastructure measures under reliable conditions, including accelerated permit procedures for adequate expansion of the grid.

Many of the described storage technologies still show considerable potential for development, but this can only be realized in the framework of larger quantities. Some technologies are still in the very early stages of development with corresponding demand for further R&D. And so new technologies on the energy storage sector will struggle to get established on the market at all without corresponding start-up support, such as incentive programmes along the lines of the EEG, but even then this will take far too long. There is therefore a risk of getting stuck half way in expanding the renewable energies so that the ambitious targets will have been set in vain.

In terms of finding a solution that is tenable for the national economy as a whole, it is necessary to strive for the best possible combination of grid expansion, load management, the use of storage facilities and the possibility of making fast adjustments to power station output. This can only succeed in a pan-European approach to ensure that one country's problems are not simply offloaded onto the neighbouring countries.

The following steps are recommended in order to narrow down the need for further action:

- Quantification of the scope for balancing out the supply of renewable energy sources on an international scale that can be achieved in a European context, and of the ensuing necessary expansion of the transmission network.
- Quantification of the additional balance of load and generation that can be achieved with load management.
- Integration of incentive systems in existing funding instruments in order to promote storage systems near to the generation site, ensuring that storage systems will also be used once these become economically competitive.
- Specific promotion of storage system development, particularly the development of battery systems as the key technology for electric vehicles.
- Enhancement of system-related research into large-scale hydrogen generation and storage respectively into the corresponding components, particularly with regard to exploiting the financial and technical synergetic effects of using hydrogen as automotive fuel and from the seasonal storage of electrical energy.

7 Glossary

Energy content / effective content

A certain quantity of electricity (net) is required for each defined task (requirements profile) for which a storage system is to be used. A corresponding effective content (gross) must therefore be stipulated for the storage system which must be sufficient for fulfilling the corresponding task. This also has to take account of the storage system’s discharge efficiency.

In order to actually tap this effective content, for technical and financial reasons the storage system will usually require a far larger energy content. The energy content is crucial when rating the storage system and thus for the costs of the actual energy storage facility.

Storage period, charging and discharging period

The decisive parameter when choosing the suitable storage technology is the period in time it is expected to cover. Here it is important to distinguish between operating period and storage period. The operating period (charging and discharging period) is the time it takes for the storage system to absorb or supply energy in a certain application case. The storage period is the time during which this energy remains stored in the system between a charging and a discharging cycle. The requirements profile for a storage system is described by a complete cycle.

Efficiency levels

The storage efficiency level differentiates between charging/discharging losses and stand-by losses (self-discharge during the storage period).

Frequency of use/number of cycles

The frequency of use indicates how often the effective energy available in the storage system is withdrawn from the system. As a rule, this is stated as full-load cycles, even if the storage system is not always used with its full capacity for many practical applications.

Access time/control speed

The access time defines the time it takes until a storage system can produce the power according to the requirement profile on demand. The control speed is an indicator of the power adjustment reaction to corresponding changes in the setpoint values.

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