POSITION PAPER

Energy Storage Systems

The Contribution of Chemistry

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1 INTRODUCTION

1 Introduction

The German energy transition ("Energiewende", the shift in German energy policy targeting a fundamental transformation of the fossil-based energy system towards a renewable-based and sustainable energy system) poses a major challenge to the adaptive capacity of the national energy system. By 2050 it is aimed to reduce greenhouse gas emissions by 80% to 95% compared to its 1990 level. The overall aim is to reduce primary energy consumption by 50% and gross power consumption by 25% compared with 2008. For the transport sector the target is a 40% reduction of final energy demand compared with 2005. A further objective is to cut primary energy demand in buildings by around 80%. These reductions are to go hand-in-hand with a significant increase in energy efficiency in all sectors. In addition to these reduction targets a long-term objective is to boost the integration of renewable energies to cover 60% of gross final energy consumption and at least 80% of gross electrical power consumption by 2050 [1].

This significant integration of renewable energies will result in a far-reaching paradigm shift, requiring acceptance by society as a whole to tackle the challenges these changes pose. The prerequisite for the energy transition to succeed and, therefore, maintain our prosperity, is to retain our strong industrial base and its qualified labour force and to create new ones through innovations in new technological areas.

In the power sector, renewable energies include not only base-loadable hydroelectric power and biogas, but also increasingly wind and solar energy. This type of power generation, however, is not demand-side oriented. This requires the future energy system to react both to potential supply shortfalls and excesses. The integration of the hitherto 25% share of power from renewable sources (already 30% in the first half of 2014) and considerably lower shares of renewable energies in the heat and fuel sectors has so far been achieved by making minor adjustments and using existing technologies. Nevertheless it is already evident that further measures to increase flexibility together with innovative storage options will be essential in the power sector if the share of intermittent and fluctuating electricity fed into the grid continues to rise.

While the various energy grids deal with spatial imbalance between supply and demand, energy storage systems can address the temporal dimension. This function does not necessarily have to be fulfilled by the same form of energy or by just one technology element alone. The resulting advantage of deploying energy storage systems is twofold: increased flexibility, and moreover these technologies can also boost the integration of renewables into other energy sectors, such as heat supply, transport or energy-intensive industrial processes, thereby fully exploiting temporary surpluses.

Power storage technologies are in different stages of technological maturity. Hence, R&D efforts will have to be stepped up if the aims of the energy transition are to be achieved without jeopardising consumer comfort and at an acceptable price for industry and the general public. Generally a significant increase in power storage capacities to harness temporary surpluses and stabilise the grids is desirable; however, this cannot be achieved without major investments.

The obvious solution to the problem of adapting electricity generation to fluctuating power generation by wind and solar would be to increase the use of gas turbines which allow very flexible operation. This option is currently not viable for economic reasons: the market value of electricity is currently too low and the gas price incurred through generating electricity in gas turbines is too high. This option, however, should serve as a reference case for economic analyses of other power storage concepts.

Whereas the issue of power supply and its storage already features prominently in the public debate, the emphasis is on security of supply. Hitherto, however, the other energy sectors, heat and transport, and their energy supply systems do not attract the same level of attention in the public debate. Chemical storage systems, in particular, facilitate extensive linkages between the different energy supply systems and application areas, while exploiting their specific individual advantages.

The key factors determining the selection of technologies for the future are the investment costs of the required storage units and the variable costs associated with the procurement of fossil energy carriers and CO_2 certificates. Further factors are public acceptance and market penetration of electric vehicles. The latter would open up new perspectives for managing an intermittent power supply. Ultimately, the political framework will be decisive.

To limit one's view to Germany would be counter-productive, since international interconnectivity, for instance through the European power grid or the international energy markets, is already a reality. In this context it should be borne in mind that the expansion targets for renewable energy integration envisaged by the German federal government differ from those of the European Union.

Definition of Energy Storage Systems

An energy storage system is able to take up a certain amount of energy in a controlled manner (charging), to contain this energy over a period of time relevant in the specific context (storage) and to release it over a period of time in a controlled manner (discharging).

2 Overview of available technologies and technology options

2.1. Power storage technologies

The increasing feed-in of electricity from intermittent wind and photovoltaic power generation has revolutionised the management of electrical energy. Power storage technologies will become increasingly important. Ideally they could become one element of the base load capacity at times of low input from renewable sources, however the reality is still a long way off. Mechanical storage technologies, both existing and under development, can absorb and release electrical energy. This characteristic also applies to electrochemical storage based on various battery concepts. Technologies that lead to chemical storage systems, by contrast, simply represent an additional load to the grid. They can, therefore, absorb excess electrical energy, but a separate facility, such as a gas turbine, is required for subsequent reconversion into electricity.

If sufficient additional users were available in the network to cover supply peaks from regenerative power (for example, the European grid or users that can adapt their needs to the supply, like electric vehicles or small, decentralised units, for instance in private households, etc.), this would only necessitate flexible back-up capacities to bridge shortfalls.

Measure or storage technology	Operating reserve	Scale	Geographical structure	Storage time frame	Notes
Grid expansion	+/-	GW	EU, regional and national, local, isolated	–	To eliminate bottlenecks and improve distribution
Import / export of electrical energy	+/-	GW	EU	–	Grid expansion, limited by cross-border interconnectors
Pumped hydro storage	+/-	GW (national), MW (regional)	Regional and national	Hours - days	Little expansion potential in Germany
Compressed air energy storage	+/-	GW (regional)	Regional and national	Hours - days	Caverns, mainly in the north of Germany
Flywheel	+/-	kW - MW	Isolated, local	Seconds - hours	High performance density, low energy density
Electrochemical storage	+/-	kW - MW	Isolated, local, regional	Seconds - hours	
Power-to-X, water electrolysis	-	MW	Local, regional and national	Days - years	Downstream methanation or fuel production possible
Gas turbine, combined heat and power	+	MW	Local, regional and national	–	Reconversion into electricity through combustion of H_2 or CH_4
Fuel cell	+	kW-MW	Isolated, local	–	Reconversion into electricity of H_2 or CH_4
Power-to-heat with high-temperature heat storage	+/-	MW	Local	Hours - days	Reconversion into electricity in steam turbine

Table 1: Overview of power storage technologies

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The following technologies are available for such cases:

- Fast-response gas turbine power plants
- Mechanical energy storage systems: pumped hydro storage plants or flywheels, which convert electrical energy into potential or kinetic energy.
- Electrochemical energy storage: various types of batteries in which electrical energy is converted into chemical energy by an electrochemical reaction.
- Hydrogen, as an energy carrier, is produced by water electrolysis. Hydrogen can be stored by physical or chemical means and re-converted into electricity in fuel cells by an electrochemical reaction or used as fuel in a gas turbine.
- In addition, hydrogen can be transformed by various processes into other energy carriers of interest, such as methane, methanol and higher hydrocarbons. Methane potentially provides a link to the natural gas grid with its well-developed infrastructure, including storage capacities; liquid energy carriers could be stored like conventional fuels.
- Thermal energy storage: the storage of greater quantities of heat at average temperatures for deferred use is becoming increasingly important for efficient combined heat and power plants, but primarily for the operation of solar-thermal plants for heat and power production.

The above-mentioned storage systems would have to be charged during peak production periods.

Table 1 lists various options for power storage and grid stabilisation together with their salient characteristics.

Some of these technologies can also be used for isolated applications (houses, farms, small businesses) or for local communities (computer centres, industrial estates, onshore wind farms). The dictates of cost-efficiency require that the investment costs of any solution must be reconciled with an

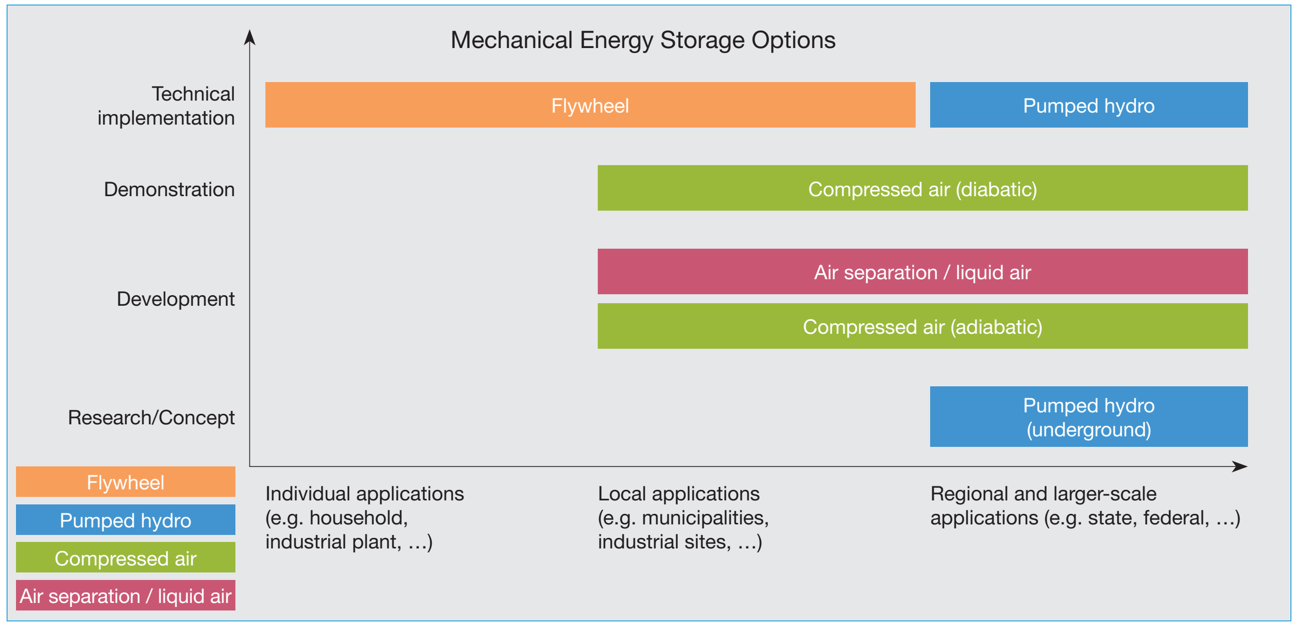

Figure 1: State-of-the-art mechanical energy storage technologies

anticipated relatively low number of operational hours or that sufficiently long hours of operation can be guaranteed by interlinking different segments of the energy system. The technical status of various energy storage technologies is classified in the following figures. The different technical stages represent a rough categorisation according to the following criteria:

- "Research/Concept" describes the investigation of the basic operating principle of a process on a laboratory scale or its theoretical feasibility based on theoretical studies. (Operating principle)

- Based on the proof of the operating principle in the Research/Concept phase, "Development" describes the continuation of the activity with the aim to derive the technical parameters necessary for its implementation. (Technical feasibility)

- "Demonstration" describes the operation of a plant/process chain on a technically relevant scale. The requisite parameters for cost-effective operation of the plant can be determined. If a process is applied in only a few isolated plants worldwide, it also falls within this category. (Economic feasibility)

- "Technical Implementation" describes state-of-the-art, commercially available processes scaled-up for cost-effective operation. (Economy of scale)

Figure 1 presents state-of-the art mechanical processes for storing electricity.

Besides mechanical processes, electrochemical processes are also suitable for electrical energy storage, see Figure 2.

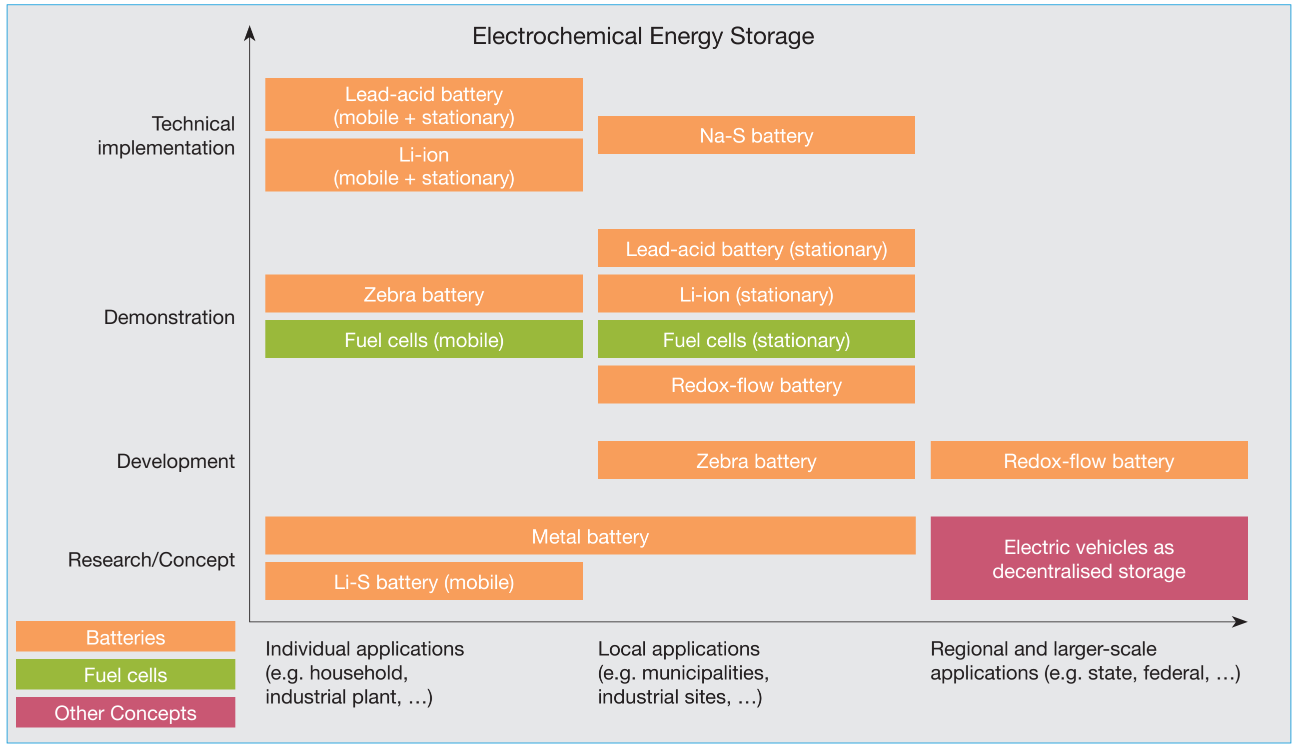

Figure 2: State-of-the-art electrochemical processes for electrical energy storage

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2.2. Thermal energy storage

In contrast to the power sector, heat supply and demand are in close proximity to each other. Heat is transported and distributed by local and district heating networks to supply buildings, and also by steam networks at different pressure levels for industrial processes. Similar to power storage, thermal energy storage requires a storage medium; the energy densities are given by the physical properties of the storage medium in question. In general, the necessary heat is supplied by means of the combustion of (fossil) energy carriers or of resistance heating from electrical energy.

In the low-temperature range, water-based stores are used as hot and cold thermal energy storage systems in buildings, thus they can back-up local and district heating networks. More recent developments permit the use of phase change materials (PCM) and also zeolites as thermal energy storage media. In the high-temperature range, by contrast, ceramic materials are predominantly used in industrial processes (e.g. steel and glass industries), since they are capable of withstanding extreme conditions and are relatively inexpensive. In-between these temperature extremes, liquid molten salts are applied, for instance, for solar-thermal power plants (see Chap. 3.2).

Thermal energy storage based on chemical reactions, for example the reversible conversion of hydrogen to hydrides, is a relatively new development. Chemical reactions as a thermal storage option are characterised by high energy density, a wide range of temperatures and practically unlimited storage capacity when the reactants are separated. Figure 3 depicts an evaluation of various state-of-the-art thermal storage technologies.

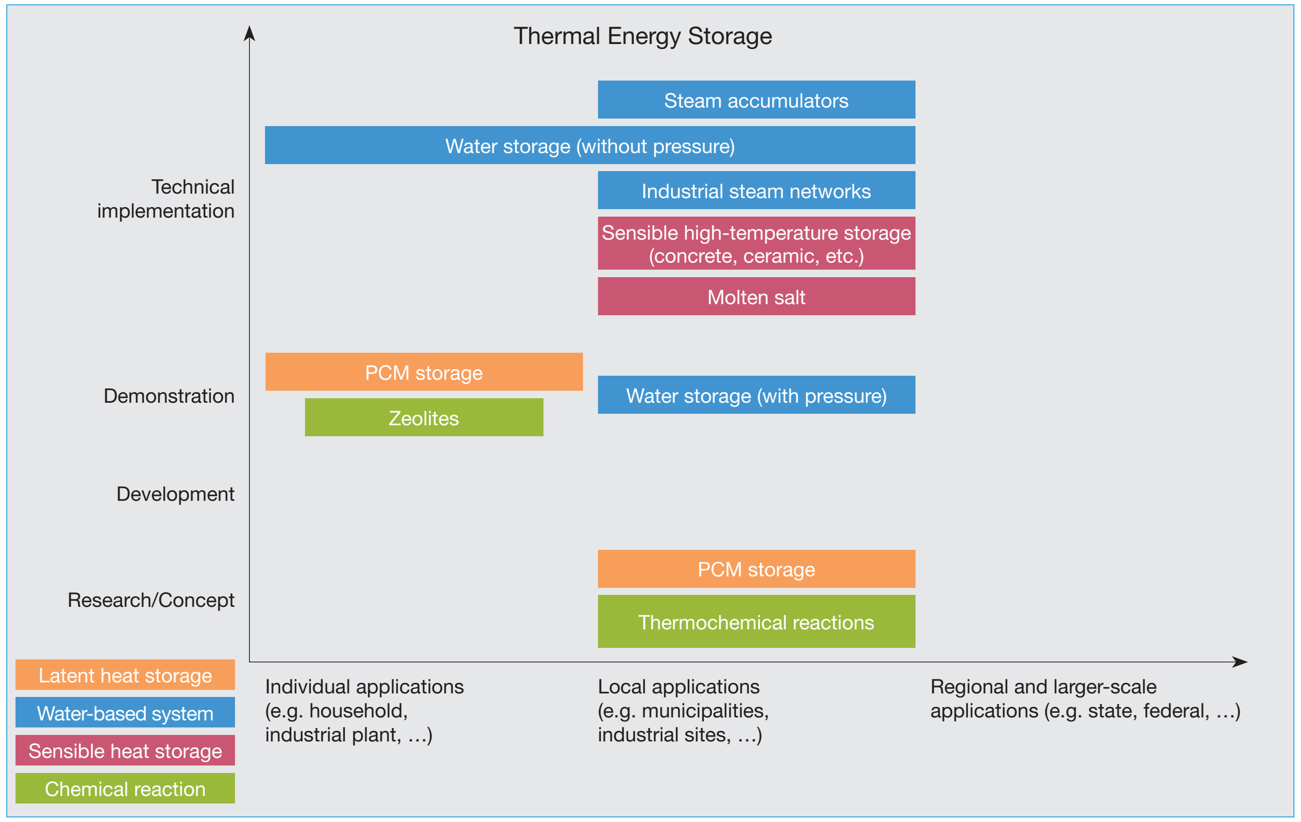

Figure 3: State-of-the-art thermal energy storage technologies

2.3 Power-to-X and chemical energy storage concepts

What all 'power-to-X' concepts have in common is the transformation of electrical energy into a different form of energy. These concepts are frequently based on the assumption of an excess[1] of electrical energy which is then available at low cost for further conversion.

The term 'power-to-X' covers the following groups of technologies:

- Power-to-gas: the conversion of electrical energy into gaseous energy carriers is based on hydrogen production by electrolysis of water. Hydrogen can be used as an independent energy carrier and, for instance, be deployed in the transport sector via fuel cell vehicles. This requires a suitable physical or chemical hydrogen storage capacity. Alternatives to the storage of hydrogen and its reconversion into electricity include its application as a feedstock for industrial processes (petrochemistry, chemistry, steel, metal processing, glass, etc.) or further transformation into other energy carriers/raw materials. One of these follow-up processes is methanation. Methanation is classified under power-to-gas, since methane is a gaseous energy carrier that can be used as a substitute for natural gas, is storable and opens up access to the heat sector.

- Power-to-liquid (including power-to-fuels): the conversion of excess electricity into liquid energy carriers also proceeds via electrolysis of water with subsequent processes leading to liquid fuels, for example via Fischer-Tropsch synthesis or methanol production. This concept primarily addresses the transport sector. The storage of hydrogen by means of liquid organic hydrogen carriers (LOHC) also falls into this category.

- Power-to-chemicals: these routes target the production of industrially relevant chemicals for further use as raw materials in chemical and industrial processes. Again, the first step is hydrogen production by water electrolysis. In principle, any process using hydrogen as feedstock, for example the conversion of CO_2 into methanol or formic acid, could be used.

Ultimately the conversion of excess power into heat, addressed in the previous chapter, should also have a place in this classification (power-to-heat).

The application of power-to-X technologies is motivated by the availability of (exergetically) very high-quality energy in the form of electricity, for instance from intermittent renewable energies that cannot be used directly by other consumers (excess electrical energy). A further option is to integrate renewable energies into other energy sectors and also to provide energy carriers or raw materials from "domestic production" for industrial use. This has the potential of reducing dependence on raw material imports of fossil energy carriers.

Figure 4 provides an evaluation of various technological elements for chemical energy storage technologies, the availability being confined solely to the use of electrolytic hydrogen, since synthesis processes based on fossil materials are state-of-the-art.

1 However, "excess electrical energy" is a misleading term, since it is a law of physics that supply and demand must be balanced. The term denotes the feed-in (e.g. on account of the priority of renewables in the German Renewable Energies Act (EEG)) of electrical energy from renewable energy sources which exceeds current demand. Under certain circumstances this oversupply can even result in negative prices on the electricity markets.

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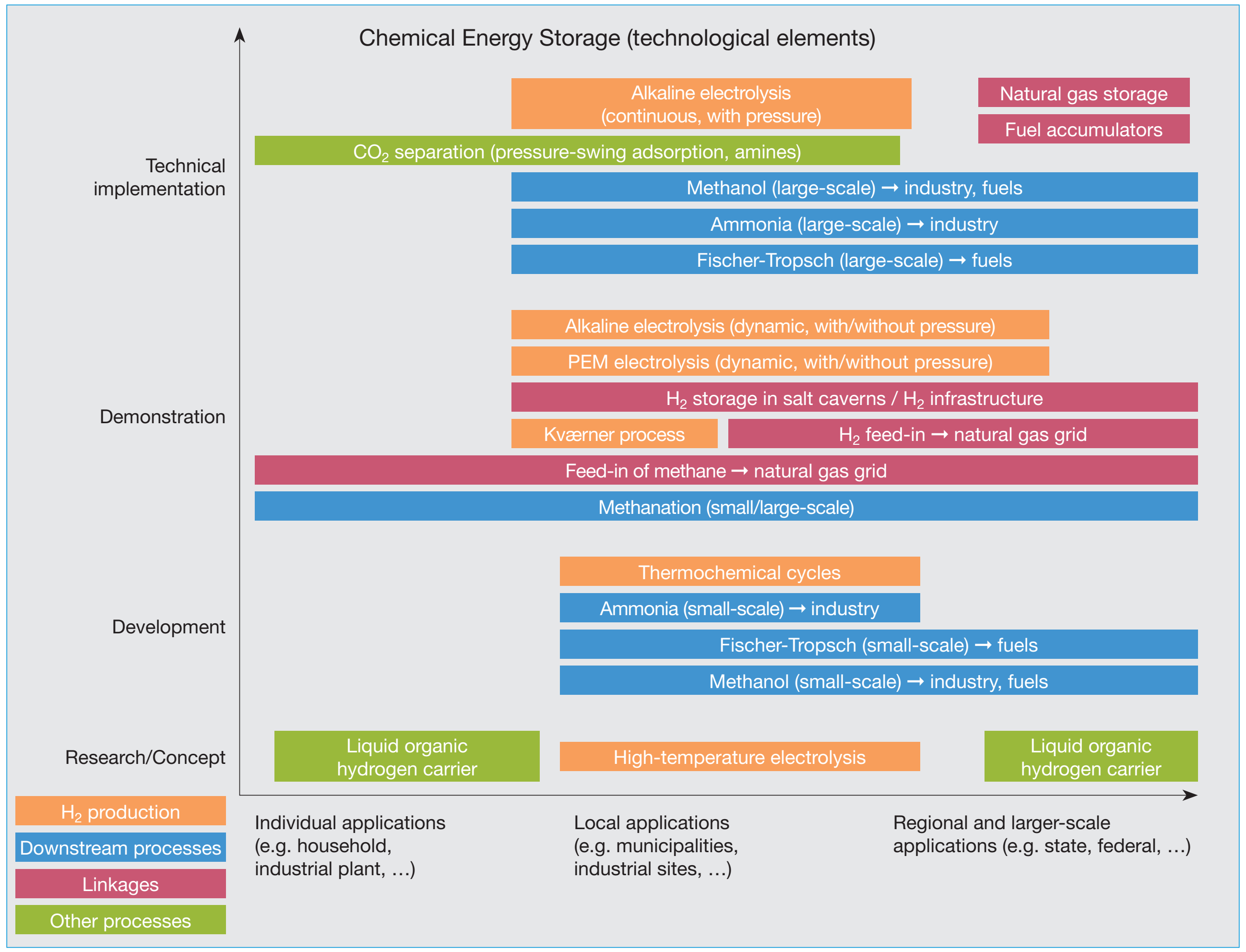

Figure 4: State-of-the-art chemical energy storage (individual technological elements)

3 Evaluation

Energy storage systems are of interest for electrical and thermal energy and also, in the form of chemical energy storage systems, for transport and industrial applications. The key demands on an energy storage system are high efficiency, low self-discharge, high capacity, high number of charging and discharging cycles, high performance and low costs coupled with a high degree of public acceptance. A glance at the available technologies reveals that no storage system fulfils all these requirements at present. They are all in different stages of development.

3.1 Established energy storage technologies

For pumped hydro energy storage and lead-acid batteries the state-of-the-art can be clearly specified. Moreover, flexible operation of large-scale industrial plants with high energy demands, and also, in part, of energy supply, has been practised for years and is well-established.

Nevertheless, a major challenge confronting all mature technologies is their profitability in the long-term and whether the requisite modes of operation can be reconciled with the increased demands of the future energy supply.

Battery energy storage devices with a capacity of 5 kWh for home use could well establish themselves in the market, since many householders might be attracted by the prospect of being self-sufficient in electricity from solar cells coupled with a storage device despite the still relatively high investment costs of approx. € 10,000 per installation. Larger-scale batteries are being tested in isolated projects.

3.2 Technologies currently under development

The interface between electrical energy and energy in chemical bonds holds the promise to become a key strategic element of the future energy system. In all current considerations this position is reserved to water electrolysis. There is, therefore, an urgent need for large-scale development of MW-class electrolysers for hydrogen production, dynamic operation being a major factor; further requirements include improved part-load capacity, higher efficiency and significantly lower investment costs than the current state-of-the-art. This is the starting point for R&D activities on the various strategies for exploiting hydrogen. Priorities are clean combustion for heat generation, its use in gas turbines and similarly direct conversion into electricity in fuel cells and further chemical transformation.

In addition, hydrogen can be used directly in fuel-cell vehicles, thereby replacing conventional vehicles. Since this avoids conversion losses, at first glance hydrogen would seem to be the most logical alternative from an economic point of view. However, this calls for a mass market roll-out of fuel-cell vehicles and an adequate, nationwide refuelling infrastructure. The entire chain from electrolysis to transport and compression of hydrogen for the refuelling process is quite complex. In principle, therefore, centralised hydrogen production and distribution via a refuelling network could be complemented by a decentralised system with vehicle owners using their own electrolysers. Apart from fuel-cell vehicles, battery-powered electric vehicles are another emission-free alternative to internal combustion engines. Once they have succeeded in penetrating the market, battery-powered vehicles could be classified as one component of the electricity grid, provided that charging and also, possibly, partial discharging can be controlled centrally and as a grid service. Intensive research into developing suitable, large lithium-ion batteries is on-going, particularly in Asia and the USA, and to a lesser extent in Europe.

Now that prices for Li-ion batteries have plummeted, they have become the battery of choice for light duty vehicles, since they no longer determine the overall vehicle price. The methanation of hydrogen and use of the gas grid for storage have implications for an extension of natural gas in mobile applications: at present the available infrastructure can circumvent investments in new filling stations and use available vehicle technologies. However, the emission benefits are lower and the overall energetic efficiency is low.

The vanadium redox flow battery is currently regarded as a promising stationary battery storage system. Meanwhile, the high-temperature sodium-sulphur battery is being produced and tested in Japan. At present, large battery storage systems cannot be operated economically; next to pumped hydro storage plants, however, they would be the most efficient power storage method in terms of overall efficiency.

In addition to storage technologies, load-shifting in households, commerce and industry is under discussion (demand-side management based on reducing the stress on the power grid). This definitely represents a means of smoothing diurnal load peaks and many consumers find a time-shift of around one hour acceptable. This makes it possible to compensate electrical storage capacities in the single-digit GW range. Hitherto heat storage has only been reported in individual cases (for example, high-temperature industrial processes and domestic hot water storage).

Nevertheless, R&D projects have been and still are addressing diverse types of thermal energy storage: molten salts as a storage medium in solar-thermal power plants to bridge

Conversion of \ Conversion into	Power	Fuels	Heat	Natural gas	Hydrogen	Industrial processes and value chains
Industrial processes and value chains	Operating reserve, DSM, hybrid processes, deferrable loads	Petrochemical industry	Integration of waste heat streams into district heating networks		Synthesis gas, chlorine-alkaline electrolysis	Products
Hydrogen	Combined cycle heat & power generation gas turbines fuel cells	(with CO_2): Methanol, Fischer-Tropsch	(Small-) Combined cycle heat & power, fuel cells	(with CO_2): Methanation with direct feed-in in natural gas grid	Storage vessels caverns	Chem. and petrochem. industries, steel industry
Natural gas	Combined cycle heat & power generation gas turbine	Via synthesis gas: methanol, Fischer-Tropsch	Combined cycle heat & power generation heating plant gas heating	Porous underground storage, caverns, natural gas grid	Steam reforming	Chem. and petrochem. industries
Heat	Steam turbine, organic Rankine cycle		Water, sensible heat storage, PCM, chem. reactions		Thermo-chemical cycles	Process heat
Fuels	Combined cycle heat & power generation	Storage vessels caverns	Oil-based heating, combined cycle heat & power generation		Synthesis gas	Chem. and petrochem. industries
Power	Mechanical storage, batteries	(with CO_2) Via hydrogen: methanol, Fischer-Tropsch	Power-to-heat	(with CO_2): Methanation with direct feed-in in natural gas grid	Electrolysis	Electrical process energy

Figure 5: Matrix depicting linkage options between various supply and application areas of energy. The fields contain the respective storage or conversion technology by which energy or storage types can be converted into each other or can be integrated into industrial processes. Example: Electrical Power (row) is harnessed via power-to-heat in the form of Heat (column). (Source: Ausfelder et al. [2])

the night hours, zeolites for air-conditioning in sunny regions (also by means of solar-thermal systems), and particularly paraffins as latent heat storage materials, the use of the reaction heat, and also concrete storage for adiabatic compressed air energy storage.

Hitherto the aim of thermal storage was to manage heat flows with a temporal delay. To date, combined heat and power has provided an effective linkage between the heat and the electricity market. Since heat costs generally correspond to the cost of the fuel used, there is only a business case for converting electricity into heat when electricity prices are extremely low. This is a situation that might confront us more frequently in the future.

3.3 Future technologies

Many different types of batteries have been investigated in the past decades, but only the nickel-hydride battery, and finally the lithium-ion battery, have succeeded in making a breakthrough. Both types are used in mobile electric devices (laptops, mobile phones, tools, etc.). Building on the success of the lithium-ion battery, various research groups worldwide are engaged in developing new battery systems, in the first instance by optimising lithium-ion technologies, but other examples are lithium-sulphur and lithium-air batteries. Even long neglected knowledge of various flow batteries is in high demand again, well-known examples being a zinc electrode in combination with an air, chlorine or bromine electrode, and also the iron-chromium flow battery.

High-temperature electrolysis has lower electrical power requirements compared to alkaline or PEM technologies on the one hand, but on the other hand it needs an external thermal energy source at an appropriate temperature level, for example from industrial processes.

In the area of heat storage, the use of chemical reactions is a good field for further development since they can be applied in extremely varied temperature ranges, allow high storage densities and permit loss-free long-term storage.

3.4 Linkage options

Storage technologies can be deployed in isolation or, using a systemic approach, link various supply strands of the energy system with one another. Chemical energy storage technologies, which, for instance, use electricity for water electrolysis to produce hydrogen, are predestined for this role. The hydrogen produced can then be utilised in fuel cell vehicles, thus serving the transport sector, or, after subsequent methanation, can be injected into the natural gas grid, thus supplying the heat sector. Since chemical storage systems can also be used as raw materials in industrial value chains, the various energy sectors are strongly interwoven and can create significant synergistic benefits. Figure 5 presents an overview of the possibilities.

4 Recommended Actions

Energy storage systems facilitate a temporal balance between demand and supply of energy; moreover, spatially separated means of production and consumption can be compensated by linkage via the various grids (e.g. the natural gas grid and the refuelling network for transport applications). By these means they can support the conventional power generation facilities which, despite their dwindling installed capacity of fossil-based fuels, will continue to make an important contribution towards stabilising the system in the medium-term.

Furthermore, chemical energy storage systems open up new, intelligent means of interlinking the various energy supply systems for electricity, fuel, gas and heat and of exploiting their respective advantages.

Present developments in our electricity system are characterised by considerably improved flexibility on the part of conventional power stations, in particular fossil ones, to adapt to just-in-time demand. This is matched by demand-side flexibility, both of the public sector and industry, to adapt to the momentary electricity supply or the momentary electricity price on the energy markets. The result is that the difference between high and low market prices for energy is not increasing, but on the contrary, for the last two years it has been decreasing. As a result, the return on energy storage systems (in particular pumped hydro) has also decreased. This has had a counter-productive impact on investments in further storage systems and consequently on R&D investments for new storage technologies. Both, however, are urgently needed. The situation will be aggravated in ten years' time when the last nuclear power stations in Germany are scheduled to be shut down. This will coincide with a further rise in the share of fluctuating feed-in of electricity produced from renewable sources.

Energy storage systems are needed both for isolated applications (e.g. for self-sufficient supply of homes equipped with PV) and local applications, and also to stabilise the grid (e.g. to buffer supply from wind farms); however, at the same time they are in competition with alternative solutions. In addition, they facilitate interconnectivity between different energy sectors. Storage systems are required both for the seconds-to-minutes range (e.g. in the case of a PV unit when a cloud passes by) and for longer periods (e.g. in wind-still conditions lasting several days with a correspondingly lower feed-in from wind turbines).

Pumped hydro storage is not sufficient to bridge longer periods of low electricity generation from renewables and has little potential for expansion. Currently, only systems based on chemical energy storage, in particular based on electrolytic hydrogen production from water, are deemed suitable. To minimise losses, hydrogen produced with excess electricity should preferably be used directly in chemical form. Priority should be given to its non-energetic use in industrial processes on account of the higher value-added. Additionally, but subject to prevailing regulations, hydrogen could be injected into the natural gas grid.

In principle, the direct use of hydrogen in the transport sector also falls within this category; however, it has to contend with a small fuel cell fleet and corresponding absence of an adequate hydrogen infrastructure.

Large-scale production of hydrogen based on renewable electricity opens up additional pathways for subsequent conversion into various chemical energy carriers of interest: the production of combustible and engine fuels, such as methanol, methane and higher hydrocarbons with CO_2 as the carbon source, and reversible bonding in compounds (for instance with aromatic hydrocarbons such as LOHC) for use as hydrogen on-demand.

The main advantage of conversion into methane is that injection into the natural gas grid fully exploits the existing infrastructure. From today's perspective it is impossible to generalise whether hydrogen, methane, methanol or other compounds will prove to be the most promising form of energy storage; that will depend on technological progress and the general economic situation.

In all probability, however, subterranean caverns for temporary hydrogen storage will be necessary for all routes in order to buffer production peaks and permit continuous chemical processing.

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4 RECOMMENDED ACTIONS

The great advantage of the reaction of hydrogen with CO, CO_2 or N_2 is that it opens up two pathways for potential use: as a chemical energy storage medium and as raw material for chemical production. The benchmark is set by the individual application, for example petrol as an energy carrier that could potentially be replaced by synthetic fuels in the transport sector.

For all these options the determining factor is to maximise the efficiency of water electrolysis operating under highly intermittent loads and to reduce costs. In contrast to the subsequent down-stream processes, interim storage cannot smooth the intermittent operation of electrolysis (especially with long down times) unless an additional electrochemical energy storage device were to be integrated; this would involve increased costs and complexity. These inherent constraints signify that the investment costs of electrolysis plants must be significantly reduced to allow competitive hydrogen production despite intermittent operation.

The only suitable alternative to use of excess power in chemical storage media, besides mechanical energy storage, is electrochemical storage. However, this calls for concerted R&D efforts to develop batteries within the relevant range of capacity. Since redox flow batteries can be easily scaled-up, they have a certain inherent advantage when high storage capacities are needed, e.g. in combination with wind farms.

Many applications require maintenance-free operation. Batteries for the transport sector have their own specific requirements, important factors being high storage density and good shock resistance as well as safety in the event of a collision. Developments in the transport sector towards more electric vehicles should be considered with respect to power grid stabilisation, since they create a potentially useful battery pool. Research efforts targeting smaller battery systems are required for large-scale energy storage, electric vehicles and individual battery applications.

The conversion of power to heat (depending on the subsequent utilisation options at various temperature levels) and its temporary storage is yet another energy storage alternative that should be addressed. Although heat storage technology is an economically attractive proposition, public R&D funding has hitherto tended to neglect it.

For all storage options, whether in mechanical, chemical, electrochemical or thermal form, even more important than the theoretically achievable efficiency of the conversion chains will be their technical implementation; the decisive criterion, however, is profitability. There is a need for more intensive discussions focusing on the costs of power supply, since ultimately the major challenge will be not to store and use as much of the excess electrical energy produced as possible, but to store and use a high amount at the lowest possible cost.

The use of storage technologies should not be considered in isolation, but always in direct competition with other measures to deliver the required energy flexibility, such as limiting capacities or holding capacities in reserve. For an economic assessment, these options should be referred to as a basis for comparison.

In order to make an economic analysis of the various energy storage options it is essential to create a data set for comparison. It should be based on realistic assumptions as to supply fluctuation, performance data in long-term operation, and scale-up. Priority should be given to establishing and quantitatively describing entire energy storage chains in pilot and demonstration projects.

At the same time the potential of energy conversion and utilization pathways (electricity, gas, heat, transport, industrial use, for example in metal production and the chemical industry) can already be described, but must be considered with respect to their interdependencies and the energy-related and economic benefits of their interconnection.

Public R&D funding programmes must be geared towards long-term technological developments. A fundamental component of future research and technology policy is a positive public attitude towards technology. This applies both to individual elements of the respective conversion chain and to their optimum linkage in the overall system.

In view of the medium- and long-term need for energy storage technologies for a wide range of applications the promotion of basic research must not only offer incentives for the development of completely new approaches, but similarly for the elucidation of the underlying mechanisms and their impacts. The priorities for research and development can be summarised as follows:

- Low-cost water electrolysis capable of efficient part-load operation and with satisfactory dynamic response
- Advances in the chemistry and processing of hydrogen, targeting smaller-scale, cost-effective operation with potential for dynamic operation
- Batteries of different capacities adapted for use in various fields
- Thermal energy storage systems for different temperature levels and their system-wide application
- Assessment of the economic feasibility of the various energy storage chains in their entirety (including determination of the pertinent database)

5 Concluding remark

This Position Paper is based on a more detailed description and evaluation of a variety of storage options, which were compiled by the chemistry organisations DBG, DECHEMA, DGMK, GDCh, VDI-GVC and VCI with the collaboration of DPG [2]. This study was published in the January/February 2015 issue of Chemie Ingenieur Technik (CIT). An English translation for publication in Chemical Engineering & Technology is in preparation.

6 References

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Energy storage systems can contribute towards the transformation and stabilisation of the overall energy system. Besides the individual technologies themselves, diverse linkage options are a source of additional potential. This is where chemistry can make a fundamental contribution. In the present Position Paper "Energy Storage Systems – the Contribution of Chemistry" (status: January 2015) the participating organisations demonstrate the significance of the linkages between chemistry and energy and pinpoint potential for research and development.