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Electricity Storage in the Power Sector

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16. Electricity Storage in the Power Sector

16.1. Introduction

Electricity storage is identified as a key technology priority in the development of the European power system, in line with the 2020 and 2050 EU energy targets [European Commission, 2007; 2009; 2010]. Power storage has gained high political interest in the light of the development of renewables and distributed generation, as a way to reduce carbon emissions, to improve grid stability and to control the fluctuations of variable resources.

Power storage systems can benefit generators, transmission and distribution utilities, and end-users. They can balance energy flows, thus facilitating the integration of variable renewables, and can provide system services[70] and support to electricity infrastructure, such as asset deferral [EAC, 2008]. Among storage technologies commercially available or under development, the following systems are mapped hereafter: pumped hydro storage (PHS), compressed air energy storage (CAES), hydrogen and fuel cells, flywheels, supercapacitors, superconducting magnetic energy storage (SMES) and conventional/advanced/flow batteries.

The services needed by the power system indicate the technical requirements to be met by the storage devices suitable for energy and for power quality applications. Energy applications differ from power applications mainly for the discharge time and the capacity involved.

For energy applications, a storage discharge time over several hours and a nominal capacity in the order of 1-500 MW are expected on the generation side, and of kW on the end-user side. Wind and solar curtailment avoidance, load shifting and forecast hedging are typical energy related applications. The most suitable technologies are pumped hydro, CAES, fuel cells and hydrogen and batteries (lead-acid, nickel-cadmium, sodium-sulphur or vanadium-redox).

Power applications are related to services provided for periods from a few seconds to less than an hour with a typical power rating lower than 1 MW. They are needed to face network disturbances requiring a response time in order of milliseconds for regulating voltage fluctuations,[71] and in the order of a few seconds for adjusting frequency fluctuations. Adequate technologies are flywheels, ultra-capacitors, SMES and some of the advanced batteries.

Figure 16.1 gives an overview of the power storage technologies, as a function of their commercial maturity stage and the power investment cost.[72] Applications suitable also for transport electrification, such as lithium-ion, hydrogen and supercapacitors are mapped with services provided to the power system only.

16.2. Technological state of the art and anticipated developments

A wide array of technologies and underlying principles - mechanical, electro-chemical and physical - is today available to store electricity, providing a large spectrum of performance and capacity for different application environments. The current installed capacities worldwide are around 127.9 GW [EPRI, 2010].[73]

Table 16.1 gives the main technical and economic features of the storage technologies which are mapped in this chapter. The various sources used for this review can provide different figures for the same technology. These sources might use different operational parameters, market indicators, prices and tariffs. Therefore intervals for some technologies can be large to withstand the uncertainty related to developing technologies, but also the specificities of project environments for different valuation methodologies.

Hydropower with storage

Hydropower with storage is a mature technology, being the oldest and the largest of all available energy storage technologies. The facilities are usually distinguished in two main categories: hydropower with reservoir and pumped hydro-storage (PHS). The basic principle of a PHS system is to store energy by

[70] System services are all services provided by a system operator to users connected to the system. Some users provide system services that are ancillary to their production or consumption of energy [EURELECTRIC, 2004].

[71] Voltage swells, impulses, notches, flickers, harmonics [EPRI, 2004].

[72] The on-line version of this document allows for an interactive overview of technologies as a function of their energy cost, efficiency and number of cycles.

[73] The following capacities are installed worldwide, admitting that the comparison of large- with small-scale capacities is not the purpose, and that the number of installed units should complement the size of capacities: PHS 127 GW, CAES 440 MW, Sodium-sulphur 316 MW, Lead-acid 35 MW, Nickel-cadmium 27 MW, Flywheels 25 MW, Lithium-ion 20 MW, Redox-Flow batteries 3 MW [EPRI, 2010], SMES 100 MW [EERA, 2011].

means of two reservoirs located at different elevations. In times of low demand, electricity from the grid is used to pump water to the higher reservoir, while in times of peak demand the water is released to generate electricity, hence operating a reversible cycle of grid electricity.

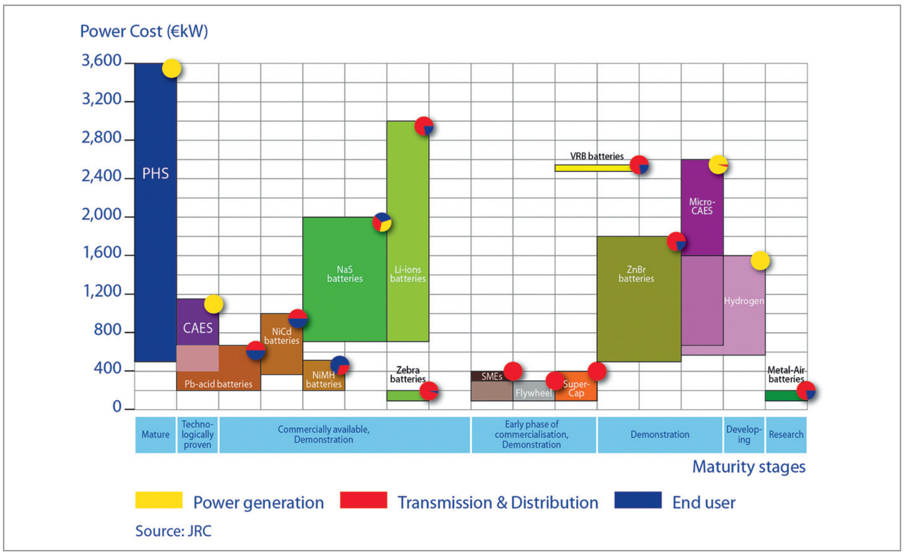

Figure 16.1: Power storage technologies as a function of their cost and development stage [Source: JRC]

In Europe, the installed capacity of pure hydro-pumped storage amounts to approximately 40 GW. It is estimated that by 2030, about 50 % of the currently installed capacity of hydro-pumped storage in Europe will have to be refurbished due to ageing [SETIS, 2008]. Some of these projects have already started and moreover, they have been optimising the turbine and pumps system in order to increase the generation capacity, for example, in the Alpine region, where new and larger converter units have being added to existing storage basins [RRI, 2008]. The capacity of planned or ongoing projects in Europe is estimated to about 7 GW to be built by 2020 mainly in Switzerland, Austria, Portugal, Germany and Spain [Deane et al., 2008]. Additionally, the large pumped hydro-storage potential existing in Norway, estimated to 10-25 GW of new projects, could be further exploited, triggered by the large deployment of wind power in the North Sea [Haaheim, 2010; SETIS, 2009].

Main barriers to the installation of new pumped hydro-plants are the environmental concern and the public acceptability when projects might affect the resource availability and inundate the ecosystem. New PHS plants require usually large electricity transmission infrastructures, which might raise political, social and regulatory issues. The initial investment costs are high, the construction time could be long up to 15 years along with the time lag for obtaining the approval for concession rights and connection to the grid [ETSAP, 2010]. Life cycle emissions related to the construction of a PHS storage facility are in the range of 35 tCO_2eq/MWh_e of storage capacity [Denholm and Kulcinski, 2004].

The main advantages of PHS systems are high storage capacity, quick start capabilities, low self-discharge, long technical life-time and high number of cycles, which make the technology suitable for regulation provision and for supporting the variable electricity generation. The main applications are load shifting, price arbitrage, tertiary and secondary reserves for up and down regulation, as spinning or standing reserve, peak power supply, forecast hedging, grid congestion avoidance, load following, energy balancing and seasonal fluctuations regulation [EPRI, 2002].

Recent technological advances are mainly related to the double stage regulated pump-turbine, which gives the possibility to utilise a very high head for pumped storage. This provides higher energy and efficiency, and also variable speed drive. This allows wider grid support and better economics, flexibility and reliability [Deane et al., 2010; EPRI, 2004]. Further developments concern the challenges to the technology of using sea water, as at present only one scheme has been built that uses the sea as lower reservoir, i.e. in Okinawa, Japan [Peters and O'Malley, 2008]. Alternatives to conventional geological formations are PHS plants using underground reservoirs [Ekman and Jensen, 2010] or former opencast mines, e.g. from granite mining in Estonia [Kruus, 2010] and from coal mining in Germany [Schulz and Jordan, 2010].

Storage technology	PHS	CAES	Hydrogen	Flywheel	SMES	Supercap	Conventional Batteries		Advanced Batteries			Flow batteries	
							Pb-acid	NiCd	Li-ion	NaS	NaNiCl ZEBRA	VRB	ZnBr
Power rating, MW	100-5000	100-300	0.001-50	0.002-20	0.01-10	0.01-1	0.001-50	0.001-40	0.001-40	0.5-50	0.001-1	0.03-7	0.05-2
Energy rating	1-24h+	1-24h+	s-24h+	15s-15min	ms-5min	ms-1h	s-3h	s-h	min-h	s-hours	Min-h	s-10h	s-10h
Response time	s-min	5-15 min	min	s	Ms	ms						ms	ms
Energy density, Wh/kg	0.5-1.5	30-60	800-10000	5-130	0.5-5	0.1-15	30-50	40-60	75-250	150-240	125	75	60-80
Power density, W/kg			500+	400-1600	500-2000	0.1-10	75-300	150-300	150-315	90-230	130-160	15-30	50-150
Operating temp (°C)				-20 - +40		-40- +85				300-350	300	0-40	
Self-discharge (%/day)	~0	~0	0.5-2	20-100	10-15	2-40	0.1-0.3	0.2-0.6	0.1-0.3	20	15	0-10	1
Round-trip efficiency	75-85	42-54	20-50	85-95	95	85-98	60-95	60-91	85-100	85-90	90	85	70-75
Lifetime (years)	50-100	25-40	5-15	20+	20	20+	3-15	15-20	5-15	10-15	10-14	5-20	5-10
Cycles	$2x10^4$-$5x10^4$	$5x10^3$-$2x10^4$	10^3 +	10^5-10^7	10^4	10^4-10^8	100-1000	1000-3000	10^3-10^4+	2000-4500	2500+	10^4+	2000+
Power cost €/kW	500-3600	400-1150	550-1600	100-300	100-400	100-400	200-650	350-1000	700-3000	700-2000	100-200	2500	500-1800
Energy cost €/kWh	60-150	10-120	1-15	1000-3500	700-7000	300-4000	50-300	200-1000	200-1800	200-900	70-150	100-1000	100-700

Note. The power price reported for hydrogen relates to gas turbine based generator. The power price for fuel cells is in range of 2 000-6 600 €/kW.
Sources: Schoenung and Hassenzahl, 2003; Chen et al., 2009; Beaudin et al., 2010; EERA, 2011; BNEF, 2011b; Nakhamkin, 2008.

Table 16.1:Technical and economic features of power storage technologies

Compressed air energy storage (CAES)

In CAES systems, the energy is stored mechanically, usually in underground caverns, by compressing the air from the atmosphere. A typical CAES system is a combination of natural gas combustion and high pressure of the compressed air to drive the turbines. When electricity is required, the compressed air is drawn from the cavern, then heated in gas burners and expanded in a gas turbine [Lund and Salgi, 2009; Hadjipaschalis et al., 2009].

The compression of air creates heat, whilst air expansion causes cooling. The way the heat and cooling are processed generates three categories of thermodynamic processes:

1) Diabatic CAES, where the compressed air is stored and the heat from the compression is lost. When energy is needed, gas turbines are used to reheat the compressed air. The efficiency is in range of 40-54 %, but alternative designs of cycles exist and result in improved efficiency rates [BNEF, 2011b]: CAES with recuperated cycle; CAES with combined cycle; CAES with steam-injected cycle; CAES with humidification.

2) Adiabatic CAES (AA-CAES), where the heat resulting from the compression process is stored and is reused when the compressed air is released. Heat can be stored in solid, fluid or molten salt solutions, at temperatures from 50 to over 600 °C [Bullough et al., 2004]. Compared with a diabatic system, the AA-CAES does not need additional gas co-firing, and the energetic process is more efficient (70 %).

3) Isothermal compression, which employs a thermo-dynamically reversible cycle, where the temperature is maintained constant by allowing continuous heat exchange during air compression and expansion. The process approaches a theoretical efficiency of 100 %.

Two CAES facilities are currently in operation, one in Germany in Huntorf built by Alstom Power in 1978, with a rated output power capacity of 320 MW and a discharge average of 3 hours per day [RWE, 2010]; and the second in Alabama, USA built by Dresser-Rand in 1991, with a rated power output of 110 MW and a discharge time up to 10 hours during weekends [Ibrahim et al., 2008]. Additional CAES facilities are under different stages of planning, construction or demonstration in USA (1 500 MW) [BNEF, 2011b], Germany (300 MW) [RWE, 2010], Italy (25 MW), Israel (300 MW), South Korea (300 MW), Morocco (400 MW), Japan and South Africa [Chen et al., 2009].

Life cycle emissions related to the construction of a CAES facility are in the order of 19 tCO_2/MWh of storage capacity [Denholm and Kulcinski, 2004]. However, the main source of emissions for CAES is linked to the natural gas consumption.

Main advantages of CAES are the large storage capacity, relatively fast time response and fast ramping rates, no self-discharge and long life time. CAES plants are designed to sustain frequent start-up/shut-down cycles, and can swing quickly from generation (discharge) to compression (charge) mode or can be designed to operate them simultaneously. The technology is therefore suitable for applications such as load following, time shifting, peak shaving, price arbitrage, frequency regulation (tertiary reserve), seasonal fluctuation regulation, grid decongestion, assets deferral, voltage control [EPRI, 2002]. One feature of the new generation of proposed CAES plants is that they may be closely integrated with wind farms, presenting a means of firming the capacity of wind energy [RRI, 2008].

The economic and technical performance of CAES plants, although based on mature components, is expected to continue to improve. This is mainly due to the possibility to use different designs for the basic process, such as different degrees of inter-cooling and humidification, and improved heat integration leading to a simplified high pressure turbo-expander design and less NOx emissions [Baker, 2008]. There are also cross-synergies within the power sector due to the use of common components with gas turbines.

Improvements in the CAES operation are expected along with the identification of new locations, such as compressed air storage in vessels or above ground (CAS or SSCAES, i.e. Small Subsurface CAES). These are small-scale CAES systems, where the air is stored in fabricated high-pressure tanks. They are independent of geology, and they can hot start in seconds and cold start in minutes.[74]

Further advances are to be noted for the adiabatic process, with the project ADELE in Germany [RWE, 2010], with 300 MW of generation and a storage capacity of 1 000 MWh, for daily charging and discharging operations. Expected improvements

[74] BNEF documents a project under discussion in USA of 1 MW, with a capital cost of $10 800/kW and $2 700/kWh, based on an isothermal process and targeted efficiency of 90% [BNEF, 2011b]. For comparison purposes, the German CAES power plant in Huntorf has a capital cost of $485/kW and $121/kWh, and a round-trip efficiency of 42 %.

are higher efficiency (70 %), no gas combustion and a longer lifetime, comparable with heat plants, 30-40 years. The cost is higher than for diabatic CAES ($1 500/kW, $380/kWh) [BNEF, 2011b]. Cost reductions are expected for the converter and the heat storage.

Hydrogen-based energy systems

Hydrogen can be produced using electricity via reversible water electrolysis. It can be stored and transformed back into electricity by means of a fuel cell or a combustion engine/turbine. The main components are the electrolyser unit which converts the power into hydrogen, the hydrogen storage system and the convertor which transforms hydrogen back into electricity [Chen et al., 2009]. Suitable large-scale storage locations are underground caverns, salt domes and depleted oil and gas fields.

The concept of hydrogen-based energy storage is currently in a demonstration phase with a focus to back-up wind farms in remote areas. The world's first-of-a-kind demonstration project was run in 2004 in Norway, in the Utsira Island, (Figure 16.2), in connection with a wind farm [Ulleberg et al., 2010]. Other demonstration projects in Europe based on wind-hydrogen hybrid systems can be found in Unst, Shetland Islands, UK, in Nakskov, Denmark, in Keratea, Greece; and in Galicia and Aragon, Spain.

Considering the main advantages such as the large energy capacity, high energy density and the very low self-discharge, the technology appears suitable in connection with very large wind farms, in support to power grids in isolated systems or in systems where grid reinforcement is very expensive. The main services provided are seasonal storage, wholesale arbitrage, time-shifting, forecast hedging, secondary and tertiary reserve, grid bottleneck avoidance, and voltage support [EPRI, 2004; Chen et al., 2009].

The current lines of future technical progress are reducing the system cost, increasing the efficiency, scaling-up electrolyzer systems and increasing the fuel cell durability and lifetime [Ulleberg et al., 2010]. Important cost reductions and performance improvements for fuel cell systems are expected from synergies with the on-going research and demonstration efforts on hydrogen and fuel cell technologies in the transport sector.

Batteries

Electrochemical batteries store electricity through a reversible chemical reaction. The essential components are the container, the electrodes (cathode and anode) and the electrolyte. By charging the battery, the electricity is transformed into chemical energy, while during discharging, it is restored into electricity. Conventional batteries have a standard design (lead-acid, nickel-based batteries), while advanced batteries have higher performances (lithium-based, sodium-based batteries). Their storage and discharge take place in the same structure. By contrast, flow batteries (vanadium-based, zinc-bromine) present a different design where the electrolyte is stored in a separate container.

Conventional batteries

Lead-acid batteries (Pb-acid) have a mature technology base, suitable for large power quality applications. Nickel-cadmium batteries (NiCd) are also mature and popular systems, with a higher density and longer life than Pb-acid, but contain environmentally-unfriendly toxic metals. Nickel-metal hydride batteries (NiMH) are an alternative to NiCd, have no toxic material and have a higher density but also higher loss rates [Chen et al., 2009].

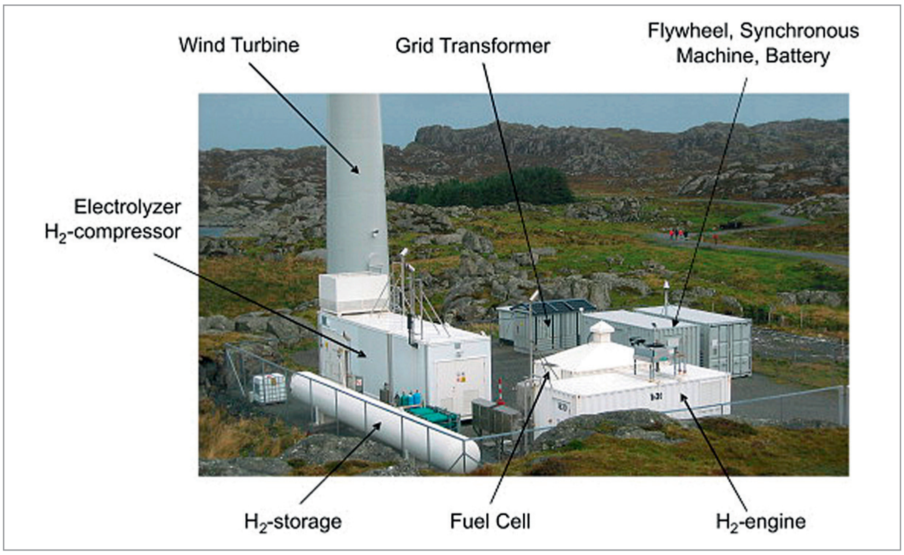

Figure 16.2: Photo of the Utsira wind/hydrogen demonstration plant [Ulleberg, 2010]

Most common applications are for power quality, such as grid reliability, frequency control, black start, uninterruptible power supply (UPS) systems, and also spinning reserve and peak shaving (EERA, 2011). If there is no restriction on volume and weight because of their low energy density, good candidates are lead-acid batteries because of their economic cost, and nickel-cadmium because of higher rates of charging/discharging capabilities. When energy density is important, NiMH is the suitable technology.

Lead-acid batteries are commonly used in stationary and automotive applications. Despite low energy density, moderate efficiency and in some cases, the need for maintenance, these batteries have a relatively long lifetime and robustness, in addition to low costs when compared to other types of battery. Several large stationary projects based on lead-acid batteries have been performed worldwide to improve grid performances, as for instance in Berlin from 1988 to 1997, for frequency regulation and spinning provision. Demonstration projects, such as the European FP6 programme DEMO-RESTORE, test the robustness of lead-acid batteries in support to PV systems.[75]

Despite advantages of NiCd over Pb-acid batteries in terms of energy density and number of cycles, projects are limited because of the harmful environmental impact of cadmium. The European Directive on batteries and waste 2006/66/EC[76] prohibits batteries containing cadmium above a fixed threshold and introduces recycling measures. NiCd batteries need maintenance and have memory effect, which is much less significant in NiMH systems.

Advanced batteries

Different chemical types are currently being used for stationary applications, such as lithium-ion (Li-ion) and sodium-sulphur (NaS). Li-ion batteries have very high efficiency, high energy density, fast charging and light weight. They are therefore suitable for small-scale applications, mostly developed for consumers, PV support and vehicles. Whereas, NaS batteries are primarily suited for large-scale applications and long-daily cycles for energy management.

Lithium batteries rely on the properties of lithium metal, the most electropositive and lightest metal. Therefore, a high energy density storage device can theoretically be achieved in a more compact system. The advantage in using Li metal was first demonstrated in the 1970s and it is undergoing important research development worldwide. Two types are available: Lithium-Ion (Li-ion) and Lithium-Polymer (Li-pol). Lithium-ion is the most mature lithium technology to date. Transport and mobile applications have so far been the main drivers for its development. However, the future prospect of PV energy has recently revived a strong interest in lithium-ion batteries.

The costs of lithium battery modules are still quite high. The deployment of Li-ion in support to renewables will require further cost reductions, particularly in research in materials and manufacturing techniques [Hall and Bain, 2008]. For instance, sodium-ion technology follows the same principle as Li-ion and is further investigated as an interesting alternative to lithium's scarcity and cost price increase [European Commission, 2011]. An alternative to lithium-ion technology is lithium-ceramic. The largest lithium ceramic battery in the world has been developed in Germany, with a power of 1 MW, storage capacity of 700 kWh, efficiency rate of 96 %, and very low self-discharge rate, see Figure 16.2.[77]

Current research is ongoing on the development of new cathode and anode materials, on safe non-flammable electrolytes, on materials for new cells and battery designs and on the improvement of the temperature operating window [European Commission, 2011]. Further demonstration projects for large systems and also for small residential applications are necessary to validate the robustness of batteries in supporting renewables.

Sodium sulphur batteries consist of molten sulphur at the anode, molten sodium at the cathode, and a solid beta-alumina electrolyte membrane which allows the battery to function without self-discharge [Chen et al., 2009; Hall and Bain, 2008]. The battery is based on a high temperature electrochemical reaction between sodium and sulphur (~ 300 °C), which implies losses with heating. Therefore the technology is suitable for short-term storage with daily, long-cycle applications such as energy management, e.g. load-following and peak-shaving.

The main manufacturer is NGK Insulators (Japan). NaS batteries have significant potential to become cost-effective, modular and bulk medium-scale

[75] http://ec.europa.eu/research/energy/pdf/synopses_electricity_en.pdf
[76] Directive 2006/66/EC of the European Parliament and of the Council of 6 September 2006 on batteries and accumulators and waste batteries and accumulators and repealing Directive 91/157/EEC.
[77] http://corporate.evonik.com/en/content/product-news/Pages/storing-the-sun.aspx

Figure 16.3: XXL lithium-ion batteries made by Evonik Industry. The technology stores solar energy and releases it when there is no sunlight. [Source: Evonik Industries[78]]

storage deployed at a large scale, since no material constraint limits their manufacture [BNEF, 2011a]. The market is expected to grow from the current 316 MW to more than 1 GW by 2020 [BNEF, 2011a]. In Europe, several demonstration projects have been conducted in Germany (Berlin-Adlershof), Spain (Gran Canaria Facility) and France (Reunion Islands). Applications on islands, aim at optimizing the electrical mix, e.g. to support renewables integration and to reduce fossil-fuel-based technologies. Current research is ongoing on beta-alumina membrane and new electrolytes, and on reducing corrosion risks of container materials [European Commission, 2011].

Sodium-nickel-chloride (NaNiCl) or Zebra batteries are similar to NaS but are able to operate at a broader temperature range (-40 to +70 °C) and have better safety characteristics [Chen et al., 2009], presenting however lower density than NaS. Zebra batteries are produced by MES-DEA (Switzerland) and further research is conducted at its Beta R&D centre in the UK. Main services are in automotive and mobile applications, but also in stationary systems in support to PV and wind, for load levelling [EERA, 2011]. Although there are few applications to the grid, some projects are being tested in Europe, such as the Livorno Test Facility in Italy [Fastelli, 2010].

Other advanced batteries, such as **Metal-Air** systems, are currently at different basic research stages. To date Zinc-Air and Lithium-Air are the most advanced. These are very compact systems and are therefore limited to small-scale applications. Research initiatives are ongoing, as the German STROM programme [European Commission, 2011], and they focus on the improvement of the porous air design, electrical rechargeability and system safety.

Flow batteries

In flow batteries, the electrolyte is stored in a tank separated from the cell stack, decoupling thus the power system from the energy capacity. The storage capacity can be increased by adding more electrolytes combined in series or in parallel [EERA, 2011]. Therefore, flow batteries could be easily scaled up to very large capacity. They have a large number of cycles and high discharge rates (~10 h), which make them suitable for large storage systems and high energy applications [Chen et al., 2009]. With low energy density, flow batteries are large and heavy, being more suitable for small-to-medium scale applications. Potential services are peak-shaving, back-up supply, power supply in remote areas, support to renewables, asset deferral. Fast response time, in order of sub-milliseconds [Beaudin et al., 2010], makes the technology a good candidate for power quality applications, UPS and voltage support.

Several flow battery types are under different stages of R&D, such as polysulphide bromine, vanadium-vanadium, vanadium-polyhalide, cerium-zinc, lead-lead, etc., but two main types raised more interest: zinc-bromine (Zn-Br) and vanadium-redox (VRB) flow batteries. Zn-Br batteries have a lower cost than VRB, while VRB are more efficient and have a longer life time.

Both Zn-Br and VRB batteries are in an early phase of commercialisation. European manufacturers for VRB include Cellstrom (Austria) and REDT (UK and Ireland). On the research side, the National Power Institute (UK) developed a system based on polysulphide-bromide (Regenesys) in the early 1990s. Demonstration projects in Europe are in Spain (La Gomera Facility), Ireland (Sorne Hill

[78] http://corporate.evonik.de/en/content/product-stories/Pages/energy-source-of-the-future.aspx

wind farm) and Denmark (Riso Research Institute). Further research focus, on increased energy density, improved membrane performance, new stack design and cost reduction [European Commission, 2011]. For VRB in particular, the replacement of vanadium media with vanadium bromide, the so-called second generation of VRB flow batteries, allowed to increase the energy density and to find further applications in mobile devices [EERA, 2011].

Flywheels

Flywheel systems store energy mechanically in the form of kinetic energy by rotating a mass around an axis. On charging, the flywheel is accelerated, and on power generation, it is slowed. The core element of a flywheel is a rotating mass which is connected to a main shaft (rotor) powered by an external source of energy. In revolving, the mass builds up inertial energy. In discharge mode, the kinetic energy is released when the rotor is switched off. The use of flywheels as an energy storage device was first proposed for electric vehicles and stationary power back-up in the 1970s. Flywheel systems are generally distinguished between low speed (up to 5 000 rpm) and high speed systems (up to 50 000 rpm) [Lazarewicz and Rojas, 2004].

Flywheel systems have the advantage of high cyclability, high energy efficiency and fast response time. The main applications are power related such as short time support in distributed power systems, including power quality for sags and surges lasting less than 5 seconds, UPS for outages lasting up to 10 minutes, voltage regulation, and support for flexible alternating current transmission systems (FACTS). Flywheels can provide ride-trough power with generators, as well as short-time support for systems providing ancillary services such as spinning and standby reserves. They can be combined with batteries to cover short-duration events and save batteries life-time [EERA, 2011].

In Europe, the project SA2VE (Spain) tests the applications of flywheels in three sectors: stationary applications for railway transport, energy management in buildings and the quality of power supply.[79]

Research and development aim at increasing the energy density, for instance through increased angular velocity, and to reduce energy losses because the system has a quite high self-discharge rate. However, increasing the rotational speed of the flywheel poses severe constraints on the bearings. Hence, magnetic bearings are used, in addition to maintaining the flywheel housing under a partial pressure or vacuum to reduce the drag force due to high rotational energy. Research on low cost and high strength composite materials would influence the development of flywheels, such as high strength fibres and high temperature superconductors. Further research focuses on improved safety and design for the deployment in residential systems, along with cost reductions [EERA, 2011; European Commission, 2011].

Supercapacitors [80]

The basic principle of a capacitor is to store the electricity in an electrostatic field formed between a pair of conductors (two electrodes of opposite polarity) separated by a dielectric or insulator layer. Main differences between conventional capacitors and supercapacitors are enlarged electrode surface areas, the use of a polymer membrane and of a liquid electrolyte instead of the dielectric solid material. In these electrochemical systems, the capacitive properties of the electrolyte-electrode interfaces, known as electrochemical double layers, are exploited to store energy [Hadjipaschalis et al., 2009; Chen et al., 2009; Naish et al., 2008].

Electrochemical capacitors are in different stages of R&D, although some devices are becoming commercially available. In Europe, demonstration projects are in Spain for ultracapacitors (STORE project in Canary Island, La Palma Facility in Los Guinchos) and for supercapacitors to optimize hydrogen-based systems (the EU FP6 project HyHeels).[81]

Supercapacitors have low maintenance needs, very fast charging and discharging times and they can stand many cycles. They are good candidates for frequency and voltage regulation, pulse power, factor correction, VAR support and harmonic protection. They have the potential for fast acting short term power back-up for UPS, transmission line stability (FACTS devices), and spinning reserve provision. They find applications in support to renewable energies and in smart grid systems [Beaudin et

[79] http://www.aicia.es/2/sites/aicia.es/files/IA-AICIA-2007-ing.pdf
[80] Terminology: Super capacitors are referred to also as electro-chemical capacitors, ultra-capacitors, ultra-high capacitance capacitors, and double layer capacitors [European Commission, 2011].
[81] http://ec.europa.eu/research/transport/projects/items/eu_funded__hyheels__takes_new_approach_to_fuel_cells_en.htm

al., 2010]. Coupling supercapacitors with batteries is a prime option to extend both the peak power capacity of batteries and the energy density of supercapacitors.

The technology is also suitable for road transport applications to capture and store the energy from regenerative braking, and to supply acceleration power for electric vehicles. Other applications are in aerospace field, as they can withstand severe temperature conditions and power emergency events; and in cranes and elevators to capture energy along downward motion [EERA, 2011].

Research is currently on going on nano-carbon materials as a promising route to increase energy and power densities [Hadjipaschalis et al., 2009]. Efforts are on improved capacitance and control of pore sizes, to increase the cycle life and the charge-discharge operations. New electrolyte solutions are also tested (solvents/ salts/ ionic liquids) in synergy with research on batteries [European Commission, 2011].

Superconducting magnetic energy storage (SMES)
SMES stores energy in a magnetic field. Once a DC electric current is injected into a superconducting coil, it creates a magnetic field where the energy is stored. It is then released when this closed circuit is opened. Up to now, coils are mainly built from niobium-titanium (NbTi) and cooled by liquid helium [Wolsky, 2002]. Emissions incurred during the manufacture of SMES facilities are about 962 tCO_2/ MWh stored [Hartikainen, 2007].

The capacity installed of SMES units is over 100 MW worldwide [EERA, 2011]. Research prototypes have been developed up to 1 MW in Italy, Germany, Finland and Spain; while successful demonstration projects operating at 20 K have been run in Germany, Finland, France, USA and South Korea [Hall and Bain, 2008]. The technology is at a mature development stage; however, only micro-SMES systems (1 to 10 MW) are commercialised.

A hybrid-storage type with a flywheel system is the Inertial Energy Storage system (INES). The basic principle consists in the rotation of a flywheel under levitating conditions with a self-stable magnetic bearing including bulk superconducting materials and magnets. The essential components are the flywheel, a power conditioning system and a vacuum vessel [European Commission, 2011].

A SMES stores electrical energy directly, without converting it into another form, so it can release the energy very quickly. The system has very high efficiency, fast response and is suitable for power quality applications, to provide active and reactive power, voltage support for critical loads, static VAR compensations, transmission lines stability and smart grid applications [EPRI, 2004; EERA, 2011].

Main SMES disadvantages are that they require large installation surfaces, and that materials only become superconducting at extremely low temperatures (0–273 °C). A research topic is the development of larger systems with higher energy density. Research efforts concern low temperature superconductivity but also high temperature systems to can reduce the cost. Additional research on these high temperature materials is needed to increase the critical current and magnetic field and to develop manufacturing processes enabling high production volumes. More efficient cryogenic cooling systems, high magnetic field and mechanically secure structure are key for future SMES development [EERA, 2011].

16.3. Market and industry status and potential

The European industry has currently a strong market leadership in large-scale energy storage technology, but it needs to maintain this industrial excellence [SETIS, 2008]. Three market leaders for hydro-pumped storage are based in Europe, and among them one company alone owns 40 % of the market share worldwide. Although the European know-how is widely used around the world, international competitors, such as Chinese manufacturers, are entering the market at a fast pace. As for CAES technologies, although they are not widely deployed, one of the two plants currently in operation was built with European technologies, while European manufacturers are actively evaluating adiabatic CAES concepts [RWE, 2010]. However, it has to be noted that six other projects on advanced CAES systems (second generation and isothermal CAES) are under construction or planned in the US [BNEF, 2011b]. For fuel cell and hydrogen technologies, the establishment of a Joint Undertaking in 2008 is contributing to the development and strengthening of the European industry.

For small-to-medium scale technologies, the European industrial base is weaker, although dynamic. Despite world-class European manufacturers of batteries and supercapacitors, the overall battery market is dominated by Asian manufacturers. This contrasts with the excellence of European research at the origin of decisive breakthroughs, which enabled the commercialisation of lithium batteries over the past 40 years. As this market is expected to grow significantly in the coming decades, accompanying the deployment of PV systems, for instance, now is the opportunity to strengthen the European industry. R&D programmes on advanced lithium storage, such as the Franco-German industrial project SOLION,[82] are indicators of the potential of Europe to play a critical role in this field.

Storage units currently operating in Europe are mostly in the form of hydro-storage plants, but interest is growing for other storage technologies. Forecasting the future needs in storage capacity is strongly dependent – among others – on the developments of the future electricity technology mix, of the trans-European power network and of the electrification of transport. Compliance with grid code requirements for wind and solar technologies is one of the main influencing drivers for storage expansion [Martinez et al., 2007]. Grid codes setting the connection rules are constantly upgraded and several Member States, e.g. France and Germany, have revised them for high voltage and medium voltage levels, in order to account for the increasing penetration of renewables [Tsili et al., 2008]. Furthermore, unlike hydropower, there is no assessment of the potential for pumped storage in Europe. One of the main reasons is that a new pumped storage plant can be greenfield or based on existing reservoirs, out-of-use mines and quarries, the sea, etc.

Electrification of road transport provides an evident ground for synergies with power storage. R&D on batteries and fuel cells for the development of plug-in hybrid vehicles and fuel cell vehicles will reinforce the development of storage. Technological development in other areas, such as power electronics, ICT and smart grid technologies, can further drive storage evolution.

16.4. Barriers to large-scale deployment

The main barriers facing electricity storage belong to four categories: technological issues, market uncertainty, regulation and economics [EAC, 2008].

Technological issues: Performance is the most decisive for most technologies which are currently at different stages of development, as shown in Figure 16.1. Except for PHS, all the technologies require R&D efforts to improve their operational characteristics and to reduce their costs. Simultaneously, installing more storage capacity depends on the availability of suitable geological formations (PHS, underground CAES and hydrogen) and on the access to materials and resources (batteries). At current extraction rates, some resources, e.g. zinc and lithium, could limit the large-scale development of technologies, such as Zn-Br and lead-acid batteries [European Commission, 2011; Beaudin et al., 2010]. Therefore, proper disposal and recycling are needed to ensure the sustainable development of storage.

Market uncertainty: Storage development faces uncertainties surrounding the power sector evolution, such as the level of variable renewables, the carbon price, the level of baseload technology deployment, e.g. nuclear power, and the level of demand side measure effectiveness in curbing and peak shaving energy consumption. Therefore it is urgent to advance the analytical framework by building scenarios on the future requirements for electricity storage.

Estimating the storage potential represents a key issue in the planning process of the transition of the European power system towards a low-carbon system and the investment in storage applications needs to be synchronised with the investment in electricity generation, as well as in transmission and distribution. For instance, the large Scandinavian hydropower storage potential can be further exploited in order to contribute with additional storage capacity to the whole European system, provided that grid connections are in place with Germany and UK, or reinforced with the Netherlands and Denmark [SETIS, 2009].

Regulation: The role of regulation is crucial for transmission and distribution utilities to help storage operators address their project specificities and for defining a clear business case [SETIS, 2008]. With the increasing penetration of distributed and variable energy sources, there is a need to further develop regulatory aspects on power quality at the European level and to contribute to integrate storage while defining grid extension planning and renewable integration targets. For example, in most of the Member States, storage is charged with grid fees both for power consumption and for generation. However, the regulation improves along with the constant increase in renewables. In Germany, the revision of the Energy Industry Act proposes to exempt new storage facilities from grid fees.[83]

[82] http://www.saftbatteries.com/SAFT/UploadedFiles/PressOffice/2008/CP_33-08_fr.pdf
[83] https://www.bmu.de/english/energy_efficiency/doc/print/47609.php

Economics: The capacity of electricity storage to provide multiple services to the power system is at the origin of the difficulty to assess its economics. In particular this is due to the fact that there is an overlap created between the levels to which storage contributes, i.e. generation, grid, end-user. For storage to be profitable, all multiple value streams need to be accumulated, and regulatory barriers must be removed. Establishing a framework to assess the economic potential of storage would enable the industry to take investment decisions and public authorities to support the development of electricity storage [SETIS, 2008].

The economic valuation of power storage in Europe faces the heterogeneity of power systems and power markets among Member States, since storage operation is strongly dependent on local conditions and regulation. However, outlining the framework of the market evaluation of storage represents one of the current priorities of the Information System of SET-Plan, SETIS [Loisel et al., 2010; 2011].

The development of a fully-integrated European power market takes into consideration all the options which can improve the flexibility of power supply and demand. Storage is clearly identified as part of the project and complements measures such as improved weather forecasting, new market-based approaches, demand control, cross-border interconnections, HVDC lines, power flow control technologies and smart meters [ETP, 2008]. Therefore strategic planning at the European level is required to inscribe storage technology and regulatory developments in the broader context of smart grid related activities and renewable energy integration.

16.5. RD&D priorities and current initiatives

Current initiatives on storage development are undertaken at the industry level, at the Member State level and at the European level. Two time-perspectives can be framed, as a function of their development stage. Short-to-medium term initiatives aim at attaining the commercial maturity and at accelerating the transition to mass commercialisation, while long-term actions consist in boosting the fundamental research on new technologies, new materials and new components.

The European Association for Storage of Energy (EASE), created in 2010 and launched officially in 2011, aims at building a common industry and stakeholders vision.[84] EASE objectives are to build a European platform for sharing information on storage and to help advance technological development, in connection with similar associations in USA, Japan, Australia and China.

With focus on the research and innovation, the European Energy Research Alliance (EERA)[85] includes a chapter "Smart Grids. Task 4.1 Electric Energy Storage technologies". It provides a review of storage technologies aimed at gaining a deeper knowledge in storage applications and capabilities to respond to grid needs from economic and technical viewpoints. In a later stage, the objective is to offer solutions which can be embedded in industry-driven research.

Focussed on batteries, the Association of European Automotive and Industrial Battery Manufacturers gathers more than 85 % of European industrial actors in the field and joins their R&D efforts in developing new solutions in areas such as electrical vehicles and renewable energy storage.[86]

The European Fuel Cells and Hydrogen Joint Technology Initiative aims to accelerate the development and the deployment of hydrogen-based technologies in a cost effective way through applied research programmes and demonstration projects.[87]

Ongoing or planned European projects financed under FP6 and FP7 programmes consist in creating networks of excellence to consolidate the European research in a particular field. For instance, the FP6 European virtual research centre ALISTORE[88] gathers 23 European research organisations structuring R&D activities on lithium systems and promoting nanomaterials. The FP7 European project MESSIB[89] focuses amongst others on solutions which reduce the energy consumption in buildings by advancing the research on materials, on phase change slurries, flywheels and VRB batteries. The FP7 project HESCAP[90] aims to develop a new generation high-energy supercapacitor based system. For the longer term perspective, EU research funding could focus on key components, i.e. for battery development, such as electrolytes, additives, new solvent solutions, new cells designs and post-lithium ion systems [European Commission, 2011].

[84] http://www.iea.org/work/2011/storage/Item11_EDF.pdf
[85] http://setis.ec.europa.eu/about-setis/technology-roadmap/european-energy-research-alliance-eera
[86] http://www.eurobat.org/
[87] http://www.fch-ju.eu/
[88] http://www.u-picardie.fr/alistore/alistore_presentation.htm
[89] http://www.messib.eu/
[90] http://www.hescap.eu/

All storage technologies need sustained RD&D efforts through demand pull and supply push actions. Demand pull policies can send a market signal to researchers and investors that there is a potential need for the technology (e.g. re-designed ancillary services markets). However, these measures mainly stimulate innovation through deployment and may lead to low amounts of additional R&D expenditure. Dedicated funds for research programmes, the creation of public-private partnerships, cost-sharing schemes, loan guarantees and prizes for achieving policy goals, are examples of supply push actions that would further stimulate innovation by providing additional expenditure. Industrial-scale demonstration projects for near-to-market deployment are necessary to build the industrial trust and to gain field experience in storage technologies [SETIS, 2008].

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Abstract

The Technology Map is one of the principal regular deliverables of SETIS. It is prepared by JRC scientists in collaboration with colleagues from other services of the European Commission and with experts from industry, national authorities and academia, to provide:

- a concise and authoritative assessment of the state of the art of a wide portfolio of low-carbon energy technologies;
- their current and estimated future market penetration and the barriers to their large-scale deployment;
- the ongoing and planned R&D and demonstration efforts to overcome technological barriers; and,
- reference values for their operational and economic performance, which can be used for the modelling and analytical work performed in support of implementation of the SET-Plan.

This third edition of the Technology Map, i.e. the 2011 update, addresses 20 different technologies, covering the whole spectrum of the energy system, including both supply and demand technologies, namely: Wind Power Generation, Solar Photovoltaic Electricity Generation, Concentrated Solar Power Generation, Hydropower, Geothermal Energy, Marine Energy, Cogeneration or Combined Heat and Power, Carbon Capture and Storage in Power Generation, Advanced Fossil Fuel Power Generation, Nuclear Fission Power Generation, Nuclear Fusion Power Generation, Smart Grids, Bioenergy - Power and Heat Generation, Biofuels for the Transport Sector, Fuel Cells and Hydrogen, Electricity Storage in the Power Sector, Energy Efficiency and CO_2 Emission Reduction in Industry (The Cement Industry, The Iron and Steel Industry, The Pulp and Paper Industry), and Energy Efficiency in Buildings.

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