TECHNICAL ANNEX

Joint EASE/EERA recommendations for a

EUROPEAN ENERGY STORAGE TECHNOLOGY DEVELOPMENT ROADMAP TOWARDS 2030

EASE
European Association for Storage of Energy

EERA
European Energy Research Alliance

The European Association for Storage of Energy (EASE) is the voice of the energy storage community, actively promoting the use of energy storage in Europe and worldwide. EASE actively supports the deployment of energy storage as an indispensable instrument to improve the flexibility of and deliver services to the energy system with respect to European energy and climate policy. EASE seeks to build a European platform for sharing and disseminating energy storage-related information. EASE ultimately aims to support the transition towards a sustainable, flexible and stable energy system in Europe.

EERA, the European Energy Research Alliance, is an alliance of leading organisations in the field of energy research. EERA aims to strengthen, expand and optimise EU energy research capabilities through the sharing of world-class national facilities in Europe and the joint realisation of pan-European research programmes (EERA Joint Programmes). The primary focus of EERA is to accelerate the development of energy technologies to the point where they can be embedded in industry-driven research. In order to achieve this goal, EERA streamlines and coordinates national and European energy R&D programmes.

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Hydrogen, Synthetic Fuels and Chemicals

Description and key property range

A hydrogen-based chemical storage system is a three-step process of converting surplus renewable electricity to hydrogen using electrolysis, storing the chemical energy as hydrogen or synthetic methane (or if convenient in the form of ammonia) in either the natural gas pipeline or local storage tanks, and discharging the stored energy for mobility (hydrogen fuelling for Fuel Cell Electric Vehicles) or power through a gas turbine generator or a fuel cell. A schematic of the Power-to-Gas and its options is shown below. The electrolyser splits pure water using an electric current into hydrogen and oxygen. In a future energy landscape with an increasing penetration of variable renewable generation sources, chemical energy storage represents an important CO_2-free option. The key attributes of Power-to-Gas are the rapid, dynamic response of the electrolyser to integrate variable renewable sources of generation and the unparalleled TWh storage capacity of the existing natural gas infrastructure. Surplus electricity can be stored on consecutive days or even consecutive weeks without the need to discharge it providing a seasonal storage capability.

Three types of electrolysers in focus: Alkaline Electrolyser (most mature and already commercialised), PEM Electrolyser based on Polymer Electrolyte Membranes (today only on small scale and as prototypes available), and high temperature electrolysis (able to split also CO_2, but still in R&D status). As for PEM Electrolysers two subgroups can be found defined by operation temperature.

Usually hydrogen produced in the electrolyser at technology specific pressures needs to be compressed to storage levels between 20 and 100 bars (or up to more than 700 bars for compressed gas storage for vehicles). Hydrogen can then be either stored above ground in gaseous form in steel or composite cylinders, in liquid form at temperatures of -253°C or at ambient temperature and pressures below 50 bars in solid state materials. For large scale storage, underground salt caverns are feasible.

Up to about 4-5vol% H_2 could also be injected into the natural gas grid. (The "NaturalHy-Study" financed by the EU as well as other studies have concluded that even higher concentrations of hydrogen could be acceptable). Finally with the addition of captured CO_2 e.g. from conventional or biomass power plants, hydrogen can also be converted to synthetic methane in a subsequent catalytic process. When injected into the natural gas grid in this form there is virtually no limit to the amount of energy that can be stored.

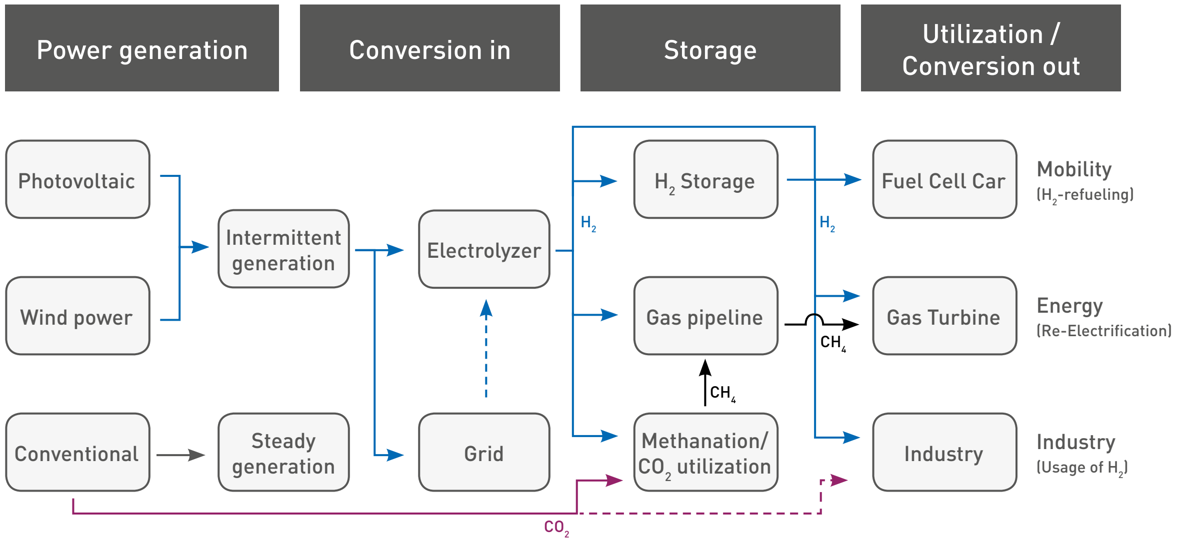

FIGURE 1 - Schematic of chemical storage pathways

Besides methanation, H_2 can react with N2 or CO_2 to form other chemicals such as ammonia, methanol, ethanol, formic acid and urea. Due to the abundance of methane in nature, synthesising these alternative chemicals will have more added value than SNG. These synthetic chemicals could pave the way for a new chemistry independent from fossil fuels.

The stored electricity in the form of chemicals can either be used directly for industrial purposes, for an upcoming hydrogen mobility or it can be re-electrified by fuel cells or - purely or admixed to Natural Gas, Biogas, etc.- using conventional combustion technologies (e.g. engines or gas turbines).

The efficiency of the complete conversion chain from Renewable energy via electrolysis to hydrogen/methane or other fuels and back to electricity can amount up to 40%, a level that is also typical for conventional coal fired steam power plants. While this round-trip efficiency is lower than other bulk energy storage technologies such as CAES or Pumped Hydro Storage, it provides a long term seasonal storage capability and the flexibility to discharge the stored energy wherever and whenever it is needed most through the existing Gas Turbine fleet (CCPPor peaker). The major losses occur during electrolysis (η~70% efficiency), (if required) in methanation (η~80%) and during re-electrification (η~40%-60%) (see figure below).

Currently there are many Power-to-Gas projects emerging in several European countries. Most of these employ alkaline electrolysers from various manufacturers like Hydrogenics, NEL and Enertrag. These components are available in size ranges from a few 100kW to several MW. Some companies (e.g. Siemens, Hydrogenics, GreenHydrogen and others) have dedicated Roadmaps towards commercialisation of PEM electrolysers which are expected to even better complement the very high ramp rates associated with variable renewable generation.

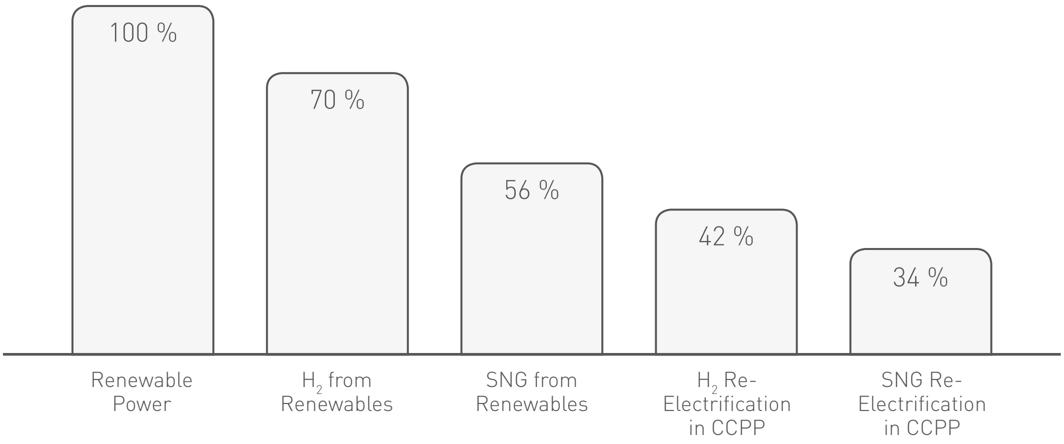

FIGURE 2 - Efficiency of hydrogen based chemical electricity

Critical gaps between needs and present performance

The major challenge for the chemical storage option is currently economics (i.e. reduction of CAPEX especially of the electrolysers) and availability of the components at large scale.

Secondly integration of the electrolysers in a compact and safe grid-connected facility without restrictions with respect to location and public acceptance is a major issue. In this context new storage media that can store hydrogen in a safe and compact way (e.g. at low pressure in suitable metal hydrides or in the form of chemical feedstock like ammonia) would mean a significant step forward. In this context specifically the transformation pathways from hydrogen to the different chemical feedstocks requires more detailed investigations.

Thirdly the storage and admixing topic will require further analysis, starting from the suitability of caverns for H_2 storage and ending at the admixing limit in the natural gas grid with the large variety of end uses for the gas.

Finally efficiency of the chemical storage systems must be further improved. Current commercially available low temperature Electrolysers can already achieve relatively high efficiencies (η~70%) and research efforts are underway to increase system efficiencies well above 80%. Besides reaching these efficiencies at higher current densities than today, there is room for improvement in the system design, e.g. pressurised operation, temperature control, electrical integration and power electronics. Further improvements in efficiency could in the medium run be expected from high temperature electrolysis. Since this technology is still not in a commercial phase there is still some way to go in order to transfer the lab results to a precommercial demonstrator.

Technically alkaline as well as PEM and solid oxide electrolysers will be suitable for transferring excess electricity to chemical storage media. Depending on the specific grid situation the one or the other electrolyser technology might be preferred: a grid situation with very steep gradients in load might favour low temperature electrolysers whereas applications close to base load operation will favour the highest efficiency devices which speaks in favour of high temperature electrolysers.

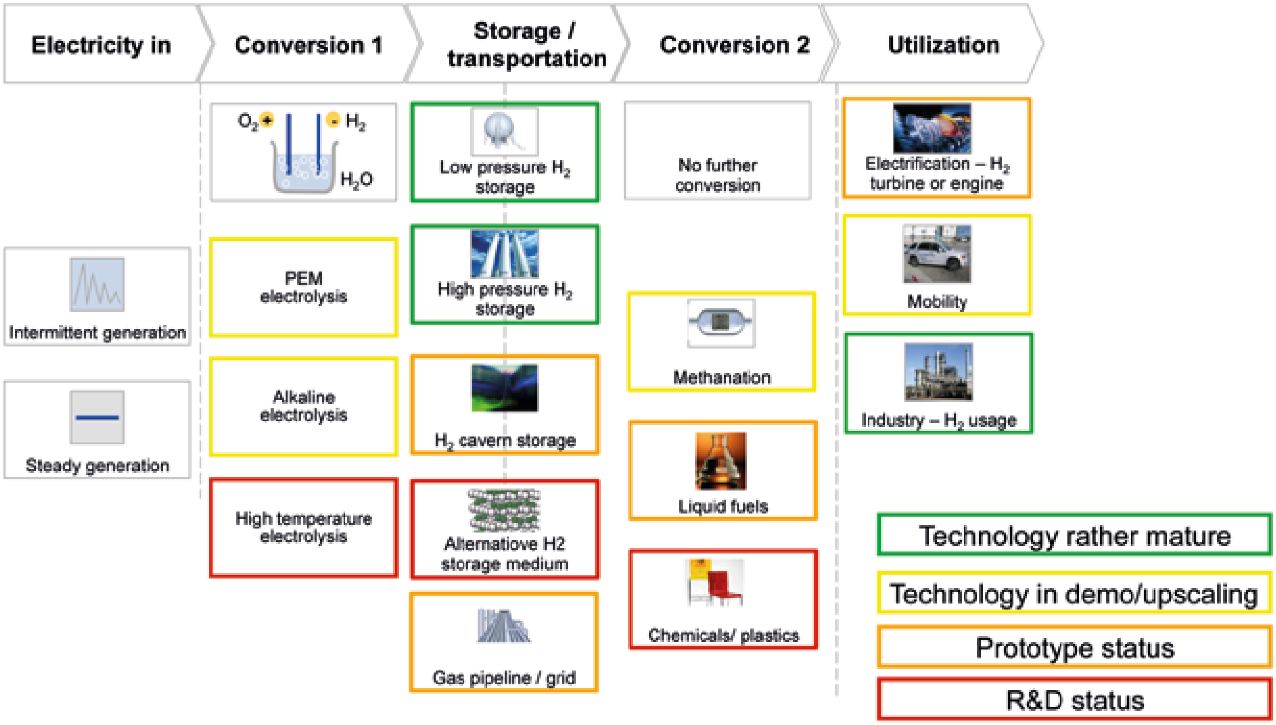

FIGURE 3 - technical Maturity of various parts of the chemical storage options

Technical development perspectives

The key challenge for Electrolysers will be to upscale the technology to a level where it becomes economically viable. The system integration of the electrolyser certainly has significant potential for improvement. Moreover the grid integration and operation in daily mode needs much more experience. For this purpose the first initiated demo projects are very valuable and will deliver important insight on the upcoming challenges. For the aspects of electrolyser cost reduction, system integration and hydrogen handling, a certain technology download can be expected from the market introduction of fuel cell cars, thus to some degree the success of chemical storage is also linked to the speed of commercialisation of hydrogen fuel cell cars.

Economic development perspectives

Compared with alternate energy storage technologies, the applications best suited for Power-to-Gas are large to very large scale systems (10-100 MW capacity) with seasonal storage capability (days or weeks). For large bulk storage systems Power –to-Gas is the lowest cost storage option (<-10€/kWh) in terms of energy capacity. Large Power-to-Gas plants e.g. for seasonal storage do need geological formations like salt caverns, but using above ground storage equipment, electrolysers can be optimally sited at points of congestion on the power grid to help alleviate the problem. Alternatively, this solution can be deployed for smaller scale distributed hydrogen fuelling stations (the fuelling station tank would effectively be a storage buffer and the surplus would be injected into the natural gas system). It is also a scalable solution. As additional 10MW Power-to-Gas modules can be added to an initial development site as required.

As demonstration plants in Germany and other jurisdictions are developed, the economics of the different applications—direct injection in pipeline, methanation, hydrogen fuelling, or industrial chemicals—for Power-to-Gas will be proven. The underlying challenge for commercial scale (10MW to 100MW) projects the ability for the Power-to-Gas developer to monetise a sufficient portion of the benefits to secure financing to build the project. Depending on the value of hydrogen for different purposes some use cases (e.g. mobility, industrial use) will economically become attractive before others (e.g. re-electrification). However, the regulatory environment for energy storage, particularly large scale energy storage, is just developing now. To foster this development new regulations are needed to provide the necessary contract mechanism, or alternatively, a combination of new market reforms such as provision of new ancillary services such as load following or ramping service, tariffs for renewable gas, and favourable electricity purchase provisions for power used for energy storage.

Realistic economic goals for the technology towards 2030

- **Electrolysers**: For the complete system with today's technology Alkaline and PEM electrolysers should reach levels below 1000€/kW (alkaline ~400-500€/kW, PEM ~500-800€/kW). New types of material (e.g. polymer membranes) currently in R&D status have the potential to further lower the electrolyser system costs. High temperature electrolysers that are still in R&D status should be able to reach cost levels of 1500€/kW by 2030.
- **Storage**: Large volume vessels and caverns do not offer significant cost reduction potential. In the area of small scale storage or high security applications storage costs is an issue and needs to be further reduced. Here high pressure composite tanks or hydrogen absorbents (e.g. metal hydrides, porous carbon or other novel absorbent or adsorbent materials) could become attractive solutions if storage costs can be reduced. These storage systems could also be used for locations, where underground storage is not an option (e.g. due to lack of appropriate geological formations).
- **Re-electrification**: The modifications of current technologies for hydrogen will not significantly change the current price level of Gas turbine plants (~350€/kW), CCPP (~600€/kW) or engine power plants (~400€/kW). Stationary Fuel cell system fuelled with hydrogen or methane will have to reach similar cost levels of 300-400€/kW.
- The conversion of hydrogen to chemicals such as methane, ammonia, methanol, ethanol, formic acid and urea will have to reach the price level of the respective benchmark market prices in order to become a competitive alternative. Specifying concrete price targets for the conversion reactors itself is currently not feasible.

Need for research

Research needs directed to existing, already industrially applied technologies

Conversion to hydrogen: Increase current densities at set point, pressure capability, dynamics and part load behaviour of stacks, improve system durability, reduce O&M efforts, daily life testing of electrolysers.

Distribution and Storage: Suitability of existing Natural gas grids for storing/distributing hydrogen-NG blends; development of measurement and separation technologies for such blends; bulk storage of hydrogen in caverns or large metallic vessels (e.g. study metal embrittlement). For high pressure composite tanks (700 bars) commonly used today for transport applications, industrialisation and cost optimisation are going to be the key issues in the following years as well as safety issues. For tanks based on hydrogen absorbents (i.e. metal hydride based tank being already on the market), as well further industrialisation, cost optimisation and additionally optimised energetic integration with different applications (stationary, transport and portable) will be key issues to take full advantage of their superior capacities at low storage pressures.

Re-electrification: The suitability of gas turbines and gas engines for H_2 or H_2-admixtures (not to talk about NH3) requires further investigation, some basic research work has to be done to improve emissions and flame stability. For fuel cells the long term stability also with respect to impurities needs to be improved.

Grid Stabilisation: The development of more efficient inverters and the dynamic behaviour of electrolysers in the grid need further analyses. Also the business models in combination with advanced market design, appropriate service remuneration and in a smart grid environment is an open research topic.

Research needs related to new concepts (not yet commercially explored)

For high temperature solid oxide electrolysers, thermal and redox cyclability are currently the most critical issues. The key research area to address these topics lies in material research. The process of co-electrolysis of CO_2 and H_2O would offer further application possibilities.

Storage of liquid hydrogen has very good storage densities close to the DOE targets but significant share (30%) of energy is lost in the liquefaction process. R&D directed towards cryo- compression could significantly improve the energy balance. Liquid hydrogen storage can also be combined with superconducting magnetic energy storage.

Hydrogen storage in solid media especially for decentralised / off-grid and small to medium scale storage or storage with special requirements on safety and improved hydrogen system efficiency (e.g. decrease of auxiliary energy consumption for compression/liquefaction). For this purpose promising advanced material candidates for high capacity hydrogen storage need to be benchmarked and prioritised with respect to wide scale applicability as well as specific applications. Besides absorption materials (e.g. metal hydrides) adsorption in light chemicals e.g. carbon metal organic frameworks (MOF) or graphene layers should be taken into account.

Further processing of hydrogen to gaseous (e.g. methane) or liquid (e.g. ammonia, methanol, formic acid or ethanol) hydrogen carriers and later extraction of hydrogen needs large efforts before wider applicability can be realised. The catalytic processes to derive these chemicals are usually well controlled in steady operation mode, but need further research in a highly dynamic load environment. New lower cost reactor concepts with optimised flow patterns are required.

Since some of these storage substances require CO_2 the separation of CO_2 from industrial processes or from air is another critical step that needs research. The extra cost for CO_2 capture, transportation and storage is a challenge for synthesis of hydrocarbons. As for synthesis of ammonia, N2 can be locally separated from air and there is not such issue.

On the other hand alternative e.g. microbiological pathways from hydrogen to methane should be studied as well.

General R&D needs

Costs/Materials

Electrolysis: Reduce noble metal loadings of electrodes, industrialise manufacturing, advanced coating processes, improve membrane permeability (possibly technology download from PEM fuel cell industry).

Storage and Distribution: Safe and cost effective storage materials for hydrogen (absorbents, adsorbents, chemical hydrogen carriers) and associated processes. Suitability of materials in the gas grid for hydrogen admixtures.

Environmental issues (raw materials, sustainable utilisation of resources, recycling possibilities, internal and external environment, land use, emissions)

Platinum, Iridium and Ruthenium are some of the noble metals necessary for the catalytic processes in PEM electrolysers. From a supply side point of view, there are enough resources, but extraction capacities will have to be expanded for H_2 infrastructure rollout in a wider scale. Low metal loadings and efficient recycling of precious metals are however the key for long term availability of the critical elements.

Some solid absorbents investigated for their hydrogen sorption capabilities belong to the rare earth groups (e.g. LaNi5H6) and need critical evaluation of their resources.

Specific development needs (E.g. degradation, durability, temperature stability)

For stationary or mobile storage applications degradation, durability and temperature stability of materials and components need to be studied thoroughly in order to reach technical targets and tackle the safety issues at the same time.

Specifically degradation under dynamic operation mode for the different electrolyser technologies need to be investigated and benchmarked with the actual requirements for delivering the required grid services.

The re-electrification of hydrogen admixtures to natural gas in conventional gas turbines is limited to concentrations of between 1 vol % to 10 vol % (present specification of most installed turbines is just 1%, though). Individual utilities operate gas turbines also at higher concentrations up to 30 % in that case starting on other fuels. The general issues related to the co-combustion of higher H_2 concentrations are expected to be resolved with new burner technologies.

Needs regarding Balance of Plant

Grid interfacing power electronics like rectifiers/inverters are products employed for a long period of time but also here increased efficiency, durability will become increasingly important.

Other BOP issues

Compact and low cost designs of storage solutions are important success factors. Especially safe, maintenance friendly solutions with low auxiliary power requirement are highly relevant for customer acceptance. Also here there is an opportunity for technology downloads from the upcoming automotive hydrogen industry. The focus for addressing the right BoP needs should be optimising the efficiency of the complete system including all conversion steps.

European strongholds

European and American companies are leading the edge for electrolysers, compressors and also for chemical processes. Taking into account the similarity to critical issues to mobility the European car manufacturers are on the similar level in terms of maturity as the Japanese competitors and are thus well prepared to complement the chemical storage option.

European economic and industrial potential (Current basis/starting point)

With the exception of few regions in Europe with locally very high shares of wind generation, today there is neither an urgent technical need for producing hydrogen from excess electricity nor is there a business case for re-electrification. Currently the most promising uses lie in direct use of hydrogen or derived chemicals in industry, upgrading of biogas with hydrogen or using hydrogen for mobility, where it can become economical in the coming years. This is especially the case in remote and small scale applications where transport costs (ecp. for hydrogen) can dominate feed stock costs. The next attractive use case could develop in off-grid applications, isolated communities and islands where a system including PV/wind generation, electrolyser and fuel cell may become an attractive alternative to Diesel gensets commonly used for these locations. The pressure to use chemical storage including re-electrification on a large scale will significantly increase over the coming years for regions with high ambitions for renewable generation combined with lack of transmission capacity or weak grid alternatively.

Demo and pilot testing

In the last couple years the storage option Power-to-Gas brought up numerous demo projects mainly in Germany. There is a wide range of application purposes, a large share of applications targets the mobility sector for hydrogen or syngas, further projects aim for the injection of H_2 into the gas grid and only a few include large scale hydrogen storage and re-electrification.

Large scale hydrogen storage itself is already operated for several years at two locations in UK and USA but a wider use in the context of fluctuating wind generation is still not realised.

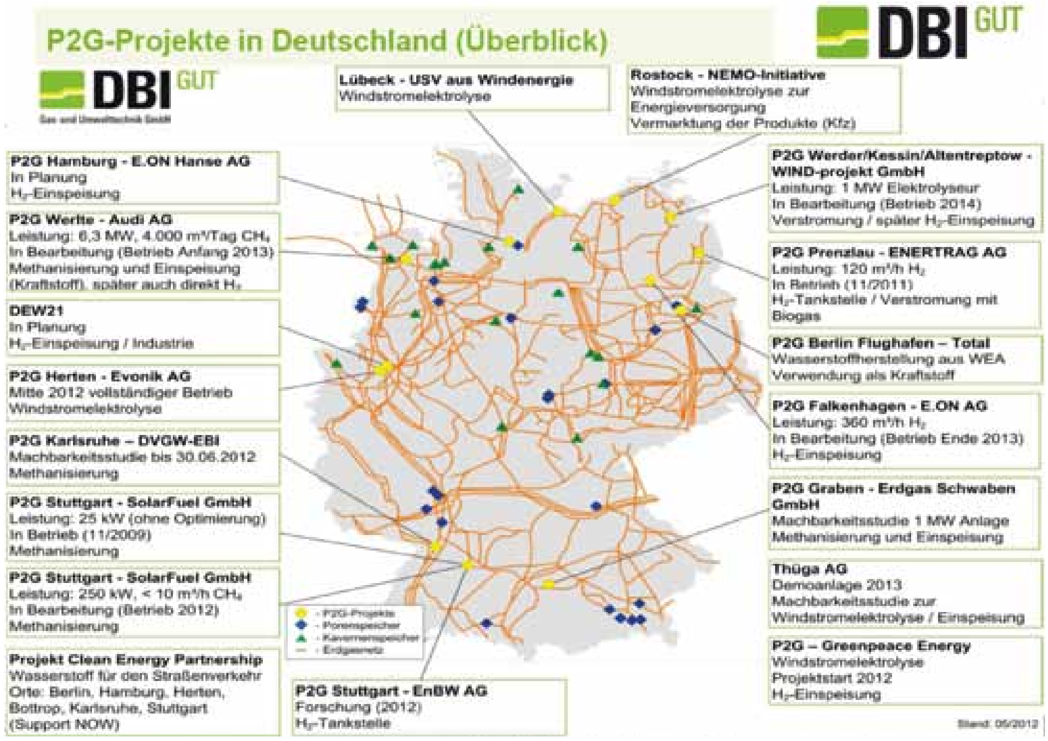

FIGURE 4 - Overview of Power-to-Gas Projects in Germany

Research group clustering potentials

Since currently the largest research efforts are observed in Germany it would be worthwhile to connect these German research groups to interested groups in other countries with similar challenges. For power to gas the highest interest could be anticipated in U.K., Ireland, Denmark, Spain and Portugal (countries with existing or anticipated high penetration of wind generation). Scotland Enterprise is also very interested in power to ammonia solutions.

Grid integration

Grid integration of chemical storage mainly refers to the Electrolyser part which absorbs electricity from the grid. The electrolysser is connected on the DC side with a rectifier that is responsible for the interface to the AC side.

The dynamics of these well-developed components is such that the rectifier–electrolyser–unit can even be used for grid stabilisation purposes. By operating the unit at a set point below the maximum level it could also be used for positive control purposes.

It has been demonstrated that Electrolysers can follow very quickly (20-100% capacity in 1sec.) the load changes produced by the output of a wind farm, so that basically electrolysers could be used as negative, or – in continuous operation - also as positive operating reserve for the grid system.

Further experience needs to be gathered how this storage system interacts with wind generation and the gas and electricity networks.

Hazards (e.g. explosion, risk of toxic emissions)

One of the risks associated with chemical storage certainly comes from the substances H_2 and methane. Chemical and Oil & Gas industry is very well used to deal with these chemicals but if these substances come into private households and small businesses special care has to be taken due to the explosion risk of these highly flammable gases. For methane odorisation is one lever to safely bring methane into private use, for hydrogen depending on the final use other measures might have to be taken in order to enable a home use of the substance. Joining forces with the hydrogen and fuel cell car industry will certainly be valuable since here many security standards have already been defined.

Social acceptance and engagement / social interfaces (incl. jobs creation)

For methane the acceptance is already widely spread but special care has to be taken for hydrogen due to many negative associations (Hindenburgh, Challenger,…). This is mainly related to security aspects that are felt to be much higher for H_2. In reality however, if properly treated, it is safer than methane

The social acceptance on the other hand can be assumed to be very good when it can be established as a green and CO_2-free energy carrier (the opposite might be true if H_2 is produced from Lignite or Nuclear power) as one of the ways to mitigate climate change or as one of the ways to reduce air and noise pollution from mobility. Chemical storage can be understood as a domestic energy carrier sourced from natural resources and thus can help to decrease the drastically rising energy imports and increase social welfare inside EU, including local job creation, without the risk of external disruptions.

Markets in focus - application areas and types

Since Europe has as a region the most ambitious plans for fluctuating renewable energies in the world and especially based upon its huge development plans for on- and offshore wind it can become pioneer employing hydrogen storage on a large scale. This technology can also efficiently complement the urgent need for grid extensions and reinforcements, HVDC grid plans, etc. Hereby Europe can analyse and prove the benefit of large scale storage systems for regions with high fluctuating energies for the complete electricity supply infrastructure. Within the next TYNDP (ten year network development plan) performed by ENTSO-E a cost benefit analysis (CBA) will analyse the respective economics of grid extension together with storage as a further option.

Electrolysers and Storage caverns would be ideally placed at sites close to the North Sea where huge amounts of offshore wind energy will have to be connected to the European electricity supply system. Incidentally here gas and electricity grid as well as gas storage caverns are available in the same location. In these areas other large storage facilities like Pumped Hydro would geographically not be feasible and would not offer the huge electricity storage capacities that are needed (see below Figure 5).

Certainly the degree of fluctuating renewable generation in the infrastructure is only one lever to quantify the relevance of chemical storage need. Further factors that influence strongly the storage demand are the interconnection, the degree of realisation of demand side management measures, flexibility of the conventional power plants, etc.

Regions with the highest demand for chemical storage are characterised by very high ambition especially of wind generation and a weak interconnection or bottlenecks, e.g. Ireland, U.K., northern parts of Germany.

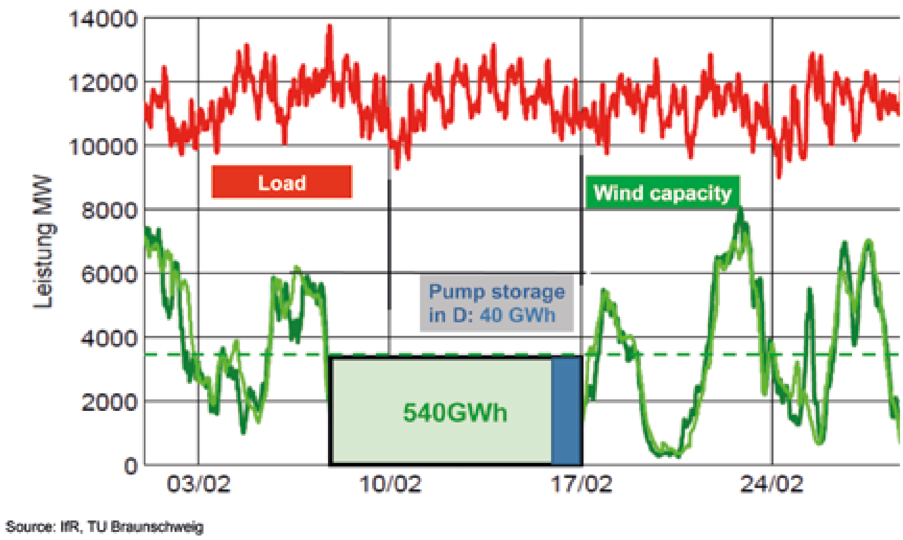

FIGURE 5 - Illustration of fluctuating renewable generation

Business cases

Hydrogen is a chemical which is usually produced via natural gas in a steam reforming process. Thus it has as a chemical a rather high value and the most attractive business cases lie in application fields where the benefits of this clean fuel are properly appreciated.

Produced via electrolysis (depending on CAPEX, electricity costs and operational hours) hydrogen from fluctuating energies can already be economically produced for mobility and industrial needs.

The use for mobility purposes is most attractive but a lack of commercially available cars and hydrogen filling stations hinders a quick market entry. If fuel cell cars are available in a couple of years this would immediately create a hydrogen sink for excess renewable generation by building decentralised hydrogen filling station network where needed. Several recent and on-going initiatives by the EC targeting a cleaner transportation sector will certainly help alleviating the issues of availability of cars and availability of infrastructure.

Other hydrogen uses where only the heat value or the electricity price is valued are in the next couple of years only economical in niche markets (e.g. islands with high fuel/electricity prices).

Only in the mid and long term when the CAPEX is reduced and the frequency of low price windows for electricity will increase (with increasing RE build out) and with properly set market design, the re-electrification will become economical and give the possibility also to fill the gaps left by wind generation. This is essential for achieving RE targets above 50% of generation.

SWOT analysis in European context

Strengths: Major electrolyser players with strong foothold in Europe. Chemical industry and geological situation in favour of starting large scale storage right in EU. Pioneering opportunity due to the high pressure in the electricity supply systems (grid extensions required) caused by the quickly increasing power of fluctuating renewables.

Weaknesses & Threats: Threat that if produced in large scale, key components will again originate from Chinese manufacturing, but threat certainly lower than for photovoltaic or batteries.

Opportunities: EU already front runner in terms of renewable energy and thus in pole position to commercialise storage and especially large scale storage.

Need for support/incentives

As for all early R&D topics also for storage certain degree of funding should be made available to accelerate market introduction and competitive integration into the energy system. This funding should be tailored towards the most promising technological bottlenecks in the system.

Due to the risk of competing incentive mechanism and over incentivising the electricity system the issue of support system should be dealt with in the framework of a new market design. Due to its unique features storage will become an important element of grid quality and reliability and if market design remunerates the real benefits of storage properly it can also compete with alternative options economically.

Standards

Standards for hydrogen are being defined in ISO TC 197, IEC TC 105 is dealing with standards for fuel cell application and ISO TC 192 with gas turbines. A new Technical Committee within IEC (TC 120) which is currently being initiated will be dealing with grid integration of storage systems. For the chemical storage option a close cooperation with the already existing committees is essential to judge whether for this storage option further standardisation efforts are required.

Sources of information

- http://www.siemens.com/innovation/apps/pof_microsite/_pof-spring-2012/_html_en/electrolysis.html
- http://www.powertogas.info/power-to-gas/energiesystem-der-zukunft.html
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- http://www.nesshy.net
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- http://www.euturbines.eu

ANNEX II: ELECTROCHEMICAL ENERGY STORAGE

Batteries

Description and key property range

Batteries are electrochemical energy storage devices based on a variety of different specific chemical systems: today the most commonly used technologies on the market available are Lead-based, Lithium-based, Nickel-based and Sodium-based batteries. They are used in and tailored for a variety of different applications. Batteries have been practically utilised as convenient power sources for about two centuries and the application range of rechargeable batteries has been dramatically expanding over the latest decades because of increasing demand for stationary and mobile power sources in numerous appliances and other devices. These technologies have been progressively developed over the years to meet the evolution of specific and increased requirements for each application, resulting in specific advanced battery products to be used in applications for which they are designed.

Batteries are based on single electrochemical cells each having voltages in the range from below 1 V up to about 4 V. The cells can be combined in series to yield very high voltages if required. Batteries hold highly attractive power densities and their round cycle efficiency (electrical energy out over electrical energy in) are generally high – in the range up to 70-95 %, depending on charge and discharge conditions. Because of the basic electrochemical cells of batteries they are highly modular and can be manufactured for very high capacities and/or power requirements.

Electrochemical batteries consist of two or more electrochemical cells. The cells use chemical reaction(s) to create a flow of electrons – electric current. Primary elements of a cell include the container, two electrodes (anode and cathode), and electrolyte material. The electrolyte is in contact with the electrodes. Current is created by the oxidation-reduction process involving chemical reactions between the cell electrolyte and electrodes.

When a battery discharges through a connected load, electrically charged ions in the electrolyte that are near one of the cell electrodes supply electrons (oxidation) while ions near the cell other electrode accept electrons (reduction), to complete the process. The process is reversed to charge the battery.

An increasing number of chemistries are used for this process. More familiar ones include lead-acid, nickel-cadmium (NiCad), lithium-ion (Li-ion), sodium/sulphur (Na/S), zinc/bromine (Zn/Br), vanadium-redox, nickel-metal hydride (Ni-MH), and others. Table 18 summarises key performances of major commercialised conventional and advanced batteries (electrochemical capacitors are also included for comparison purposes).

TABLE 1 - Key performances of major commercialised conventional and advanced batteries

Electrochemical storage			Key properties					
			Energy density		Specific power	Cycle life	Efficiency	Working temperature
			[Wh/kg]	[Wh/l]	[W/kg]	cycle number @ 80% DoD	[%]	[°C]
Lead	flooded		25-40	60-100	140-350	200-1500	70-75	20-40
	VRLA		30-40	80-100	140-300	300-1000	80-85	20-40
	compressed		40-50	100	140-250	800-1500	70-85	20-40
Alkaline	Ni-Cd							
	type	power	25-40	130	500	800-1500	70-75	-40-50
		energy	40-50	130	120-350	800-1500	70-75	-40-50
	NiZn		60-80	200-300	500-1000	200-1000	60-65	0-40
	NiMH							
	type	power	40-55	80-200	500-1400	500-2000	70-80	0-45
		energy	60-80	200-350	200-600	500-2000	70-80	0-45
High temperature	NaS (module)		103	150	100	4500	89	-20-45
	Zebra - Na-$NiCl_2$		90-120	182	100-120	2500-3000	90	-20-45
Lithium	Li-ion							
	type	power	70-130	150-450	600-3000	800-3000	90-95	-20-60
		energy	110-220	150-450	200-600	800-3000	90-95	-20-60
	Li Polymer		100-180	100	300-500	300-1000	90-95	-20-110
Flow batteries	Energy		60-80	75-80	50-150	10.000	70-75	0-40
Electrochemical capacitors	Power		3-5	3-10	2000-10000	500k-1M	95-100	-20-90
	Energy		10-20	3-6	2000-10000	500k-1M	95-100	-20-90

Critical gaps between needs and present performance

For batteries as mobile power sources the most critical gaps between needs and present standard performance over the coming 10-20 years are energy density, power performance, lifetime, charging capabilities and costs.

Even though batteries have been strongly demanded over decades for critical applications, e.g. military, communication and transport, present battery technology still displays energy densities between one and two orders of magnitude lower than traditional chemical energy carriers (e.g. hydrocarbons).

Batteries for grid applications should in the first place to be considered as stationary installations to be specifically developed to fulfil functionalities for grid balancing, such as supporting primary and secondary reserve power, contributing to reserve capacity building and ancillary services to support transmission. Batteries have high potential because their flexibility in sizes and characteristics but can only contribute efficiently if correctly designed and tailored to contribute to time-shifts, peak shavings and in particular to support capacity firming of intermittent renewable sources. For stationary grid applications, most important properties to improve are cycle life time and calendar life time in order to develop reliable and costs-effective products.

Whereas batteries in EVs cannot solve the grid issue alone, some smart grid plans in Europe include batteries in electrical vehicles, the idea being to use batteries on board vehicles as a balancing component (G2V and V2G) in the grid. In this case the property gap for batteries is particularly insistent. Battery electrical vehicles are marketed with driving range up to 150 km, which is in practice usually even considerably lower due to need for auxiliary power in the vehicles (defrosting, cabin heating, air conditioning etc.) as well as weather conditions and road friction. The chances that batteries in vehicles can play the described balancing role in the electrical grid depend on the consumers' demand for those vehicles and this will in turn be stimulated by improved battery technology in the form of longer charging intervals (higher energy density in the battery) and lower charging times (more rapid chemical reactions and faster transport within the battery). Further logistical obstacles must be overcome, including ways to avoid compromising the battery warranty provided by car manufacturers to their customers.

Batteries can be grouped in: conventional batteries (lead-acid and alkaline), advanced (high temperature, redox and lithium-based) and emerging (not yet commercialised).

Lead-acid batteries

This battery has been for years the most diffused and applied storage system in the world, for its commercial and technological availability. Low cost and abundant raw materials with a well-organised recycling chain have been winning aspects for the technology. Lead-acid batteries have been used for more than a century in grid applications.

This battery is mostly used in mobile applications, as primary source of energy in conventional cars, while has been limitedly used for propulsion.

Lead-acid batteries are commonly used by utilities to serve as uninterruptible power supplies in substations, and have been used at utility scale in several demonstration projects to provide grid support. A few large demonstration plants have been built starting from the second half of 80's in Berlin (8.5 MW or 17 MW and up to 14 MWh) by BEWAG for grid frequency regulation and spinning reserve applications; in Chino (California), a plant of 10 MW and 40 MWh for load leveling; in San Juan, Puerto Rico a 20-MW/18-MWh plant was built. Similarly, in remote area power supply situations, there is a demonstration operating in a village in the Amazon region of Peru.

Main limitations are however present: low specific energy and power, long charging time, sensibility to temperature, maintenance needs and low cycle life and reliability.

Even after a hundred years in use there remains extensive potential for advanced lead acid battery technology. Specific power is being improved with advanced active materials and lower resistance designs. Further cost reductions are being realised through automation and process improvement. Cycle life will be doubled through design enhancements and intelligent battery management. Complete turnkey systems up to the MW size are being developed, and lead acid batteries will be integrated into hybrid systems in combination with other power and storage technologies to maximise benefits and minimise costs. Through these improvements, additional cost savings in the range of 40% for RES systems will be realised.

Alkaline batteries

Alkaline batteries are the most used electrochemical storage after lead-acid systems. There are a number of these batteries currently available or under development, including Nickel-Cadmium (Ni-Cd), Nickel-Metal Hydride (Ni-MH) and Nickel-Zinc (Ni-Zn). Ni-Cd and Ni-MH are currently the most developed and diffused for grid applications, even if there are few examples of their application to electricity markets: the Golden Valley Electric Association (GVEA) in Fairbanks, Alaska installed a large-scale Ni-Cd Battery Energy Storage System (BESS) to provide 27 MW of electricity for a minimum of 15 minutes to stabilise the local power grid in the event of sudden loss of generation.

TABLE 2 - Basic performances of alkaline batteries

System	Ni-Cd (pocket)	Ni-Cd (sealed)	NiMH	Ni-Zn	Ni-Fe (pocket)	$Ni\text{-}H_2$
Voltage, V	1,2	1,2	1,2	1,6	1,4	1,2
Energy density, Wh/l	40	100	75	60	55	105
Specific energy, Wh/kg	20	35	240	120	30	64
Power performance	Low	High	High	High	Low	Medium
Discharge profile	Flat	Flat	Flat	Flat	Flat	Flat
Cycle life, number	2000	700	600	500	4000	6000

High temperature batteries (NaS and NaNiCl2)

Technical challenges associated with sodium-beta battery chemistry generally stem from the high temperature requirements. To maintain a 300°C operating point the battery must have insulation and active heating. If it is not maintained at such a temperature, the resulting freeze-thaw cycles and thermal expansion can lead to mechanical stresses, damaging seals and other cell components, including the electrolyte. The fragile nature of the electrolyte is also a concern, particularly for Na-S cells. In the event of damage to the solid electrolyte, a breach could allow the two liquid electrodes to mix, possibly causing an explosion and fire. Na-S batteries are manufactured commercially for a variety of grid services ranging from short-term rapid discharge services to long-term energy management services.

A number of MWh systems have been demonstrated on the electrical grid, being the NaS battery the most used electrochemical storage system currently used in electricity grid. The largest system currently under construction is a 34-MW/238-MWh (7 hours) Na-S storage for the Rokkasho wind farm in northern Japan, while another one, for daily storage, has been built in a Hitachi factory with an impressive energy content of 57 MWh; other demonstration plants are built or under construction in the rest of the world (50 MW in Abu Dhabi, 1.2 MW in Charleston, USA), but an unclear recent accident in a storage system in Japan has temporarily stopped any installation and production to clarify the safety aspects of the technology.

The primary sodium-beta alternative to the NaS chemistry is the Na-NiCl2 cell (typically called the ZEBRA cell). Although ZEBRA batteries have been under development for over 20 years (and used in EVs since 1998), they are in the early stages of commercialisation for Storage and Telecom as UPS. Nickel chloride cathodes offer several potential advantages including higher operating voltage, increased operational temperature range (due in part to the lower melting point of the secondary electrolyte), a slightly less corrosive cathode, and somewhat safer cell construction, since handling of metallic sodium—which is potentially explosive—can be avoided. Other advantages are: intrinsically maintenance free, long life and high reliability, and concerning safety these batteries have passed all safety tests defined by the European Automotive Industry and USABC and are 100% recyclable. They are likely to offer a slightly reduced energy density. The concept of ZEBRA was proposed in 1978. MESDEA (Switzerland) acquired the ZEBRA technology and has since been involved in commercialisation efforts. Recently FIAMM (Italy) and MES-DEA formed a new company, FZ Sonick SA (now completely FIAMM), to further develop the technology. The use of solid or semisolid cathodes makes Na-NiCl2 batteries intrinsically safer and less corrosive than Na-S batteries. The high voltage of Na-NiCl2 batteries helps energy density.

Flow batteries

The use of energy flow cells for electric power transmission applications provides effective use of existing plant investment, flexibility in operation, and better response to price changes. Stored electricity can be made readily available to meet immediate changes in demand, allowing effective operation of base load units at high and essentially constant levels of power. Flow cells use off-peak power for pumping and/or charging. This stabilises operations and provides flexibility for buying or selling electricity during on-peak or off-peak periods. Modular construction technologies allow high power rating, long energy storage time, and excellent response time; full power can be delivered in few seconds. Such characteristics are important in the competitive electricity market. At the generation level, energy storage can be used to increase the load factor, helping utilities cope with load increases and covering operating and contingency reserves. Thus there is a significant potential market for energy storage products. The foundational work on flow batteries was carried out at NASA in the early 1970s for space applications.

Flow batteries can be divided in two classes: Redox type, in which active electrode materials are both external to the reaction chamber; and Hybrid type, in which only one active material is external to the reaction chamber, while the other may be deposited on one of the electrode. Table 20reports the most common flow batteries investigated for grid applications.

TABLE 3 - Electrochemical cells most investigated for flow batteries

System type/active material	Cell voltage, Volt	Electrode materials	Electrolyte
Redox		Anode/Cathode	Anode/Cathode
Vanadium, VRB	1,4	V^{2+}/VO^{2+}	H_2SO_4/ H_2SO_4
Vanadium-bromine	1,3	$V^{2+}/1/2Br_2$	VCl_3-HCl/NaBr-HCl
Bromide-polysulphide, PSB	1,5	$2S_2^{2-}/Br_2$	NaS_2/NaBr
Iron-chromium	1,2	$Fe^{2}+/Cr^{3+}$	HCl/HCl
H2-Br2	1,1	H_2/Br_2	Polymeric membrane / HBr
Hybrid		Anode/Cathode	Anode/Cathode
Zinc-Bromide, ZBB	1,8	Zn/Br_2	$ZnBr_2$/ $ZnBr_2$
Zinc-Cerium	2,4	$Zn/2Ce^{4+}$	CH_3SO_3H/ CH_3SO_3H

The most developed flow battery has been the VRB, followed by PSB and, mainly, ZBB. One advantage of PSB and ZBB is the use of the abundant, low-cost chemicals. These two batteries have a higher voltage than VRB and potential higher energy densities. But their cycle-life, efficiency, and reliability may be inferior to VRB. In addition, the formation of zinc dendrites upon deposition and the high solubility of bromine in the aqueous zinc bromide electrolyte has hindered the ZBB development. Its self-discharge rate is also higher than VRB and PSB. With all the stated advantages and the successful demonstration of systems up to MWh levels, none of the RFB technologies have seen broad market penetration.

The first large VRB (50 kW/200 kWh) was built by Kashima-Kita Electric Power, a Mitsubishi subsidiary, and went into operation in 1995. Since then systems up to MWh levels were developed and demonstrated. Several VRB systems have been deployed, including:

- A 15-kW/120-kWh unit operating over three years in a smart grid application by RISO in Denmark and a 50 kW/200 kWh unit operating over 1 year at CENER in Spain.
- A 250-kW/2-MWh unit at Castle Valley, Utah by PacifiCorp, which operated 6 years before being discontinued when the application need changed.
- A 200-kW/800-kWh unit at King Island, Tasmania by HydroTasmania.
- A 4-MW/6-MWh unit at Tomamae, Hokkaido, Japan by JPower.
- Smaller 5-kW units that have been deployed in field trials.

Li-based

Compared to the long history of lead-acid batteries, Li-ion technology is relatively young. There are many different Li-ion chemistries, each with specific power versus energy characteristics.

The main advantages of Li-ion batteries, compared to other advanced batteries, are:

- High energy density (150-200 kWh/m3, 140 kWh/ton at battery level)
- High efficiency (near 100%)
- Long cycle life (>3,000 cycles @ 80% depth of discharge) combined with long calendar life of 20 years+
- Maintenance-free
- Versatility: electrodes can be optimised for different power / energy patterns
- SOC & SOH indication (state of charge, state of health)

The high energy density and relatively low weight of Li-ion systems make them an attractive choice for areas with space constraints. Given their attractive cycle life and compactness, in addition to high ac-to-ac efficiency that exceeds 85%–90%, Li-ion batteries are also entering several utility grid-support applications such as DESS (distributed energy storage systems), transportable systems for grid-support, commercial end-user energy management, home back-up energy management systems, frequency regulation, and wind and photovoltaic smoothing. Both electric utilities and Li-ion vendors are interested in selecting one or two high value grid-support applications that offer a combination of large market size and high value to accelerate the volume production of PHEV batteries. Many experts believe stationary markets for Li-ion batteries could exceed those for transportation.

The implementation of Li-ion batteries in the stationary field has significantly increased since 2010 and has benefited from the extensive experience gained in the development of batteries for electric and hybrid vehicles. About 100MW of stationary Li-ion batteries are operating worldwide in grid connected installations: Systems in association with distributed renewable generators from a few kW to several MW, as well as for grid support with voltages up to 6000V have been designed and successfully tested. Whereas early systems were implemented for demonstration purposes, a commercial market is now developing for such applications in different regions of the world.

Technology improvements will further increase energy density, cycle and calendar life. System developments have reached the MW power class, whilst building up of industrial capacity for mass production of industrial size cells and batteries is poised to reduce system cost in the future. According to the Energy Storage Association (ESA) the main hurdle associated with mass energy storage systems using Li batteries is the high cost due to special packaging and internal overcharge protection circuits.

In particular for Li-ion systems the following issues are critical:

- Cost: The critical parameters limiting presently the diffusion of the technology are costs for all applications.
- Safety should be reinforced for end user applications (i.e. residential storage).
- Life time: Some relatively new technologies such as high energy NMC, spinel manganese or iron manganese phosphate (LFMP) technologies are highly interesting in terms of energy density and/or cost, but still need major efforts to reach the required calendar and cycle life of industrial applications.

Technical development perspectives

Batteries are well established on markets for mobile and stationary power sources. The annual European and Middle East (EMEA) market size is approaching 1 billion EUR[1] (EUROBAT members) as electricity storage devices and can be expected to increase over many years to come. If the technical performance of batteries is further improved, as targeted by this Roadmap - the market demand will become enormous.

However, significant scientific and technological progress is still needed on various competing and emerging batteries to move them to the market place, as reported in Table 4. Information has been collected from multiple sources[2 3 4 5].

TABLE 4 - Status of development of major electrochemical storage systems for grid applications

Status	Electrochemical Energy Storage
Mature	Lead-acid
Commercial	Lead-acid, NaS (sodium-sulphur)
Demonstration	ZnBr (zinc bromine), advanced lead-acid, VR (vanadium redox), NiMH (nickel-metal hydride), Li-ion (Lithium-ion)
Prototype	Li-ion, FeCr (Iron Chromium), ZEBRA (sodium nickel chloride = $Na\text{-}NiCl_2$)
Laboratory	Zinc-air, advanced Li-ion, new electrochemical couples (other Lithium-based)
Idea -concept	Nano Supercapacitors, new electrochemical couples (metal-air, Na-ion, Mg-based and so on)

Use of lead acid batteries for grid applications is limited by relatively short cycle life. Work to improve lead-acid battery technology and materials continues. Innovation in materials is improving cycle life and durability, and several advanced lead-acid technologies are being developed are0 in the pre-commercial and early deployment phase. These systems are being developed for peak shaving, frequency regulation, wind integration and photovoltaic smoothing applications. Some advanced lead batteries have "supercapacitor-like" features

1 http://www.eurobat.org/sites/default/files/website_industrial_statistics_2012.pdf
2 J. Eyer e G. Corey, "Energy Storage for the Electricity Grid: Benefits and Market Potential Assessment Guide", Sandia National Laboratories, Report SAND2010-0815, February 2010.
3 R. Alanen et altri, "D4.1 Electrical Energy Storage Technology Review", EERA Joint Programme on Smart Grids, Sub-Programme 4 "Electrical Storage Technologies", March 2012.
4 S. Inage, "Prospects for Large-Scale Energy Storage in Decarbonised Power Grids", Report IEA (International Energy Agency), 2009.
5 EUROBAT White Paper – Importance of Battery Energy Storage for Renewable Energy Supply, November 2011.

that give them fast response similar to flywheels and supercapacitors. Advanced lead-acid systems from a number of companies are anticipated to be in early field trial demonstrations in a short time.

In general, **alkaline battery technology** would benefit from a better understanding of the mechanisms associated with the operation of the porous electrode. This should be feasible, as electrochemical modeling of the electrode operation is now becoming fairly sophisticated. The most urgent issue requiring attention is the low-temperature performance of the hydride anode. Here, a better understanding of hydrogen in the alloys, including the diffusion and bonding, might identify new alloy compositions. Finally, the energy efficiency and stability of nickel cathodes should be improved. Nanostructured materials or additives may improve the rate capability, while electrolyte additives may be used to raise the oxygen overvoltage.

Technical challenges associated with sodium-beta battery chemistry generally stem from the high temperature requirements. To maintain a 300°C operating point the battery must have insulation and active heating. If it is not maintained at such a temperature, the resulting freeze-thaw cycles and thermal expansion can lead to mechanical stresses, damaging seals and other cell components, including the electrolyte. The fragile nature of the electrolyte is also a concern, particularly for Na-S cells. In the event of damage to the solid electrolyte, a breach could allow the two liquid electrodes to mix, possibly causing an explosion and fire.

For Na-Ni-Cl batteries still a large potential for technology improvements exists.
- Specific power needs to be improved - in laboratory scale - with advanced additives to the positive active materials and lower resistance of ceramics solid electrolyte.
- A lot of effort is now related to improve the recharge power.
- Further cost reductions are needed through automation and process improvement on top of the increase of production volume.
- Cycle life should be increased through design enhancements such as new more corrosion resistant glass materials.
- To match the smart grid requirements a flexible BMS s.w. and a standardised communication protocol should be developed.

For **flow batteries**, the current technologies are still expensive. Advances in science and technology continue to bring down the cost; VRB, for example, is about $500/kWh or higher, which is about two–three times higher than the target expected for broad market penetration. The high cost is directly dependent on the high cost of materials/components and performance parameters including reliability, cycle/ calendar life, energy efficiency, system energy capacity, etc.

Flow battery R&D efforts include improving the performance of commercially available products and developing new chemistries. For vanadium redox cells, research seeks to decrease the vanadium required and increase energy density, for example, by up to 70%. New redox couples that increase efficiency, improve specific energy, or utilise more cost effective or less toxic materials are also the subject of investigation. These chemistries include iron-chromium, zinc chloride, hydrogen-halogen, hydrogen-bromine, lead, and others. An earlier flow battery type (sodium-bromide/sodium-polysulfide) reached the initial stages of commercialisation, but was discontinued. It is unclear if development of this chemistry is being pursued. Another key requirement for large-scale deployment will be achieving demonstrated reliability and longevity. These requirements are complicated by the toxic and corrosive electrolytes, which pose significant materials challenges for the hydraulic subsystems and ion exchange membrane, particularly for chemistries other than vanadium in which electrolyte mixing is unacceptable.

Lithium-ion is one of the most promising systems in development for the next 10-15 years, still needing important R&D programs to take profit of all its potentiality. Beyond this period new generations of lithium batteries – including new materials and new design – are under investigation in public and industrial Research Centres such as lithium-sulphur or lithium-air.

The versatility of Li-ion, both in terms of power to energy ratio and in specific performance/life/safety characteristics of a given anode/cathode combination makes Li-ion an interesting technology to meet the various requirements of grid connected energy storage applications: whilst all of them require long calendar and cycle life, the optimum performance, energy and power characteristics can be matched for each application by selecting the most adequate Li-ion technology and improving its weak points to an optimum level. None of the existing or known Li-ion technologies matches ideally all application requirements, and all still have a significant potential of progress in one or more critical areas. Battery electrolytes should also be adapted to the operation temperature requirements.

TABLE 5 - Different kinds of Lithium-ion technologies

	NCA	NMC	HE-NMC	LMO	5v Sp	LFP	LFMP
Energy	++	+ (4,2V) ++ (4,5V)	+++	- -	-/+	-	+
Safety	-	+/-	+/-	+	?	++	++
Life	++ (4,0V)	+	-	+/-	Tailored by electrolyte	+/-	-
Power	+	+/-	- -	++	++ ?	+	- -
Cost interest (cost/kWh)	-	+/-	+	++	+	+/-	+/-
Maturity	commer-cial	commer-cial	Pilot	commer-cial	Research: depends on advance on electrolyte	commer-cial	Pilot

Main perspectives

- **Cost:** Both material research and manufacturing technology will contribute to drive costs down.
- **Safety:** new materials, electrolytes and system components will enhance safety
- **Life time:** Some relatively new technologies such as high energy NMC, spinel manganese or iron manganese phosphate (LFMP) technologies are highly interesting in terms of energy density and/or cost, but still need major efforts to reach the required calendar and cycle life of industrial applications.

Need for research

Research needs directed to existing, already industrially applied technologies

Intensive materials research will be required for substantial breakthroughs and increased applicability for batteries to grid applications for all mature battery technologies (Lead-based, Lithium-based, Nickel-based and Sodium-based batteries) should be considered, as each technology has the potential for significant further technical improvement, and can all provide distinctive and important functions to grid operators.

Research should be directed both at improving performances at the battery cell level, and battery system design level (connectors, interaction with the grid, etc.). Research on the chemistry itself has also high potential as it has not been carried out sufficiently for these new functionalities. It should also include focussed research on intelligent battery management, including the electronics and systems for quality control and battery "smartness". In addition, novel battery chemistries offer the potential of reaching energy densities which are considerably above that of the state-of-the art systems. Moreover, other conversion based systems offer capacities which are considerably beyond that of the state-of-the art Li-ion battery.

Immediate priorities to include are improvements to the cycle life and overall calendar life of advanced batteries. Advanced lead, nickel, Sodium and lithium batteries have still high potentials that should be further developed increasing the safety of Li-ion batteries and extending their temperature range of operation (from -20 to +60 °C).

Some of the breakthrough research needs are extracted from [6].

Advanced Lead-based batteries have the potential to contribute to the advancement of grid-scale energy storage in both power and energy management applications. Lead-based batteries can serve as a promising intermediate solution that can be deployed in the near term as newer technologies are being developed and improved. There are a variety of activities and initiatives that could help overcome the current gaps and limitations of these technologies in areas such as electrolyte advances, electrode development, diagnostics and modelling, and technology demonstration and validation. These solutions aim to optimise the effectiveness and increase the value of energy storage devices by increasing the energy density and efficiency of these devices.

Nickel-based batteries. Research activities and areas that should be addressed are

- Active materials: nanostructures
- Optimisation of current collector materials
- Research on additive materials to reduce self-discharge and to increase cycle life
- Material cost and production

The fundamental challenge for current sodium-based batteries is that their cost is still higher than the targets for broad penetration in stationary markets. Reducing the cost of sodium-based batteries requires improvements in performance, reliability, and durability. Challenges involving chemistries, materials, battery design, manufacturing and stack design, controls and monitoring, and testing and deployment must be identified and addressed before sodium batteries can achieve widespread deployment at grid-scale storage levels.

6 Nexight Group, Advanced Materials and Devices for Stationary Electrical Energy Storage Applications, Sandia National Laboratories and Pacific Northwest National Laboratory on behalf of US Department of Energy, December 2010.

The fundamental challenge currently restraining the market penetration of existing flow batteries is their inability to fully meet the performance and economic requirements of the electric power industry.

The first lithium-ion cell was commercialised in 1991 in Japan for application to portable electronic devices. 20 years later, the production reaches 2 billion cells per year for these applications.

However, in large industrial applications and namely for energy storage, very different requirements are needed for life duration, cost and safety. With a strong growth of grid scale deployments since 2010, reaching 20-30MWh per year, Lithium-ion batteries have not yet done their full deployment in industrial applications.

Research for the coming years needs to be directed to existing, already industrially applied technologies, in order to realise their full technical potential and make them available in high volume, low cost versions, on highly automatised production lines ensuring highest levels of quality and reliability.

Research needs related to new concepts (not yet commercially explored)

Exploratory research on novel materials for completely new electrochemical systems (e.g. metal-air, liquid batteries, Mg and metal halide based batteries) with the additional targets for the 2020-2030 period may further reduce the battery cost of more than 40%.

There are a number of other emerging chemistries in the early stages of research whose medium- and long-term applicability to electricity grids need to be better described. The new chemistries, with potentially much better technical performances, include other lithium-based systems (such as lithium- sulphur and lithium-air) and Mg-based systems, and more advanced nitrogen-air, sodium-ion, fluoride-ion, chloride-ion, other conversion-based and liquid metal battery. Sodium ion batteries function in principle like lithium-ion batteries, by shuttling positively charged ions between electrodes. Sodium ion batteries differ from the sodium beta batteries by the use of non-reactive electrode materials allowing the elimination of the ceramic separator and enabling room temperature operation. The combination of highly available materials with aqueous electrolyte and low voltage cells has the potential to provide the low cost and high safety necessary for grid applications, with cost claims competitive with lead-acid, but with cycle life exceeding 5,000 cycles and 100% Depth of Discharge.

Metal air chemistries are promising exceptional improvements in technical performances (up to 3 times those of Li-ion) and potential cost reduction associated with cheaper and more abundant raw materials.

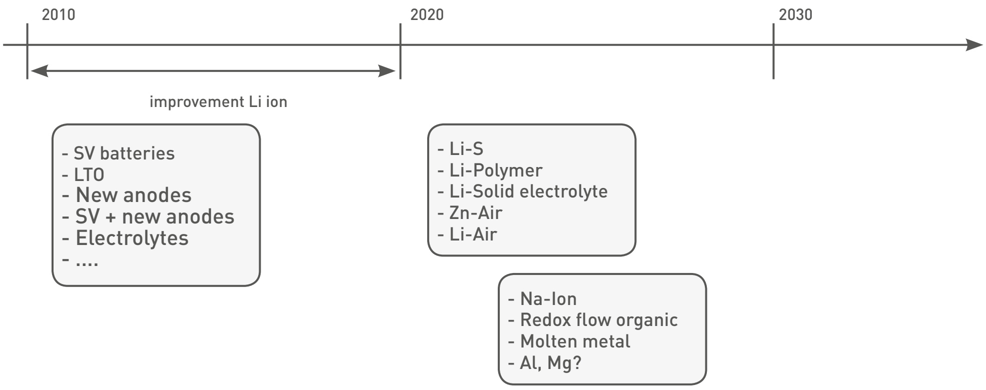
Fluoride- or chloride ion batteries are based on the shuttle of singly charged negative ions between a metal halide (cathode) and another metal (anode) which has the advantage of getting access to all the possible oxidation states of the metals. This leads to very high theoretical energy densities which can reach up to 50% more than the theoretical capacity of a $Li\text{-}O_2$ battery.

Mg based systems have the advantage of abundant materials and a safe anode. Moreover, the volumetric energy density is considerably above that of related systems based on Li. For example, the Mg-S battery offers a theoretical capacity of 4000 Wh/L, compared to 2600 Wh/L for the Li-S battery.

Research should also be directed into hybrid battery technologies (for example advanced lead flooded-VRLA for high power and high energy gel behaviour, Li-Pb batteries, Li-Super-capacitors etc…). Current battery technologies on the market do have a lot of potential and the industry is investigating but asking for longer term support on fundamental research, possibly to be coordinated by a dedicated Integrated Electrochemical Storage technology platform (IESS). It would bring synergy, and, possibly, contribute to support the other storage technologies in improving their performances. This collaboration will be aimed at developing highly efficient, safe, robust and affordable battery systems, highly flexible for easy integration in the grid, up to systems of about 50 MW or more.

Expressed in a time line new battery system development could be as follows:

FIGURE 6 - Time line new battery system development



New material needs by 2020	
LiMnNi(Co) oxides $LiNiPO_4$ $LiCoPO_4$ $LiVPO_4$ + others	class cathode materials 4,5 - 5V
LTO C/Metal composites Si, Sn-intermetallics	class high capacity nem anodes
additives electrolyte SV electrolytes	stable electrolytes

New material needs by 2030	
Li and Sulphur, improved conductive polysulphides	- Na-Ion materials - new redox flow systems materials - molten metal/salt systems - introduction of Al or Mg in metal-air, metal-sulphide or ion based systems
Development of new solid electrolytes (non-polymer)	
Development of correctly rechargeable Zn or Li-anodes, electrolytes and air cathodes	

Exploratory research is strongly recommended on novel materials for completely new electrochemical systems (e.g., metal-air, fluoride and chloride ion batteries, liquid batteries, Mg-based batteries, battery cell voltage up to 5V,) with the additional targets for the 2020-2030 period to further reduce the battery cost of more than 40%. In general, the targeted technical and economical performances of the emerging electrochemical technologies may be estimated to be in the horizon 2020-2030: more than 500 Wh/kg, more than 3000 complete charge/discharge cycles and a cell cost below 350 €/kWh.

Economic and technical development goals

Based on the so many years of expertise in different sectors, the Battery Industry could extrapolate promising targets for the period 2020-2030. However, such targets are always in relation to specific conditions and should be further defined by grid operators to allow the battery industry to come up with concrete figures.

For **lead-based batteries**, activities and initiatives can accelerate progress in the following areas:

- ELECTROLYTE ADVANCES – Exploring the use of electrolyte additives and acid mixing can help to address the performance of lead-carbon batteries related to acid stratification.
- ELECTRODE DEVELOPMENT – Developing high-energy carbon electrodes can help to increase the energy density of lead-carbon batteries to a level that is suitable for grid-scale operation. Further research of natural carbon electrodes, as opposed to nano-electrodes, can help to keep down the cost of lead-carbon batteries, maintaining their cost-competitiveness in comparison to other energy storage technologies.
- DIAGNOSTICS AND MODELLING – Modelling could help device developers gain an understanding of why the current battery design has a specific energy well below the theoretical specific energy of lead. Once this issue is better understood, energy storage device experts may be able to increase the specific energy of lead-carbon batteries, making them more attractive options for grid-scale storage.
- TECHNOLOGY DEMONSTRATION AND VALIDATION – Testing and demonstrating lead-carbon batteries can help to validate technology lifetime, ramp rates, and other performance characteristics that need to be proven to encourage stakeholder buy-in.

Targets for Lead technology for the period 2020-2030:

› Energy cost < 150-100 €/kWh or << 0.08-0.04 €/kWh/cycle
› Temperature operating range for stationary applications: -30 to +60ºC
› Specific performances: 60-100 Wh/kg and 140-250 Wh/L
› Cycle life: > 3,000 (80% DoD) -10,000 cycles (60% or 80% DoD)

For **Ni- based batteries** :

Targets for Nickel-based technology (NiCd, NiMH, NiZn) for the period 2020-2030:

› Energy cost < 250-1,000 €/kWh
› Temperature operating range for stationary applications: -40 to +70ºC
› Specific performances: 60-140 Wh/kg up to 80-200 Wh/kg and 80-450Wh/L up to 100-600Wh/L Cycle life: > 6,000 - 8,000 cycles (80% DoD)

For **high temperature batteries**, and in particular for ZEBRA, after only 15 years in use there is very extensive potential for technology improvements. Specific power is being improved, in laboratory scale, with advanced additives to the positive active materials and lower resistance of ceramics solid electrolyte. A lot of effort is now related to improve the recharge power. Further cost reductions are being realised through automation and process improvement on top of the increase of production volume. Cycle life will be increased through design enhancements such as new more corrosion resistant glass materials. Complete turnkey systems with a power rate up to the MW size and 3 to 6 hours energy are being developed and are currently under test. Additional activities and initiatives can accelerate progress in the following areas:

- MODIFICATION OF ELECTRODE CHEMISTRIES AND OPTIMISATION OF INTERFACES – The performance of sodium batteries is largely determined by interfaces and minor chemistries at the cathode side. The ceramic electrolyte often does not demonstrate a satisfactory wetting property to the molten sodium. Surface treatment and interfaces are required to enhance electrical contact to decrease resistance. Minor additions, such as a second electrolyte in the cathodes, have to be optimised to maximise the battery performance. Using surface-science techniques to identify and understand impurities on sodium battery anodes and cathodes can increase the cost-effectiveness and reliability of sodium batteries. Increased understanding of battery degradation modes can help to increase the tolerance of system components to impurities, extending system life.

- NEW SOLID SODIUM-ION CONDUCTING ELECTROLYTE – Beta alumina is the only mature sodium-ion conducting membrane. Discovery of a new solid-state electrolyte that can demonstrate satisfactory sodium-ion conductivity and other required properties can lead to the development of more cost-effective devices that allow satisfactory operation at reduced temperatures.
- STACK/SYSTEM CONSTRUCTION – Developing robust planar electrolytes can reduce stack size and resistance and provide an alternative to current cylindrical electrolyte designs. Identifying low-cost materials that can encase high-temperature cells, reducing operation temperature.
- OPERATIONAL – Implementing pilot-scale testing of battery systems can help to develop performance parameters for grid applications.

Low cost technology targets for high temperature batteries (sodium-based) with a substantially increased cycleability (in excess of 10,000 complete charge/discharge cycles).

The following installed cost targets (set for everything needed up to direct current output to the converter) reflect the push and pull of the energy storage market:

- Current: $3,000/kW
- 2020: $2,000/kW
- 2030: $1,500/kW

The following range of lifecycle costs could also help achieve system targets:

- Current: $0.04–$0.75/kWh/cycle
- 2020: $0.01–$0.27/kWh/cycle
- 2030: $0.01–$0.08/kWh/cycle

Flow battery developers must identify and resolve materials, cell chemistries, and stack and system design and engineering challenges, all of which factor into system cost. For flow batteries, progress can be made in the following areas:

- Basic and applied research on new chemistries for faster kinetics, higher voltages and higher energy densities;
- Develop new electrolytes to replace Vanadium. Use of less expensive raw materials for the electrolyte;
- Development of low cost membrane materials with long lifetimes;
- Proof of concept for redox systems without membrane (undivided cells and micro fluidics);
- Basic and applied research on novel electrode materials with higher electrochemical activity without detrimental effect on durability or with further improvement under battery cycling. Research on nanomaterials and specific surface treatments to increase the electrocatalytic activity;
- Development of innovative designs, electrode, flow systems, modelling, stack design, sealing, taking into account manufacturing issues which especially relates to larger systems, with high cell voltage.

Low cost technology targets for redox flow:

Targets for the period 2020-2030: Energy cost 120€/kWh and Power cost of 250€/kW. Temperature operating range -20°C to +60°C, while maintaining the rest of the figures in values similar to current Vanadium technology: 15-25 Wh/L, > 10,000 cycles.

Major research areas for Li-ion systems are

- Materials for anodes (graphite, silicon) and cathodes (new materials, blends, …) for cost, life and performance and ability to withstand symmetrical Charge/discharge profiles or even charge rates higher than discharge rates
- Electrolytes for safety
- Separators for life time and safety
- Manufacturing process technologies
- Environmental issues (raw materials, clean manufacturing processes, sustainable utilisation of resources, recycling possibilities, internal and external environment, land use, emissions

The goals can be reached by substantial improvement of conventional electrode and electrolyte materials: layered oxides based on Mn and Ni; phospho-olivines based on Fe and Mn; cheaper lithium iron/manganese silicate based cathodes; development of improved Nickel-Manganese-Cobalt-based cathode materials; silicon/carbon composites; fully lithiated silicon alloys and porous active materials (chemical etching processes); development of thermally stable separators and of solid state electrolytes; improvement of cell design and module assembly with innovative control systems. Improved safety and management control systems; partial or total substitution of vanadium with cheaper metal ions; removal or substitution of Nafion (Dupont trade mark) ion-conductive membranes in redox flow batteries.

Furthermore, the possibilities to improve resource efficiency and reduce dependency on strategic materials should be investigated.

Targets for Li ion technology for the period 2020-2030:

› Energy cost < 200 €/kWh or << 0.10 €/kWh/cycle and Power cost <20 €/kW.
› Temperature operating range for mobile applications: -20 to +60ºC
› Temperature operating range for stationary applications: 0°C to 40°C
› Specific performances: 180-350 Wh/kg and 350-800 Wh/L, > 10,000 full cycles.

Current estimates figure a market for Li-ion energy storage systems of several billion Euros per year beyond 2020 (Pike), i.e. a significant increase over the existing industrial battery market (all technologies).

RWTH Aachen's calculation of an optimised European electricity system with close to 100% renewable generation conducts to a need of short term (hourly) storage of about 2000 GWh. A similar approach for Germany alone depicts an optimum size of short term storage of 56GWh. Even though Li-ion would cover "only" a given market share these projections confirm the extraordinary potential for battery energy storage in a high renewable energy scenario in Europe.

Specific development needs

A serious disadvantage for rechargeable batteries is the notable tendency towards degradation of battery performance over time. Degradation – the fact that energy capacity decreases as a function of parameters like number of charging cycles, lifetime (including shelf life and aging), operating temperature and charging and discharging patterns – has a significant impact on particularly costs, since durability and lifetime is severely affected. Battery degradation is often due to specific undesirable side reactions. The reactions are frequently complex and increase the internal resistance of the battery while at the same time inactivating material, which could otherwise be a part of active component in the battery.

A deeper understanding of degradation mechanisms subsequently leading to knowledge about how to prevent the relevant reactions is an important step towards better battery properties and more competitive products for European industry. A dedicated research effort will be needed based on advanced joint European research and characterisation facilities (e.g. synchrotron and neutron sources) able to analyse and map internal battery reactions, phases and crystal structures in situ as well as in operando.

In addition, a series of further cross-cutting research and development actions are necessary to reinforce the European research capability, to accelerate the full comprehension of battery behaviour and to assist the fast transfer to the market place:

- Improved modelling tools are important already now and will become increasingly important in the future. Advances in algorithms for theory, modelling and simulations, and computer technologies provide unparalleled opportunities for understanding the complexities of chemical processes and materials needed and simulate the behaviour under application-oriented duty cycles to elucidate the underlying reaction mechanisms and heat conduction processes for the next generation of electrochemical storage systems. Modelling and simulation can effectively complement experimental efforts in fundamental scientific research on ES and can provide insight into novel charge storage mechanisms, predict trends, and provide design criteria for new materials and guidance for experiments. Various modelling and simulation tools are already available, but it is necessary to improve the integration with quantitative data coming from newly developed dedicated testing activities.
- Development of dedicated testing procedures (from materials to complete systems) for grid applications.
- Pre-normative research on novel duty cycles, even including the evaluation of "second life" possibilities of exhausted batteries in mobile applications.
- Technology benchmarking through round robin tests for accelerating rapid transfer of research results to industrial technologies and standards setting bodies by test profile analysis, test procedure development and experimental validation.
- Fundamental and technological research assessment studies will be required.
- Development of advanced tools for the techno-economic analysis of energy storage applications using batteries and electrochemical capacitors, to identify potential benefits, target costs and appropriate technologies for each scenario.
- Organisation of joint workshops and conference symposia including both European industry and research community can contribute positively to the desired technological development
- Enhanced exchange of early stage researchers across European institutions
- Common definition and validation of modelling and simulation tools
- Establishment of an Integrated Electrochemical Energy Storage Simulation Platform (IESS)
- Improved sharing of experimental and test facilities

- Establishment of a stable and well-connected network with international laboratories in other continents (e.g. Korea, Japan and United States as well as others), based on relationships and continuous exchange of experience and, possibly, researchers and joint research actions.

European strongholds

Europe's established automotive and battery industry provides a strong environmental friendly manufacturing base for mature battery technologies, with Europe's leadership worldwide on advanced lead technologies. Amidst strong international competition, European policy-makers should urgently began to financially support battery manufacturers to build upon this expertise, with increased R&D directed towards the development of batteries for new markets related to renewable energy storage and e-Mobility.

Batteries are important strategic components in key functions of the modern society within communication, mobility and defence and therefore a recent interest in reversing the outsourcing tendency has been demonstrated among European political decision makers. For many reasons it is important to secure and reinforce this trend and maintain production know-how and electrochemical competences in industry, research and education.

Competences within electrochemistry are well in place in many centres widespread over the European Union and those competences are likely to play a central role in the future sustainable energy system of Europe where the primary energy supply will be in the form of electricity from wind or solar power or similar. Recently, there have been several European activities presenting work on new battery chemistries which has originally been done in Europe. Conversion and storage of electricity often requires technologies based on electrochemistry and the services offered by battery storage facilities will be required in the European electricity grid to maintain power quality and stability.

The European market share in manufacturing of conventional batteries in Europe was decreasing over the last three decades mainly due to low labour cost in Asia. However, batteries are important strategic components in key functions of the modern society within many different areas such as communication, mobility and defence. Therefore, a recent interest in reversing the outsourcing tendency has been demonstrated among European political decision makers. Consequently, both, European research efforts focusing on battery technology and European battery industry are strongly expanding these years. By reason of high strategic importance it is mandatory to consolidate and reinforce this trend and to maintain production know-how in European industry and to strengthen electrochemical competences in research and education.

European economic and industrial potential

The current worldwide energy storage capacity installed in electricity grids is estimated in about 127,000 MW, of which 99% is made with pumped-hydro systems. The electrochemical storage amounts to about 446 MW, made of Na-S (365), lead-acid (35), Ni-Cd (27), Li-ion (16) and redox flow (3).

The economic and industrial potential in Europe within batteries is huge. The EU battery Industry represents over 40,000 employees[7]. As mentioned above, the European battery market size is large itself and in addition to home market export opportunities must be counted too.

7 EUROBAT White Paper – Importance of Battery Energy Storage for Renewable Energy Supply, November 2011

Batteries are already well established on the market for different mobile and stationary power applications. According to a very recent market analysis by BCC Research, large and advanced batteries represented a $15.3 billion global market in 2009 and $16.7 billion in 2012[8]. BCC projects a market of more than $21 billion by 2017 and a compound annual growth rate (CAGR) of 4.6% between 2012 and 2017 making it one of the largest and fastest-growing, technology-driven electrical/electronic sectors. The term "large-and-advanced batteries" introduced by BCC means secondary (rechargeable) electrochemical energy storage devices, "large" in terms of size and capacity and technologically advanced. So this definition excludes all primary and lead-acid automotive batteries as well as small-size cylindrical and button cells.

The hybrid electric vehicle (HEV) and plug-in electric vehicle (PHEV) battery market is expected to grow from nearly $4.1 billion in 2012 to $5.2 billion in 2017, a CAGR of 5.2%.

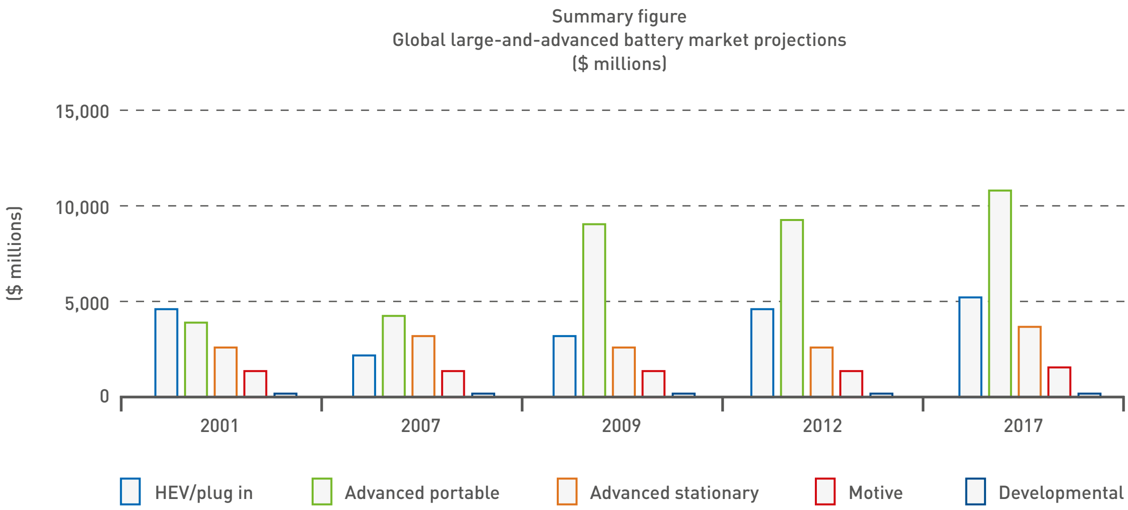


FIGURE 7 - Global large-and-advanced battery market projections

If the technical performance of batteries is further improved, as targeted by this Roadmap - the market demand will grow even faster. E.g. according to a recent study from Roland Berger[9] already the global vehicle Li-ion batteries market (EV, PHEV, HEV, e-bikes, electric rollers etc.) will already grow from 1.1 billion EUR to 7.6 billion EUR until 2015 and under optimistic conditions until 38 billion EUR in 2020. The batteries in these vehicles could be also used in vehicle-to-grid (V2G) applications to store energy from the grid.

The European battery industry is well committed in developing and producing conventional and some of the advanced battery technologies: strong historical positions are on advanced lead-acid and alkaline, with technology leadership positions in advanced systems including Lithium-ion. Industrial capacities in both technologies are being increased by European firms both in Europe and North America. . The position on raw material production and recycling facilities is in general satisfactorily good.

Research group clustering potentials

Clustering of research groups in Europe as well as organisation and effective distribution of efforts between electrochemical research centres in Europe is required as an important

8 bcc research, Large and Advanced Battery Technology and Markets, February 2013
9 Roland Berger Strategy Consultants, Global Vehicle LiB Market Study Update, April 2012

step stone on the way to consolidating the full benefit of European battery potential in the future by integrating and complementing current national and European research programs and projects for optimal utilisation of resources and efforts. A stronger and more intelligent coordination of resources (central EU resources as well as national resources in member states) will improve the overall outcome to the benefit of the European population.

The same is true for utilisation of large joint European research facilities as for example ESRF in Grenoble and the hopefully soon coming European spallation source ESS, which are (will be) outstanding possibilities for European breakthroughs within materials research and development also in the topic of batteries.

Markets in focus - application areas and types

Electrochemical storage systems are estimated to be one of the key storage technological enablers of the transition from the current mostly centralised electricity generation networks to distributed ones with increasing penetration of variable and not programmable renewable energy sources (e.g., wind and photovoltaic) and more "intelligent" management of the energy flows (with Smart Grids and "pro-users", who are end-users with more active role in the electricity market).

A schematic comparison, as presented in Table 6, of the key applications with the various electrochemical storage competing technologies shows the extreme variability of possibilities and the effective suitability[10].

TABLE 6 - Comparison among different electrochemical storage systems for the key grid applications

Application	Pb acid	Ni/MH	Na/S	Na/$NiCl_2$	Redox Flow	Li/ion	Super capacitor
Time-shift	Suitable	Less suitable	Suitable	Suitable	Suitable	Less suitable	Unsuitable
Renewable integration	Suitable	Suitable	Suitable	Suitable	Suitable	Suitable	Unsuitable
Network investment deferral	Less suitable	Less suitable	Suitable	Suitable	Suitable	Suitable	Unsuitable
Primary Regulation	Suitable	Suitable	Suitable	Suitable	Suitable	Suitable	Unsuitable
Secondary Regulation	Suitable	Suitable	Suitable	Suitable	Suitable	Suitable	Unsuitable
Tertiary Regulation	Suitable	Less suitable	Suitable	Suitable	Suitable	Suitable	Unsuitable
Power System start-up	Suitable	Suitable	Suitable	Suitable	Less suitable	Suitable	Suitable
Voltage support	Suitable	Suitable	Suitable	Suitable	Less suitable	Suitable	Suitable
Power quality	Less suitable	Unsuitable	Less suitable	Unsuitable	Less suitable	Less suitable	Suitable

● Suitable ● Less suitable ● Unsuitable

Table 4 qualitatively also presents the competition in place among storage technologies, but does not give any description of the real status of development in economic and technical terms in relation to the various grid applications.

The most imminent business cases for grid application of batteries are expected to arise from demand for grid services in consequence of still larger penetration of renewable fluctuating energy sources in Europe and the parallel phasing out of fossil plants, which have until now taken care of the services.

10 RSEview, L'accumulo di energia elettrica, (in Italian), Il Melograno Editore, December 2011.

Also decentralised application of batteries in the low voltage end of distribution grids is expected to become an early business case following the dramatic increase in solar power installations seen all over Europe. Local solar power may lead to constraints in the low-voltage grid, which can be prevented by local storage capacity (battery) and thereby defer reinforcement of the local grid, which is often an expensive path.

According to BCC research there are more areas where the advanced battery industry could experience the explosive growth usually associated with emerging industries. Examples include utility-load levelling systems and wind-power energy storage. According to a recent study of Pike research the worldwide capacity for advanced batteries for utility-scale energy storage will multiply nearly 200-fold from a few hundred megawatts in 2013 to more than 10,000 MW by 2022. Thus the market for advanced batteries for utility-scale energy storage will roughly double each year over the next 5 years, reaching $7.6 billion in 2017. Over the ensuing half-decade, growth will level off to a still-robust compound annual growth rate (CAGR) of 31 percent, and revenues in the sector will reach $29.8 billion in 2022[11].

Hazards (e.g. explosion, risk of toxic emissions)

Safety risks are inherent in storing energy and therefore safety testing must be an integrated part of battery R&D. Testing aiming at characterising electrochemical cells under abnormal or heavy duty operating conditions/environments must be done to identify potential risks and describe mitigation measures to be used in design, control and usage of future batteries. Similarly safety testing to study thermal performance of electrochemical cells and batteries must be done to generate data crucial for designing battery management systems.

Social acceptance and engagement / social interfaces (incl. jobs creation)

The battery industry is already a major industrial sector in Europe contributing to employment and social welfare and batteries are well accepted in the European society. The ability to maintain or improve employment and further increase the deployment of new technologies is highly dependent on the strong manufacturing base for batteries in Europe. A sustainable industrial base for battery production is a requirement for continued research and technology development by industrial companies in Europe, which in turn supports the competitiveness of the industry in Europe in wider sectors, such as those that incorporate batteries as essential components of their electronic and electrical technology. According to a recent Assessment Report within the SET Plan Education and Training action there is a considerable future need for skilled workers for the battery sector[12].

In a still not finally published work[13] it is estimated that worldwide 323,500 new jobs can be expected in NaS batteries, 249,000 in redox batteries and 143,500 in Li ion batteries within electricity storage by 2030. The report indicates as reasonable and obtainable target that about 1/3 of the jobs could be created in Europe.

Environmental issues

The EU Battery Industry is very committed to waste prevention and recycling. The Battery Directive establishes a principle of producer responsibility. The combination of the legal obligations on the take-back of batteries and the ban on landfilling and incineration ensures the collection of used batteries. In addition, spent industrial batteries are highly unlikely to

11 Pike Research, Advanced Batteries for Utility-Scale Energy Storage Applications, 3Q 2012
12 Assessment Report for the Working Group Energy Storage within the SET Plan Education and Training action, September 2012
13 SET-plan Education and Training, Assessment Report for the Working Group Energy Storage, Draft: September 2012 (Bignucolo, Cabeza, Chiaberge, Fastelli, Folke, García-Naveda, Garde, Martin, Mulder, Riu, Seifert, Stelzer, Ziebert)

be disposed of in the municipal solid waste stream because professional users appreciate the economic value of materials recycling.

Infrastructure for the collection and recycling of batteries exists all over Europe and therefore minimises the negative impact of batteries and waste batteries on the environment, thus contributing to the protection, preservation and improvement of the quality of the environment. Battery transportation and safety via ground, air and sea is dealt with via specific EU regulation.

Life cycle analysis (LCA) of new technologies and materials concepts is a fundamental step in development and deployment of new technologies and this is especially important for electrochemical storage technologies. For example, before development of new concepts it is essential to know whether it depends upon strategic or scarce minerals and the environmental footprint of the materials production. The useful lifetime of batteries needs to be understood and compared to alternatives and finally it is important to adopt appropriate designs to minimise materials use and facilitate materials recycling. Large battery recycling facilities and consortia already exist for conventional batteries (mainly lead-acid and alkaline), while for lithium-based a recycling facilities have been already developed, such as at Umicore Belgium but further need to be deployed worldwide. This should be a major undertaking given the often complex nature of electrochemical storage.

However, the European battery industry can build upon the precedent already set with Lead-based batteries; over 90% of which are collected and recycled in a closed loop system. Equivalent recycling systems for other battery technologies are expected to be developed as demand increases in line with the growth of renewable energy storage and e-Mobility.

Standards

The rapid growth and the new technologies involved in electrical battery storage in the near future as well as the expected installation of batteries by consumers will impose particular requirements for their characterisation and safety via the development of dedicated standards. For the new specific applications in grids, the industry started with significantly update of stationary battery standards and largely extend the newly developed standards for electric and hybrid vehicle applications. Experimental pre-normative research, aimed at defining and validating test procedures for electrical, thermal and safety characterisation of novel electrochemical storage systems for grid uses is strongly required over the first coming decade. Standards related to grid-connected battery storage should be further developed to increase the flexible use of batteries in the grid.

Electrochemical capacitors (supercapacitors)

Description and key property range

Conventional capacitors store electrical energy electrostatically by physically separating opposite charges, with no chemical or phase changes taking place, and the process is highly reversible and the discharge-charge cycle can be repeated over and over again, virtually without limit. Electrochemical capacitors (ECs), also referred as "supercapacitors" or "ultracapacitors," store electrical charge in an electric double layer at the interface between a high-surface-area carbon electrode and a liquid electrolyte. Consequently, they are also quite properly referred to as electric double layer capacitors (EDLC). This mechanism is highly reversible, therefore ECs can be charged and discharged more than 500,000 times. Electrode surface area in capacitors determines the capacitance and thus, the energy storage capability of the device. The amount of energy stored by ECs is very large compared to a standard capacitor because of the enormous surface area created by the porous carbon electrodes and the very small charge separation created in the double layer.

Since its invention in 1957 by Becker, ECs have been significantly modified with the scientific and technological advancements in materials.

Beside most commercialised EDLCs, there is a class of energy storage materials that undergo electron transfer reactions yet behave in a capacitive manner. These materials store the energy using highly reversible surface redox (faradaic) reactions in addition to the electric double layer storage, thus defining pseudocapacitive storage.

The most recent EC designs are asymmetric and hybrid and comprised of two capacitors in series, respectively, two electrodes with the same active material but with different mass and capacity loadings, and one capacitor-like electrode and the other a battery-like, with varying electrode capacity ratios, depending on the application. The battery-like or pseudocapacitor electrode relies on highly-reversible redox (electron charge transfer) reactions. In this design, the capacity of the battery-like electrode is generally many times greater than the capacity of the double layer capacitor electrode, which is the basis for the name "asymmetric or even hybrid". In practice, the variable combination of these materials, electrodes and novel electrolytes has created a variety of alternatives and designs not easily identifiable. A tentative classification of EC categories is summarised in the taxonomy in Figure 8[14,15,16]

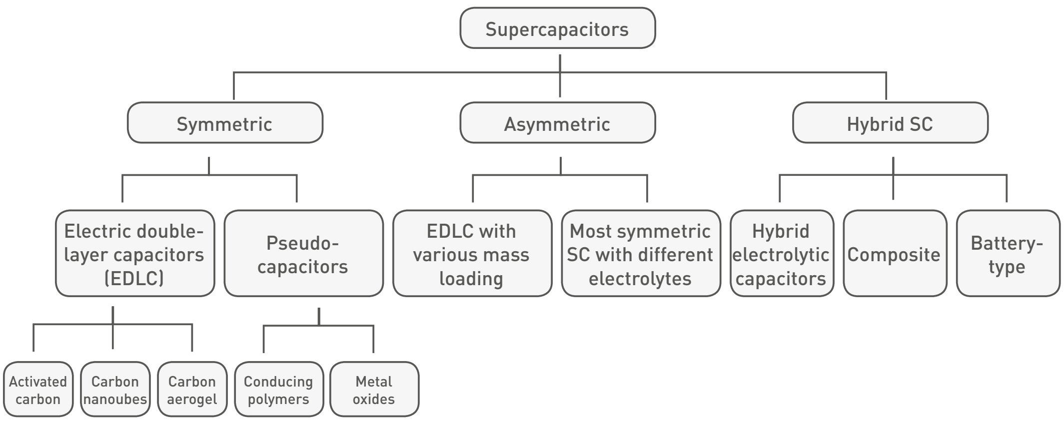


FIGURE 8 - Taxonomy of electrochemical capacitors (categories and classes)

14 J. R. Miller, P. Simon, Fundamentals Of Electrochemical Capacitor Design And Operation, The Electrochemical Society Interface, Spring 2008.
15 M. Conte, "Supercapacitors: technical requirements for new applications", Fuel Cells- Special Issue "Supercapacitors", 10 (5), 806-818 (2010).
16 R. Alanen et alii, "D4.1 Electrical Energy Storage Technology Review", EERA Joint Programme on Smart Grids, Sub-Programme 4 "Electrical Storage Technologies", March 2012.

The earliest ECs were symmetric designs (two identical electrodes) in aqueous electrolyte, H_2SO_4 or KOH, which limited operating cell voltage to ~1.2 V/cell and nominal cell rating to ~0.9 V. In the second generation of ECs, the use of organic electrolyte —typically an ammonium salt dissolved in an organic solvent, such as propylene carbonate or acetonitrile—, with higher dissociation potential, allowed to increase the rated cell voltage up to 2.3-2.7 V/cell. Several novel asymmetric and hybrid EC designs are under development able to further enhance the cell voltage in excess of 4 V, and consequently the related energy content.

All these new materials and designs have been able to significantly improve specific performances (some not commercial yet) to more than 5 Wh/kg and in excess of 10 kW/kg, with a life lasting well beyond 500,000 complete charge/discharge cycles.

Critical gaps between needs and present performance

ECs are interesting for their capacity to store very high power in a small volume and weight with high stability for a long time. The storage system round-trip efficiency is extremely high, around 95%.

The low energy density and high capital costs (estimated in the range of 1100-2000 €/kW, including installation costs)[17] limit the use of ECs in electricity grids to high-power applications (up to 10 MW) with growing interest from electric utilities, which are looking to these devices for performance improvement and reliability in a variety of areas, with much higher power levels and with distribution voltages up to 600 V.

Technical development perspectives

According to a market report from Pike Research, worldwide sales of ECs (for large applications) will grow tenfold from just $28.2 million in 2011 to $284.1 million by 2016, with cumulative revenue of $901.3 million during that period. Supercapacitors can be produced at a less cost than their earlier versions as new materials, such as nanomaterials, and novel designs emerge. In addition to new material development, efficient manufacturing would be paramount in reduction of cost. Being used for an increasing number of purposes in electric vehicles, mobile phones, energy harvesting, renewable energy and other products of the future, IDTechEx estimates a roaring market up to over $11 billion in ten years from 2013 with considerable upside potential.

In the near term, EC systems are likely limited to power-related (rapid discharge) applications for both grid and transportation applications. The low energy density and high cost per unit of energy stored makes ECs currently uncompetitive for energy applications where discharge times of minutes or more are required. These early markets continue to decrease EC manufacturing costs. According to Nano-market's research, because of their low maintenance and fast discharge rate ECs will be used extensively in frequency-regulation of grids and the transportation market share, which currently accounts for almost 60% of the EC market, will fall by half. ECs can be produced at a less cost than their earlier versions as new materials such as nanomaterials and novel designs emerge. In addition to new material development efficient manufacturing is paramount in reduction of EC cost.

17 S. Inage, "Prospects for Large-Scale Energy Storage in Decarbonised Power Grids", Report IEA (International Energy Agency), 2009.

Need for research

Current EC research primarily targets reducing material and device cost and increasing energy density without sacrificing power and life. Specific areas of research and development (see Figure 9) include:

- Reducing component and finished electrode material manufacturing costs;
- Increasing the capacitance of electrodes by increasing surface area and tailoring the pore size and shape;
- Finding electrolytes capable of voltages beyond 2.7V, preferably with less toxicity.

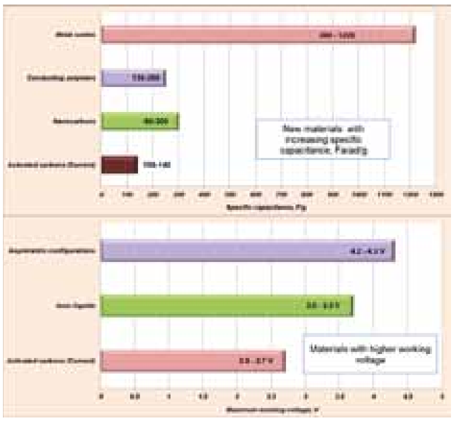


FIGURE 9 - R&D challenges for high energy density ECs[18]

Carbon remains the preferred material for EC electrodes as it is non-reactive in most electrolytes. Carbon can be derived from a variety of materials and its structure is tunable during manufacturing, allowing the designer to control surface area, pore size and pore volume. While the cost of raw carbon may be low, highly purified finished carbon is generally expensive. However, carbon electrodes have the potential to cost less in the future. Carbon nanotubes (CNTs) or fibers (CNFs), fine-tuned microporous carbons and graphene structures are also under investigation as possible EC electrode materials. High surface area electrode materials (in general nanomaterials) maximise this interface, resulting in larger capacitance.

Economic and technical development goals

Materials, process and system integration low cost technology targets for supercapacitors: new low cost materials for cathode: Development of new low cost electrode and electrolyte material able to increase working voltage and overall specific energy. The focus will be: for the cathode on mixed metal oxides/nitrides, organic redox compounds, carbon nanotubes (CNT), graphene and new high surface carbons (e.g., aerogels) and for anode on new carbons, organic redox compounds, graphene and CNT; for the electrolyte on neutral aqueous electrolytes, organic electrolytes, Ionic liquids (ILs) and Polymer electrolytes; improvement of cell design and module assembly with innovative control systems.

Targets @2020-2030: much less than 1 Eurocent/F, corresponding to an energy cost of less than 3 €/Wh and a power cost of less than 0,3 €/W, specific performances: >10-15 Wh/kg, while maintaining similar high power capability and long cycle life as current ECs.

18 K. Naoi, P. Simon, New Materials and New Configurations for Advanced Electrochemical Capacitors, The Electrochemical Society, Interface, Spring 2008.

Research needs related to new concepts (not yet commercially explored)

New, transformational or complementary power devices beyond current designs ECs could play a role in advancing grid-scale storage. Such devices to be addressed are asymmetric or hybrid capacitors with increased specific energy, which could be combine an EDL capacitor electrode with a battery-type electrode, and large-scale dielectric capacitors, which could be enabled by the development of new materials and production processes.

- The synthesis and development of new low cost and high performances materials for electrodes such as metal oxides/nitrides, carbon nanotubes (CNT), nanofibers (CNFs), graphene, graphite based hard carbons, carbide-derived carbons, carbon gels and other nanomaterials (nanoparticles in 1D/2D/3D nanostructures). Optimisation of the electrode fabrication and scaling up the process and related technology;
- Development of low cost and environmental friendly electrolyte materials. Very promising will be electrolyte materials with wider voltage window such as neutral aqueous and polymer electrolytes, new formulation of mixtures of organic electrolytes, innovative Ionic liquids, ILs. Hence, Ionic Liquids and other aqueous systems could allow higher voltage ranges with wide operational temperatures and high conductivity. Moreover, ionic Liquids-solvent mixtures with high voltage solvents as developed in Li-ion batteries (additives/new solvents);
- Proof of concept of asymmetric and hybrid Li Ion Capacitor (LIC) systems: improve life cycle and improve symmetry of charge-discharge rates to achieve 20-30Wh/kg in synergy with high power Li-ion batteries; proof of concept of ceramic ECs with dielectric or insulator with very high permittivity;
- The design of new devices and modules will influence both the performances and manufacturing costs, which could be achieved by new electrodes mass production, improvement in cell performances and devices optimisations. The low cost manufacturing process gain advantages from the ability to design energy storage components having the required physical shapes and properties. The reference technologies will be coating and printing processes that allow easy scale-up and low cost manufacturing. Starting from these technologies in status, optimisations of coating and printing processes will be further implemented for the evaluation and development of possible new processes;
- Basic and applied research on aqueous hybrid systems for very low cost and low environmental impact using activated carbons;
- There are extraordinary opportunities for taking advantage of materials that exhibit pseudocapacitance to produce high-performance ECs. Improved understanding of charge transfer processes in pseudocapacitance is a critical step that will lead to the design of new materials and multifunctional architectures offering substantially higher levels of energy and power density. Novel transition metal oxides of lower cost and better performances need to be explored for EC applications because of their layered structure (oxides such as Nb_2O_5 which yield layered structure) and ability to adopt wide variety of oxidation states;
- Unlike oxide materials, which have been extensively studied for supercapacitors, nitrides and sulphides have received limited attention. Conventionally, some nitrides are known to have better conductivity than oxides and are hence more suitable for high rate devices like capacitors.

Figure 10 summarises the roadmap of ECs with projections towards 2030, in which are evidenced the future visions on development of new high performance materials for electrodes and electrolytes. The design and development of devices, modules in asymmetric and hybrids configuration capable of delivering high energy and high power and highly cost effective and safety. The cost issues will be managed by electrodes large scale coating and printing manufacturing process. These devices will be integrated in grid systems.

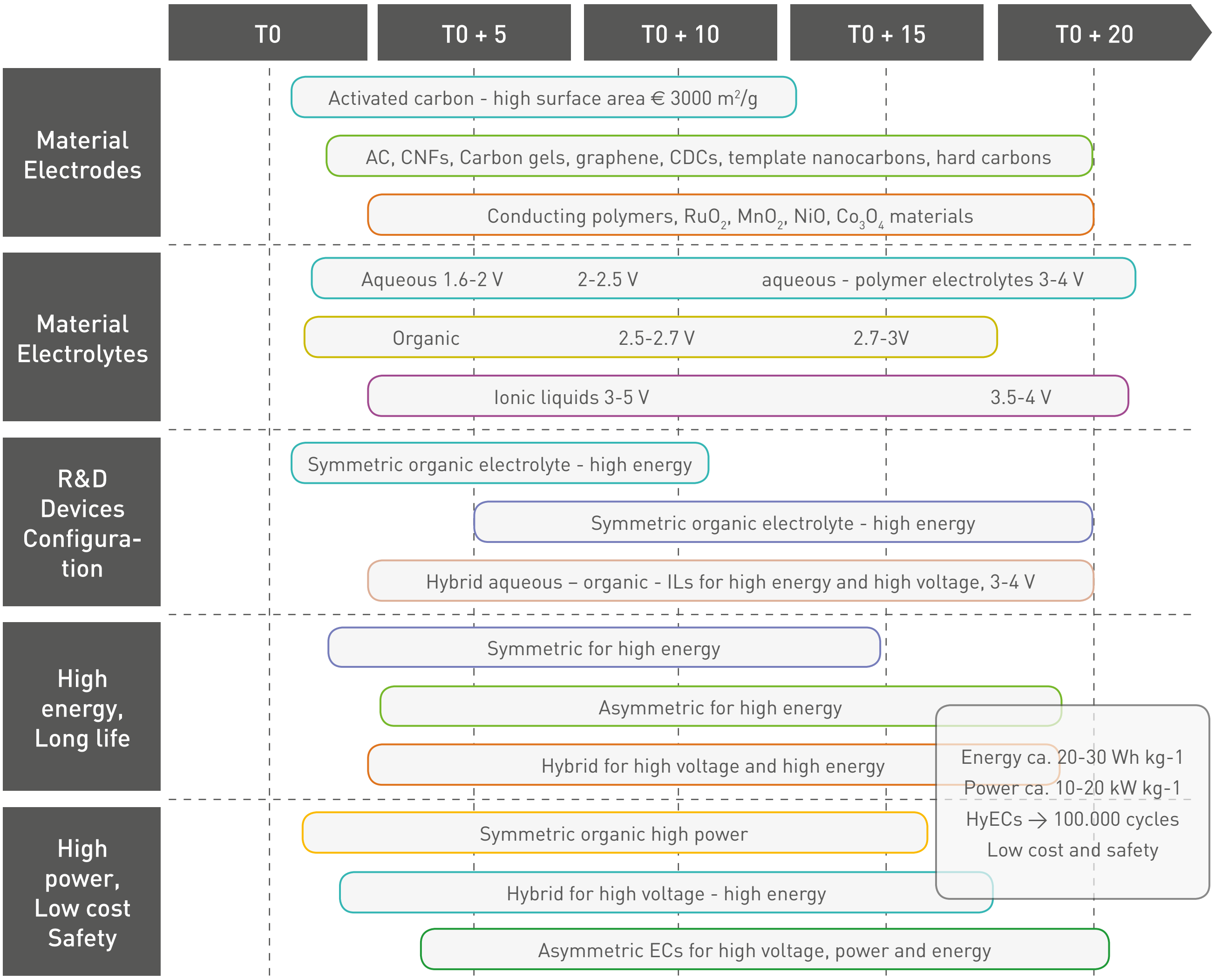


FIGURE 10 - Tentative roadmap for SCs with vision to 2030 (prepared by CNR-ITAE from [19,20,21,22]).

General needs related to R&D

Testing and demonstrating ECs can help to validate technology lifetime, ramp rates, and other performance characteristics that need to be proven to encourage stakeholder buy-in. Diagnostics and modelling could help to provide an understanding of the limitations of current electrochemical capacitor designs and could help to drive the development of high-energy electrodes, process optimisation with the new electrodes, and scale-up of fabrication with new electrodes as well as new cell design.

19 P. Staiti, A. Arenillas, F. Lufrano, J.A. Menendez, J. Power Sources 214 (2012) 137.
20 Q. Gao, et al., Energy Environ. Sci. 5 (2012) 9611.
21 S. Makino, et al., RSC Advances, 2 (2012) 12144
22 K. Naoi, et al. Energy Environ. Sci., 5 (2012) 9363

Specific development needs

Novel concepts for the development and design of electrodes, electrolytes, and interfaces can be more functional for the development of ECs more suitable for grid applications, with increased energy content and more compatible cost prospects. For instance, the integration of multiple physico-chemical functionalities or the synthesis of materials with micro- and mesopore size distributions show enhanced charge storage efficiency. Also the search for new materials and nanofabrication technology may further enable the development of nano-architectured electrodes for high performance pseudocapacitors as well as hybrid devices with appropriate dimensional control for ion channels.

European strongholds

55% of the manufacturers and intending manufacturers of ECs in East Asia, 28% are in North America but Europe is only at 7% [IDTechEx Market Survey, 2013]. A recent patent survey carried out in the on-going European Project ElectroGraph (Graphene - Based Electrodes for Application in Supercapacitors) has shown that only 5% of the worldwide patents (search with keywords: graphene, supercapacitors and electrochemical methods) in the second half of 2011 were originated in Europe (only Germany).

IDTechExreport lists 70 manufacturers around the world interested in EC supply, of which only 9 are currently located in Europe including Estonia, Russia and Ukraine.

Nevertheless, the scientific and technological competence on key materials and on ECs related electrochemistry are largely available in various research centres and academia well distributed in the European Union with advanced infrastructures for supporting all the steps of the value chain from advanced and novel materials research up to innovative designs optimisation.

Technology and scientific excellences present in Europe need to be better interlinked and develop hand-in-hand.

European economic and industrial potential

The economic and industrial potential in Europe is potentially high, despite the current limited industrial involvement, which accounts for a few tens of direct jobs. No figures are available on the materials market associated with materials production, while the strong interest of European car manufacturers on start-stop vehicle applications of ECs is driving a significant growth of the related market, also pushed by more severe emission regulations, putting Europe at front edge of this niche application.

Demo and pilot testing

Until now, for grid applications the most common use of ECs in UPS (Uninterruptible Power Systems) has been complemented by a very few demonstration projects, such as the use for load levelling in industrial services (by improving the efficiency of cranes), a pilot project of ENEA in Italy, or a 450 kW project in Palmdale, in California (USA), for wind generation and power reserve of a 1.25 MW micro-grid, used for a water treatment plant.

These application areas are essentially more suitable for ECs and strongly indicate the unique potential of ECs for use in combination with energy harvesters.

Research group clustering potentials

Clustering of research groups in Europe as well as organisation and effective distribution of efforts between electrochemical research centres in Europe is required as an important step stone on the way to consolidating the full benefit of European electrochemical storage potential in the future by integrating and complementing current national and European research programs and projects for optimal utilisation of resources and efforts, as is underway in EERA collaborations. A stronger and more intelligent coordination of resources (central EU resources as well as national resources in member states) will improve the overall outcome to the benefit of the European population: this optimisation process has been started on a voluntary basis in EERA, which are also aiming at integrating resources and infrastructure.

Markets in focus - application areas and types

Progress in ECs has made them suitable for high-power applications with growing interest from electric utilities, which are looking to these devices for performance improvement and reliability in a variety of areas, with much higher power levels and with distribution voltages up to 600 V. The key peculiar features of ECs are extremely appealing for a variety of applications in electricity grids: fast response time in milliseconds, high-energy efficiency (more than 95%), high power density and long calendar and cycle life. Various functions can be then performed by EC devices in electric grids, such as, for example:

1. Transmission line stability. The stability of a transmission system by adding energy storage. This serves to dampen oscillation through the successive generation and absorption of real (as opposed to reactive) power. There is also transient stability – the stability required after a utility event (loss of substation or major line). During a transient event, achieving stability requires a substantial capability to absorb energy quickly. This is somewhat analogous to "dynamic braking" because generator turbines must be slowed. A typical specification is 100 MW with 500 MJ (< 5 s).
2. Spinning reserve. This is the generation capacity that a utility holds in reserve to prevent service interruptions if a generator fails. An EC system can be built to supply power during the interruption, until quick-start diesels begin to supply power. A typical specification is 20 MW to 100 MW and 300 MJ to 1500 MJ.
3. Area and frequency control. The lack of matching between electrical energy production and energy consumption (including losses) appears as a frequency variation. EC system, thanks to its fast response time, would be considerably more effective than a generating plant in supplying frequency regulation. A system based on ECs can absorb or supply energy as required, freeing other generation sources from frequency regulation or tie-line control duties. A typical specification is 100 MW to 1000 MW and 0.1 MWh to 10 MWh.

Hazards (e.g. explosion, risk of toxic emissions)

As with batteries, ECs present potentially dangerous voltage levels, which, for grid applications, represent very little incremental risk. Aqueous electrolytes may contain hazardous materials including potassium hydroxide and methyl cyanide. Furthermore, certain electrolytes are flammable, such as acetonitrile, which releases hydrogen cyanide when burned.

This may provide limited risk in grid applications, where there is lower risk of release, and the expectation is that installation and maintenance would be performed by trained personnel only. As with batteries, ECs must be properly disposed or recycled at end-of life. The majority of materials in current ECs include common materials such as carbon, nickel, steel, aluminium, and a variety of plastics. Advanced asymmetric ECs would use several materials used in advanced batteries, such as lithium and vanadium. It is difficult to estimate the total material requirements, but they would unlikely be greater than those for batteries, and this requirement must be placed in the context that the target applications for capacitors are those with limited actual energy capacity [23].

Social acceptance and engagement / social interfaces

Electrochemical storage industry is already a major industrial sector in Europe contributing to employment and social welfare and batteries are well accepted in the European society. The ability to maintain or improve employment and further increase the deployment of new technologies is highly dependent on a strong manufacturing base for batteries in Europe. A sustainable industrial base for battery production is a requirement for continued research and technology development by industrial companies in Europe, which in turn supports the competitiveness of the industry in Europe in wider sectors, such as those that incorporate batteries as essential components of their electronic and electrical technology. According to a recent Assessment Report within the SET Plan Education and Training action there is a considerable future need for skilled workers for the battery sector[24].

Environmental issues

Life cycle analysis of new technologies and materials concepts is a fundamental step in development and deployment of new technologies and this is especially important for electrochemical storage technologies. For example, before development of new concepts it is essential to know whether it depends upon strategic or scarce minerals and the environmental footprint of the materials production. The useful lifetime of electrochemical storage technologies needs to be understood and compared to alternatives and finally it is important to adopt appropriate designs to minimise materials use and facilitate materials recycling. This should be a major undertaking given the often complex nature of electrochemical storage.

Standards

The rapid growth and the new technologies involved in electrochemical storage technologies in the near future as well as the expected installation of these technologies by consumers will impose particular requirements for their characterisation and safety via the development of dedicated standards. For the new specific applications in electricity grids, it will be necessary to significantly update the old standards and largely extend the newly developed standards for electric and hybrid vehicle applications. Experimental pre-normative research, aimed at defining and validating test procedures for electrical, thermal and safety characterisation of novel electrochemical storage systems for grid uses is strongly required over the first coming decade.

23 P. W. Parfomak, Energy Storage for Power Grids and Electric Transportation: A Technology Assessment, CRS Report for Congress R42455, March 2012.

24 Assessment Report for the Working Group Energy Storage within the SET Plan Education and Training action, September 2012

ANNEX III: MECHANICAL ENERGY STORAGE

Compressed Air Energy Storage

Description and key property range

CAES plants are used to store electrical energy. During charging the storage the electrical energy is converted into and stored as pressurised air. Turbo and/or piston compressors can be applied to compress the air. The compressed/pressurised air can be stored in underground caverns or other (above surfaces) tank(s). Heat generated during compression can be stored in order to increase the round-trip efficiency. During discharging the air from the cavern or tank(s) is released and drives the expander of a turbo or piston expander, improve efficiency and boost power density. Before expansion the compressed air must be preheated to avoid freezing of the expander. In case that the heat from compression is used to preheat the air before expansion the process is adiabatic. If natural gas is used to preheat the air by combustion the process is diabatic.

Today world-wide two plants exist:

1. Huntorf, Germany built in 1978, charging power 60 MWel (8 hrs), discharge power 321 MWel (2 hrs)
2. McIntosh, USA built in 1991, charging power 60 MWel (45 hrs), discharge power 110 MWel (26 hrs)

CAES plants can be used to provide grid scale storage services on a daily or even weekly basis.

Critical gaps between needs and present performance

Where are the most urgent needs for energy storage in 10-20 years?

For the time being CAES achieves a relatively low round-trip efficiency; plants in operation achieve between 40 to 54% AC-AC roundtrip efficiency rate (in particular due to the heat losses during the compressing stage and the fact that compressor and expander cannot be attached to one shaft). Moreover these plants use natural gas for preheating of the compressed air before expansion, thus producing some – albeit limited – amounts of CO_2. As there exist only two plants worldwide, the efficient turbo machinery design is not available "of the shelf" and the existing steam turbine expander solutions are adapted to fit the special thermodynamic specifications of these CAES plants. This turns small scale applications more expensive. Today, all compressed air reservoirs are of constant volume type and their power output is not constant once the reservoir pressure falls below the maximum expander inlet pressure. The constant pressure storage approach – which would be more advantageous from compression and expansion efficiency point of view – due to the required brain shuttle pond faces public acceptance problems in Europe.

Technical development perspectives

How far can we get in the next decade?

The objective for CAES deployment is to improve the roundtrip efficiency of diabatic CAES plants by using the waste heat of the flue gas from the gas turbine exhaust to preheat the pressurised air before the combustion chamber during discharge. This measure is already applied in the McIntosh plants and would lead to efficiencies of new build diabatic plants of around 55%.

The efficiency potential of CAES is at about 70 to 80%. In order to achieve this, the heat from the combustion process must be stored in addition to the pressurised air. Several concepts are currently under investigation. In the upcoming months several adiabatic pilot plants will be commissioned at different sites.

ADELE – Adiabatic compressed-air energy storage (ACAES) for electricity supply

This concept aims at storing the heat from compression heat recovery is done in an "interim heat-storage device"[25]. The heat storage facilities are pressurised containers with beds of stones or ceramic moulded bricks through which the hot air flows. Material issues have to be solved for the pressure vessel and the piping. Another challenge is the development of the high temperature compressor for temperature up to 600°C at 100 bar. It is claimed that a demo plant could be in operation in 2016 at the earliest. The efficiency of such a plant should be around 70%.

LTA - Low Temperature Adiabatic CAES

In order to avoiding the technical challenges of the ADELE concept, a Low-temperature Adiabatic Compressed Air Energy Storage (LTA-CAES) plant based on a two-tank non-thermocline TES was developed by Fraunhofer[26]. A multistage radial compressors and expanders with single stages arranged at the ends of several pinion shafts rotating with different- and for the assembled impellers optimal speeds - is applied in this concept. The proposed LTA-CAES design shows cycle efficiencies in the range of 58 to 67%. However, it is claimed that its fast start-up characteristics and wide-ranging part load ability is superior to the ADELE concept. On the other side this concept exists only as a paper study and there are no identified manufacturers and suppliers who could provide credible data in a feasibility study.

Isothermal compressed air energy storage (ICAES)

The concept of isothermal compressed air energy storage (ICAES) proposed by SustainX[27] is based on isothermal compression thereby avoiding the inherent challenges of high temperature heat storage. Compressed air at near ambient temperature is stored until needed. A mechanical drivetrain utilises an electric machine and a crankshaft. This mechanical link powers a two-stage, mixed-phase (water-in-air) heat-transfer process within pneumatic cylinders. During piston strokes, water is sprayed into the air-filled chamber of each cylinder, allowing heat to be transferred from water to air during expansion or from air to water during compression. The same ICAES power unit provides both isothermal compression and expansion, eliminating the cost of separate compressor and expander subsystems. A similar concept is proposed by LightSail Energy and General Compression. The efficiency of ICAES processes is claimed to be u over 70 %. Because of the piston drives the proposed scale of these plants is considerably small (100 kWel).

25 RWE
26 Fraunhofer
27 SustainX's ICAES™

Pnu-Power Compressed Air Battery for back-up power applications

A UK company, Pnu-Power (Energetix Flows Group) developed a small scale "compressed air battery" which is up to 200kW for single unit and can be connected in parallel to achieve over a MW or a few tens of MWs power rate. Pnu-Power battery does not consider the process of compression and treated the compressed air available from a source. The compressed air battery only considers the expansion stage from compressed air to electricity. The battery uses an energy efficient scroll expender and it is claimed that the scroll expender can have over 90% energy conversion efficiency. So the overall battery efficiency is over 80%. This is an example to demonstrate the importance in developing efficient turbo machinery.

Reservoirs

As the costs for the reservoir represents an important part of the overall CAES cost (€/kWh_el), all improvements with regard to construction and maintenance costs will result in overall lower costs for CAES. Composite materials could play an important role for pressure vessels in decentralised CAES applications.

Existing Reservoirs

Both existing plants are based on salt caverns. Some American projects studied the possibility to store compressed air in a porous underground storage.

- Isobaric Adiabatic Compressed Air Energy Storage – Combined Cycle (ISACOAST-CC)

Usually the reservoir is of a constant volume type which results in variable pressures for compressor and expander during charging and discharging. To increase the efficiency a brine shuttle pond at the surface can be used to drive out the stored air at nearly constant pressure[28]. Thereby the losses are reduced due to high constant differences of the storage pressure within the cavern. But building brine ponds in highly populated areas faces significant challenges

- Storage tanks

For small scale CAES applications air can be stored in above ground air or empty natural gas storage tanks. Thus these types of CAES plants are almost site-independent as the suitability depends much less on the geological conditions[29] but can become too expensive for larger application. Underwater storage seems another solution to be considered, with inflatable or rigid containers, because of the low cost for this kind of envelope, and the better efficiency induced by constant pressure.

Economic development perspectives

Realistic economic goals for the technology towards - 2030

The envisaged increase of variable renewable energy in the generation mix by 2030 will likely trigger the need for large scale energy storage as well as decentralised small scale generation.

28 Reinhard Leithner TU Braunschweig
29 ESA, LightSail

Among the energy storages, CAES facility is characterised as a large scale storage, centralised (connected to transport network) and flexible instrument. Indeed, CAES is designed to buffer fluctuations coming from a large number of sources on both generation and load. It prevents curtailment of renewable and base load electrical generation, helps to balance the electrical grid both short term (ancillary services) and long term.

For CAES, it can be expected that reduction in costs (estimated to around 20%) as well as significant efficiency improvements beyond 70%, are achievable. In the future decentralised CAES plants could be deployed in the distribution grid and even at consumers.

Need for research

Different orientations can be jointly supported, without a-priori ranking of merit.
- Research directed to existing, already industrially applied technologies could be valuable to improve the global round-trip efficiency for electricity at Grid level.
- For CAES research in the field of piston and turbo machinery in combination with intelligent heat storage systems would be most helpful.

General R&D needs

Materials

New and/or improved materials are essential for high temperature CAES processes. High temperature heat storage requires cost effective, highly durable material in mass quantities whereas for the turbo machinery part less material is required but the requirements towards reliability and manufacturability are even higher.

Isobaric caverns

The development of isobaric storage can be investigated in very different sizes and technologies:
- caverns requires a deep understanding geological formations and monitoring capabilities. Detailed investigations of potential suitable sites as well as development of measures to guarantee the stability of the caverns are crucial.
- surface combination of pipes, possibly including systems for constant pressure, could smooth the geographic constraints for CAES and foster deployment of small CAES units dispatched on Distribution Grid or in industrial sites.
- undersea volumes anchored in deep water could provide relevant association of CAES with offshore wind.

Specific development needs

Existing turbo machinery as well as piston drives could be modified and/or adapted to fit to the needs of low temperature adiabatic and/or isothermal process. Developments become more expensive and less attractive for manufacturers the more a completely new design is required which is finally only applicable for CAES plants. This might favour small scale low temperature solutions. However as these processes often require the handling of air/water mixtures, other engineering challenges, like valves and valve control systems may appear.

With regard to the storage reservoir maintenance efforts and erections could still be reduced by improved engineering approaches.

Needs regarding "balance of plant"

No special requirements exist for CAES plants with regard to grid integration.

European strongholds

In the field of large and medium scale turbo machinery European know-how is on a world class level. This also applies to reservoir engineering.

However a lot of new patents and processes appeared recently in the area of smaller scale low temperature/isothermal processes. Currently no major European supplier has taken up the opportunity to step into this kind of process family although the competencies should be available.

European Economic and industrial potential

With increasing share of renewable energies, the potential for CAES is huge in the large scale and medium electricity storage sector. However it has to be stated that at present storage demand is limited and that CAES has to compete with other storage technologies such as pumped storage plants and aggregated small scale batteries and/or medium size batteries (e.g. Redox-Flow). The economic potential is highly dependent on the regulatory framework changes for fluctuating renewable generation.

Demo and pilot testing

Initially foreseen to go into demonstration by 2013 the ADELE project was challenged by less optimistic market conditions. Additionally concept studies proved the necessity to more thoroughly analyse possible technical system designs for economical optimisation. Hence the demonstrator was postponed to earliest 2016 and a dedicated engineering project by name of ADELE-ING will be completed in the meantime. It will determine the final plant design. The demonstrator will be sited in Staßfurt, Sachsen-Anhalt. If the currently most promising design will be chosen, most probably only a 1-train demonstrator will be built with about 100 MW rated power and 4 h powering time.

An ICAES 100 kWh pilot plant was completed in 2012. It is planned to build an 1 MW, 4 MWh system, likely at a coal plant, in conjunction with AES. The large-scale demonstration is scheduled to come online in early 2013.

Pilot projects are also announced from different stakeholders: General Compression, Light-Sail Energy, SustainX, Agnes, and other undisclosed players. They are in different phases, form preliminary R&D up to building phases.

Research group clustering potentials

In Europe several research groups (TU Braunschweig, DLR; Fraunhofer; etc.) are working on exploring the technical and business potential of CAES. Also several utilities and suppliers (RWE, GE, GDF SUEZ etc.) are active in the field of CAES. Clustering the research group potentials could improve the effectiveness of the research. However it has to be noted that suppliers and utilities collaborations are limited by European and national anti-trust laws.

Joint use of research infrastructure in Europe

As far as new components are concerned European supplier own sufficient testing facilities to test compressors/turbines etc. System and process design requires computer modelling capabilities that are widely spread and available throughout Europe. The existing CAES site in Huntorf, Germany offers optimum preconditions for testing of CAES demo and pilot plants because of the existing infrastructure (caverns, etc.).

Grid integration

CAES is a proven technology and its further deployment would not pose any issues as regards its grid integration. However market integration potential in combination with possible applications and technical requirements could an issue. It is not cleared yet, how a CAES but generally an electricity storage facility is considered. Different ownership and operation structures are possible, of course the applied market model will influence on the art of grid integration.

Hazards (e.g. explosion, risk of toxic emissions)

As the medium to store energy is air and in case of adabatic and/or isothermal CAES stones, concrete, gravel, water or similar substances the risk arising from CAES plants is low. In case of diabatic CAES plants the risk is similar to the risk of combined cycle gas turbine plants.

An additional impact to the environment is created by creation of caverns. However the leaching of caverns and their operation for pressurised natural gas is state-of-the-art and proven technology. The risk arising from operation with pressurised air is far lower. If pressurised air is stored in above ground tanks a risk arises from these pressure vessels. However the technology is also state-of-the-art and proven technology.

Social acceptance and engagement / Social interfaces (incl. jobs creation)

Especially CAES processes which are operating without natural gas are to a great extent environmentally neutral. The public is currently not much aware of this technology. However the plants which are in operation are widely accepted. It can be expected that the CAES technology will be publicly accepted.

Markets in focus - application areas and types

CAES is basically suitable for large to small scale storage applications. However small scale CAES has not yet achieved the same technical maturity as large scale CAES. Markets are expected in northern Europe close to off-shore wind farms. CAES could be applied to serve off-shore wind farm by balancing generation and demand. In addition CAES can be applied to provide secondary and tertiary balancing power as well as black start capability.

Business cases

It is expected that first business case emerge in the markets described above. However CAES is today not economically viable when only single applications are used to generate revenues. This means that CAES will probably have to act on different market simultaneously in order to justify the necessary investments.

Other conceivable business cases are small scale, site independent CAES in medium voltage grids - potentially interconnected - to serve as VPPs and grid support.

SWOT analysis in European context

Strength: Can be applied in regions close to off-shore wind farms, the specific storage cost related to the stored energy quantity is relatively low, decentralised CAES can be built site independently

Weaknesses: Relatively low round-trip efficiency compared to batteries.

Opportunities: New process variants can lead to significant costs reduction, efficiency increase and new market applications.

Threats: New process are predominantly developed overseas, permitting process for large scale CAES hinder early deployment, need of a clear market model to ensure the revenue along its lifetime.

Need for support/incentives

CAES technology needs R&D support for technical development to improve market maturity. However as long as the feed-in tariffs of their potential customers (on-shore and off-shore wind farms and PV parks) are fixed and not dependant of market prices for electricity and power quality, the incentives for storage technology deployment will remain limited and also the renewable generation asset operators will not be motivated to store electrical energy.

Standards

CAES does not have a need for significant modification of existing or creation of new standards. However it could be specified that the IPPC directive does not apply to adiabatic CAES processes. Permitting processes to leach caverns for CAES could be simplified in order to accelerate CAES planning/building time.

Flywheel Energy Storage

Description and key property range

Kinetic Energy Storage (KES) based on Flywheels is a technology of energy storage considered as fast energy storage, a particular type within the group of technologies, with the main characteristics of high power and energy densities and the possibility to decouple power and energy in the design stage. Moreover a large number of life-cycles, the possibility to be installed in any location (even on board applications are being considered) and high power but usually low energy compared with some other Energy Storage Devices, are other important characteristics. Among the fast energy storage technologies, the most relevant are: Super Capacitors, Flywheels (also called Kinetic Energy Storage Systems-KESS) and Superconducting Magnetic Energy Storage (SMES).

In the first case, the energy is stored in the electrical field of a capacitor, in the second as kinetic energy in a rotating flywheel and finally, in the third one, in the magnetic field of a lossless inductor (superconducting). All forms of storage are dual and can be expressed as half the product of a parameter given by the geometry of the device, times the square of a state variable (see Table 7)

TABLE 7 - Energy equations for three fast Energy Storage Devices

Technology	Geometrical parameter	State Variable	Energy
Supercapacitors	Capacitance (C)	Voltage (V)	$\frac{1}{2}CV^2$
KESS	Moment of inertia (J)	Angular speed (ω)	$\frac{1}{2}J\omega^2$
SMES	Self-inductance (L)	Current (I)	$\frac{1}{2}LI^2$

Any energy storage device can be defined by two basic parameters, the power and the energy. Usually both are independent resembling, somehow, the flow rate and the volume of a water tank: One can image for instance, a big deposit (high energy) with a small drain (low power) or any other combination of these two variables. It is also very common to speak in terms of energy and power densities, normalising with the mass or the volume of the device.

A kinetic energy storage system is composed simply by a flywheel driven by an electrical machine, able to work as a motor or a generator. When the machine (acting as a motor) exerts a positive torque T to a flywheel with moment of inertia J, it increases its speed at a rate T/J, until it reaches maximum velocity, storing a given kinetic energy. At this stage the energy can be maintained constant by just supplying the idle losses with the motor. For releasing the energy, the electrical machine (acting as a generator) applies a negative torque –T to the flywheel, braking at a rate – (T/J) and pumping the energy back to the source to where it is connected.

In order to achieve efficient charging/discharging processes, flywheel losses should be kept to a minimum. Basically, there are two sources of losses: aerodynamic friction between the wheel and the gas surrounding it and mechanical friction in the bearings that support and guide the wheel. The round trip efficiency of flywheel modules is in the 80-85% range, being dependent on bearing and winding losses and cycle time. During the power exchange the efficiency is relatively high, depending on the type of electric machine used. However, the time on standby (no power exchange) affects very much this value depending on the aerodynamic friction. The way of reducing them is by decreasing the pressure and using advance bearing systems with low losses. Ideally the flywheel should work in vacuum, but sometimes a residual pressure is left to help evacuating any heat which is generated inside. Concerning the bearings, most of the flywheels use either magnetic or even superconducting bearings and in many cases magnetic levitation is required.

For a rotating disk, there are some useful and simple mechanical expressions that allow making interesting considerations on its size and speed. On the one hand, the kinetic energy stored in a spinning disk will be proportional to its mass times the square of the tip speed, while centrifugal stresses will be proportional to the material density times the tip speed, hence the specific energy (per unit mass "em" or volume "ev") can be expressed as:

$$e_m = \frac{\xi\sigma}{\rho}$$

$$e_v = \xi\sigma$$

Where σ is the maximum stress level in the disk, ρ its density and ξ a form factor that only depends on the disk shape. For a cylinder its value is 0.6, for a ring 0.3 (even if it is a thick-wall cylinder) and 0.87 for an optimised geometry with the highest possible value for ξ. Obviously mechanical stresses in the flywheel during operation must be below the yield strength of the material.

Previous equations allow making considerations on how an optimum flywheel should be designed. First, it is important to distinguish whether volume or mass restrictions are more important. In general, for stationary applications volume is more a concern than the mass, while for moving applications mass optimisation is mandatory. In any case, to achieve high energy densities, a high value of ξ is required. Ring-shape flywheels should be avoided. Optimum-shape ones provide a high value for ξ but are difficult to fabricate. Cylindrical flywheels are usually the preferable option.

Regarding the material, there are also two choices: for high mass energy density, high strength and light materials should be used, while for high volume energy density, only the high strength of the material is a concern. Following table shows the mechanical properties of some selected materials and their ideal energy storage capability for a disc-shape flywheel.

It can be inferred from the table that the best choice for making an "energetic" and light flywheel is using carbon fibre, while using high strength steel will allow to make "energetic" and small machines but much heavier. Nevertheless carbon fibre is usually wound for making ring-shape flywheels leading to a very anisotropic behaviour, with poor properties in the radial direction. For a fair comparison between materials, this fact should be taken into account. Steel rotors have specific energy up to around 5 Wh/kg, while high speed composite rotors have achieved specific energy up to 100 Wh/kg.

TABLE 8 - Mechanical properties of some selected materials

Material	ρ(MPa)	ρ(Kg/m3)	em(kJ/kg)	ev(kJ/m3)
Steel (AISI 4340)	1800	7800	140	1.092.000
Alloy (AlMnMg)	600	2700	135	364.500
Titanium (TiAl62r5)	1200	4500	162	729.000
Fiberglass (60%)	1600	2000	485	970.000
Carbon fiber (60%)	2400	1500	970	1.455.000

A very interesting point to consider is the required speed to achieve a given energy. Apparently, once the flywheel material is chosen, the equations above state that a certain amount of mass is required regardless the rotational speed: it doesn't matter how slow or fast the wheel turns. The reason is that the material is supposed to work at a certain level of stress and this automatically imposes the speed as a function of the density: Light materials will rotate fast while heavy ones will be slow.

A crucial aspect when designing a flywheel is its dynamical behavior. The flywheel shaft, the bearings and the housing, constitute an elastic structure prone to oscillate in two typical modes: conical and cylindrical, presented in the figure. The problem is that gyroscopic effects must be taken into account leading to the fact that the natural frequencies for those two modes depend on the rotating speed.

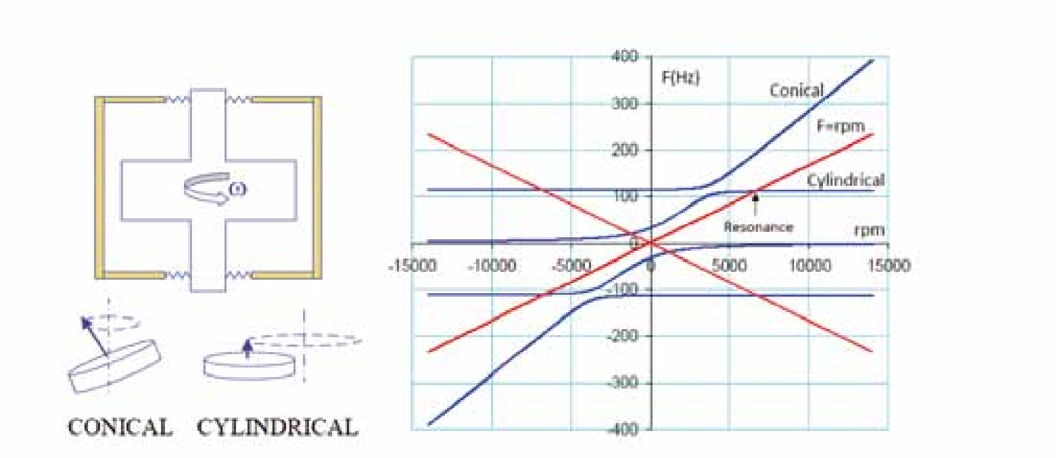


FIGURE 11 - KESS Mechanical Structure and Oscillating Modes

A typical way of representing the solution is using the so called Campbell diagram in which the natural frequency is plotted against the rotating speed. Intersection with the line frequency equal to speed, will give the natural frequencies which should be avoided for both cases.

The interesting fact is that bellow a certain flywheel aspect ratio (Height/Radius) both lines will never intersect for the conical mode, and this is the reason why flywheels are usually flat.

Two electromagnetic systems are the basis for operating flywheels: Electrical machines and in some cases electromagnetic bearings.

There are many types of machines with very good performances in terms of efficiency, robustness or reliability, among others. Nevertheless, not all the electrical machines are good candidates for driving a flywheel. Those of them with wound rotors should be avoided. This includes dc machines, conventional synchronous machines and induction motors (although some successful applications for flywheels have been done with asynchronous machines or with modified synchronous ones). The reason is that when spinning at such speeds, brushes or slip rings should be avoided and even for the case of squirrel-cage induction machines where none of those elements are present, the heat generation in the rotor windings is inadmissible, since heat is difficult to extract.

Presently, there are three families of electrical machines that fulfill the previous conditions for driving flywheels: Homopolar, Reluctance and Permanent Magnet machines.

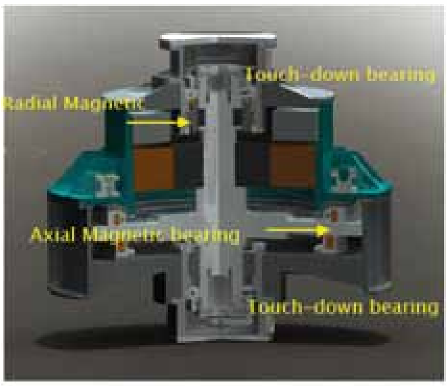
The other aspect where electromagnetism plays a key role in KESS is in the guidance of the flywheel. Either in high mass energy density machines or in high volume energy density ones, conventional bearings are limited. In the first case, because their weight is small, but the speed is very high (> 50,000 rpm). In the second one, speed is admissible (<10,000 rpm) but not the weight. Even if high speed precision bearings can be used, the loads they are subjected are huge and their life is significantly reduced making maintenance very expensive.

In the case of low speed flywheels there is a simple solution: alleviating the weight of the flywheel using magnetic suspension. Usually, a set of permanent magnets is placed in the upper cap of the housing. Since the wheel is generally made from a magnetic material, an attraction force will pull upwards compensating its weight and reducing static loads on the bearings.

A step forward is replacing the conventional bearings with active magnetic bearings. They are based on the use of coils exerting forces on the axis to be guided. Since this type of levitation is intrinsically unstable a feedback is required: a sensor measures the axis position and a power amplifier feeds the coils to keep the axis rotating in its position. Finally, some prototypes of flywheels use HTc superconducting bearings.

They are usually based on the interaction between bulk superconductors and permanent magnets. A superconductor in front of a permanent magnet behaves like a magnetic mirror: it is equivalent to place another magnet in front of the real one, thus exerting a force. This force appears when the superconductor is cooled below critical temperature and is intrinsically stable: The superconductor will react to any change in its relative position to the magnet trying to maintain the initial magnetic flux.

Most of the developments using this technology take profit of the stable levitation force between the magnets (usually placed in the flywheel) and the superconductor (placed in the housing). Nevertheless it is very usual that conventional bearings are still used to enhance radial stability as well as a touch-down system in the event of a failure.



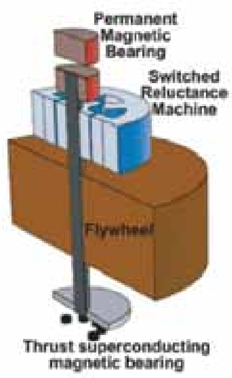


FIGURE 12 - Flywheel based on SRM and magnetic bearings (courtesy of Tekniker)

Power electronics is one of the key issues in this type of energy storage since the flywheel and more properly the electrical machine is driven and connected to the load through a power electronics converter. It is a pulse width modulation (PWM) bi-directional converter that uses insulated-gate bipolar transistor (IGBT) technology with a topology like is presented in the following figure.

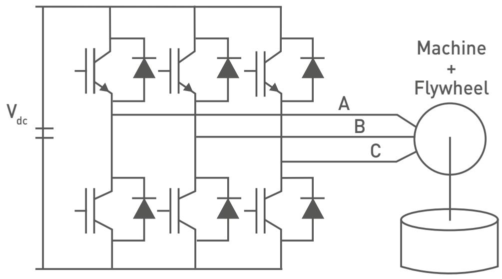
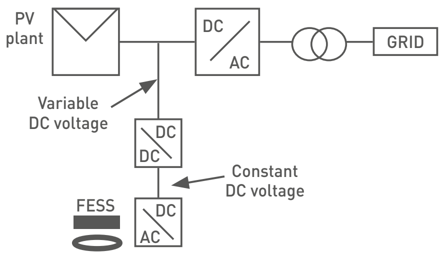
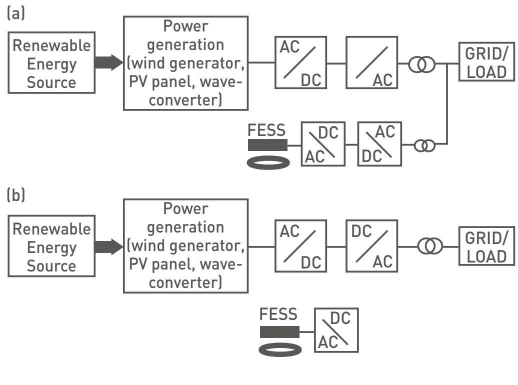


FIGURE 13 - Typical PWM topology for driving the electrical machine of a Flywheel

Most of the renewable applications where a flywheel is suitable to be installed are composed by a back to back converter with a common dc-link. The dc voltage is maintained constant by one of those converters. The connection to it ensures a faster response, a lower cost for the whole system and a better energy management due to the integration with the generation device. Many times the owner of the generation power system does not permit the access to the already installed power converter because it implies several design and operation modifications and responsibilities in the system behavior. That is not only the case of connecting fly wheels but any other type of energy storage device. The next figure presents the two connection possibilities, a) for AC connection and b) for DC connection. The recommendation is to connect the smallest power converters to increase the reliability of the system.



For instance, in wind energy and wave energy converters, the Flywheel Energy Storage System (FESS) can be connected to the dc-link easily. However, in the case of solar PV-plants, if the FESS is connected directly to the inverter at the PV-panels side, the dc voltage depends on the optimum operation point and it will change continuously, so the flywheel-machine might have variable voltage and an extra dc/dc converter could be required, as presented in the following figure.



Considering the previous limitations related to the modifications in the control, it would be better option to connect after the PV inverters, using a grid-side converter (GSC).

One important factor to take into consideration is the voltage level at the connection point. When the connection voltage level is the same as the flywheel-machine voltage (supported by commercial IGBTs) a conventional dc/ac converter should be used. IGBTs technology permits to achieve a dc-link of 4 kV using 6.6 kV IGBTs with currents of 1 kA and a switching frequency of around 500Hz. Only in the case of necessity of improvement of current quality or even higher voltages, a multilevel converter results a better option. However, machines for flywheels with voltages higher than 1 kV are not common.

In case of dc connection, a dc/dc converter should be used. When power level and the voltage ratio are low a boost-buck topology results appropriate; for other options it is better to select a topology with intermediate ac link using a medium frequency transformer.

In case of ac connection, the voltage adaptation is usually carried out with a power transformer. This solution might appear more expensive -since an extra converter is required- but the FESS adds value to the system through its grid-side converter (GSC), which permits controlling the reactive power supplied to the grid. Currently, many of the inverters used in renewable energies do not provide the possibility to adjust power factor or protection against voltage sags.

Large power machines have not been developed for flywheel application but usually the applications, like frequency regulation, require an important amount of power and energy. Usually there will be a matrix of FESS to accomplish the power regulation problem with higher level of power and energy, as presented in the next figure. Using just one GSC, all the units of this matrix can be connected to the same converter using single power transformer and electric grid protections for the whole system. Modularity is an important issue because it reduces the total cost of the elements (especially the flywheels), increasing the reliability of the system. Moreover, it results convenient to package the FESS together with the power electronics in a similar way of a dc battery to increase the integration and robustness of the FESS.

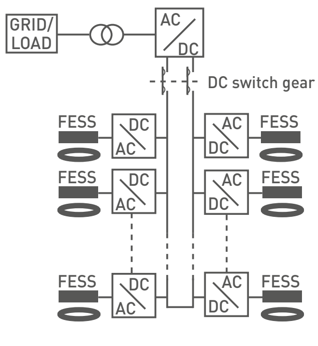


FIGURE 14 - Matrix connection of FESS

Operation of a flywheel system depends on the application that it is used for. The usual regulation scheme is based on a dead-band control scheme. The flywheel charges when the variable exceeds the top of the dead-band and discharges when the variable drops to the lower limit. The width of the dead-band is adjusted depending on the application and the response time of the frequency at the electric grid.

For instance, the control scheme for reducing the grid frequency variation by using FESS is presented in next figure. The electric grid frequency (F) is measured with an appropriate method. A PD controller determines a primary output active power reference ($P_{0,ref}$); When the frequency decreases, the FESS supplies power to the grid. When the frequency increases, the FESS absorbs power. This power value is modified by a term named Δ_{Pw} that depends on how far is the flywheel speed from the speed related with the half of the maximum stored energy, denoted by $\omega_{0.5E,FESS}$. The value of $P_{0,ref}$ is modified to a lower value when the rotor speed is under $\omega_{0.5E,FESS}$ or to a higher value when the speed is over $\omega_{0.5E,FESS}$. That way, the flywheel increases the charging power level when is more discharged and the discharging power level when is more charged. The new reference is P'_{ref} would have some limitations due to boundary speeds, ω_{max} and ω_{min}, as included in the figure.

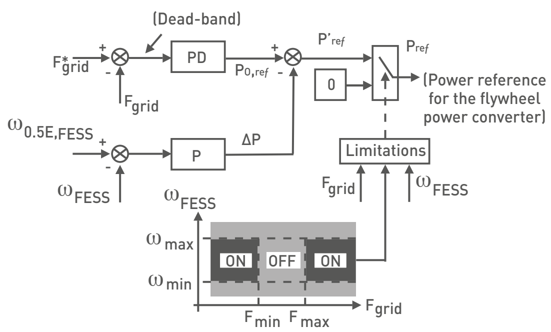


FIGURE 15 - Regulation scheme for frequency stabilisation

Critical gaps between needs and present performance

Although there are some commercial products available in the market, some needs are still being demanded by the users. In general terms, an increasing of the power and energy densities is required in order to lead the alternative technologies, and the reduction of the high investment cost. These needs comprise a higher speed machines and flywheels that implies better materials for the flywheel, high performance electrical machines, low losses electromagnetics and power electronics and very fast and robust control platforms.

Where are the most urgent needs for energy storage in 10-20 years?

Most urgent needs for the energy storage applications where flywheel technology is suitable to be used are:

- Fast and robust energy storage with very low maintenance requirements.
- Energy storage devices where the available volume is very reduce and therefore a very high power and energy density are required.
- Energy storage with the possibility to locate in any place or with no especial specifications.
- Uninterrupted Power Supply with the security of the level of energy available, more direct in flywheels than in batteries, since it is dependent of the speed, easy to measure.
- Very fast response energy storage systems to solve the stability problems in the electric grids, especially the weak ones.
- Very high efficient energy storage devices to improve the total energy efficiency of industrial facilities.
- Integration in transportation to reduce the CO_2 emissions and to improve the efficiency.

Where are the decisive challenges for meeting the needs in 10-20 years?

Challenges to increase the use of energy storage in the areas of transportation, energy generation and industrial environments are to work hard in R&D to increase the reliability and efficiency of the existing systems, reducing the investment costs at the same time.

Demonstration plants are one of the key issues that will probe to the industry the convenience or not of flywheel technology for certain applications. So as, research centres together with companies have to work together in the integration of flywheels in facilities where fast energy storage is required to test its reliability. That would achieve further cost reduction.

Technical development perspectives

The technology gaps in detail have been separated in relation with the different parts of a flywheel device:

- Flywheel disc, especially fibre flywheels. It is desired to get higher energy density flywheels at a lower cost by improving the fabrication procedure. Metallic flywheels can also be used in some applications, where the power and energy densities and the performance required are different. The mechanical dependence has been considered as a drawback compared to batteries or ultracapacitors (as examples of fast energy storage) but it is becoming more and more released of maintenance in the case of flywheels and in fact they are more robust in terms of number of charge-discharge cycles.
- Electrical machines, which drive the flywheels. The machine is related to the system power as well as the flywheel is responsible of the energy. The machine is also related to how fast the flywheel is able to exchange the energy with the load or the grid. In any case there is a need for developing very high speed electrical machines that are robust and efficient at those velocities.
- Bearings. Since the system is usually rotating to a very high speed (in many cases > 50,000 rpm) at the same time than supporting a high axial force, conventional bearings are not always suitable to be used. Magnetic bearing is a quiet extended technology for high speed systems but a lot of research is still required to ensure the robustness in flywheels and also to guarantee a good dynamic behaviour, avoiding dangerous resonances. Since magnetic bearing consume energy, its efficiency is also a key issue to improve the overall performance of the kinetic energy storage.
- Power electronics. The speed range of the flywheel is quiet large and the machine has to be able to supply or to absorb a certain amount of power. A power electronic converter is in charge of managing the power behaviour of the system, both towards the machine and the electric grid. Moreover, it is possible to get additional advantages of the use of a power converter since it can be used as STATCOM or any other type of grid support, with a minimum increase of the complexity and cost. As the case of the Electrical Machine, there is a challenge in developing efficient power converters for very high speed drives.
- Digital control and communications. Digital control provides a powerful platform to achieve a high performance in fast energy storage systems together with power electronics, being able to implement complex control strategies and permitting a high performance drive. High operational speeds require ultrafast control strategies that need to be developed.
- Security case or frame. The safety conditions of the flywheel have to be deeply studied and the design of the external case is one of the important issues to work on.

Economic development perspectives

High performance Flywheels is currently a expensive technology in terms of cost per kW or kWh from the point of view of fabrication and commercialisation. One of the big challenges of the flywheel technology is to reduce the total cost and still maintaining the high performance characteristics. It is required an economic study of every stage in the development and the technology used to ensure that the final product is completely competitive in the industrial market. There is no economical target information collected yet. That will be included in the drafts published in the following months. However, the key issue to be a competitive technology with respect to the others is to fit more properly a certain application increasing the performance at a similar cost than conventional technologies.

Compared with some other devices, the cost per kWh is very high but the main characteristic to consider is the cost per kW. Economic targets are to reduce the cost compared with the competitor technologies such as batteries, ultracapacitors and SMES, to have, in the medium to long term (2020), a specific investment cost below 650 €/kW.

Need for research

Scientific and technological challenges to be covered comprise:

- Flywheel disc. Study of better materials for fibre flywheels (high density) might be carried out in order to reduce the total cost. Also optimisation of geometries are required to reduce stresses to the minimum possible level, especially in those directions in which composite materials are very sensitive due to their strong anisotropy.
- Electrical machines. High performance/High speed machines are required to be used in these devices and although permanent magnet machines seemed to be the best option, the high cost of the magnets has redirected the research to search new machine concepts with less magnets.
- Bearings. Faster control systems are being developed to improve the bearings response and more efficient actuators are used to increase the performance of the complete system. There are also interesting and promising approaches like the use of superconducting magnets that can highly improve the efficiency of the bearings.
- Power electronics. Increase the added value of the power electronics in an energy storage system, ensuring the robustness and reliability, specially working at such speeds which imply working at very high commutation frequencies.
- Digital control and communications. Communication improvements permit to control the system with guaranties of robustness, being able to analyse a lot of variables, maintaining a complete analysis of the application from anywhere, being easily integrated with some other subsystems. Fast control strategies and technologies are mandatory for driving such high- speed systems
- Security case or frame. A better knowledge and a wider experience in prototypes would reduce the cost in security.
- Increasing the energy density of storage materials
- Reduction of the losses in the magnetic material of the electrical machine as well as the switching losses at the power electronics.
- To identify the possibility of hybridising with some other energy storage technologies which provide higher energy, such as batteries or hydro pumping storage.

General R&D Needs

- Study of the round trip efficiency related to the application in order to study the exact number of cycling, charge-discharge frequency and power and energy levels required in each application.
- Development in materials to achieve high speed performance
- Development of power electronic semiconductors in order to reduce the switching losses to achieve high speed.
- Simulation models to integrate easily the model of the energy storage device in different scenarios, to find suitable applications and operation modes.
- Thermal studies to ensure the continuous operation of the system under safe conditions.
- Economical study to get an appropriate target price in the industrial market.

Needs regarding "balance of plant"

The BOP for a kinetic energy storage system comprises a low pressure system in order to ensure the low aerodynamic losses, a control system to coordinate the operation and a testing system to measure the state variables for the safety. Moreover, a communication platform for operation and monitoring of the system is also required.

European strongholds

Flywheel is a mature technology completely introduced in the industrial market. More than 20 manufacturers have been identified all over the world and many other research centres are focused on this technology as well. However, many technological aspects have been identified to be improved. Although most of them are established in America, there are some important manufacturers in Europe:

- Active Power (Germany) GmbH. An der Leege 22, 37520 Osterode am Harz. Germany.
- Active Power Solutions Ltd UK. Unit 7, Lauriston Business Park, Pitchill. Evesham | Worcestershire | WR118SN | United Kingdom
- Piller Power Systems. Osterode, Germany
- Centre for Concepts in Mechatronics (CCM), Nuenen, Brabant, Holland.
- Flybrid Systems LLP. Silverstone Technology Park. Silverstone, Northamptonshire NN12 8GX United Kingdom
- Magnet-Motor GmbH. Petersbrunner Straße 2, D-82319 Starnberg, GERMANY
- Ricardo Media Office. MediaTechnical Ltd. 4 Hampden Rd, Brighton, BN2 9TN , UK
- Williams Hybrid Power. Grove, Oxfordshire, OX12 0DQ, UK
- Zigor Corporation S.A. Portal de Gamarra Nº 28, 01013 Vitoria-Gasteiz (Spain)
- Tekniker. Calle Iñaki Goenaga, 5· 20600 Eibar · Gipuzkoa.· Spain
- Ciemat. Av. Complutense, 40. 28040 Madrid. Spain.

Hazards and Risks

There are some requirements using flywheels related with the safety:

- Since a high speed spinning part is always present, the system must provide a case to prevent crash in case of the worse fail
- No toxicity and non-corrosive materials
- Thermal sensors must be provided to check the moving parts
- Vibration detectors are required in order to detect possible failures in bearings.

- Electric protections in the electric part of the system related with the grid connection.
- Acoustic noise reduction is sometimes required, depending on the technology used.

Social acceptance

Flywheels are already in the industrial market and it is a product already accepted by the consumer. In fact, sometimes is preferred instead of alternative products, as the UPS, since they provide more reliability in critical loads support.

Nevertheless there are still some concerns coming from the point of being a mechanical system with mechanical problems with expensive solution in case of failure, or the high cost produced by the maintenance requirements. The technology development can solve these concerns achieving a very robust system

Depending on the technology used in the flywheel, sometimes the system can achieve high levels of acoustic noise and cannot be installed in residential areas or occupied by people.

Market in focus – application areas and types

Some specific applications have been also identified as suitable for flywheels utilisation in different areas:

- Transportation, to reduce CO_2 emissions and to increase the efficiency.
  - Electric and hybrid large automobiles (electric buses)
  - Light trains and underground transportation
  - Ferries
- Renewable energy generation, to ensure the grid stability, frequency regulation and voltage support.
  - Wind energy
  - Solar photovoltaic energy
  - Wave energy generation
  - Smartgrids
- Industry applications, to ensure power supply or increase the efficiency
  - UPS
  - Cranes and elevators

A deep study of the potential applications could be able to reveal some interesting uses, increasing the industrial market for the companies.

Moreover, recent research studies have demonstrated that the use of flywheels not substituting but completing the operation of conventional technologies, such as batteries, can increase their life-cycle.

Hydro Energy Storage

Description and key property range

Reservoir hydro and pumped storage hydro is amongst the most efficient and flexible large-scale means of storing energy available today. This proven technology is helping utilities to efficiently balance the grid and to develop their renewable energy portfolios. Up to 80% of the energy consumed during the overall cycle is recovered, which can be sold when demand peaks.

Flexible reservoir hydro and pumped hydro storage are therefore set to play a key role in enabling countries to meet their ambitious targets to cut greenhouse gas emissions and to build additional clean, renewable energy capacity.

The usual way of taking economical advantage of hydro storage is as follows:

Reservoir hydro plants are able to reduce or stop production and store water when prices are low, and use this water for production when prices are higher.

Pumped hydro storage plants use pumps or pump-turbines to pump water into an upper reservoir and store it when prices are low due to low demand or surplus of energy production in the system. When prices are high due to high demand or lack of energy production in the system, the water is released through turbines to a lower reservoir and the electricity is sold at high prices.

Lately this price spread has been fairly reduced and it does not incentivise the deployment of new hydro storage/ pumped hydro storage plants

Further revenue could also be derived from the ancillary markets, in which the regulation services provided by pumped hydro energy storage plants should be better remunerated.

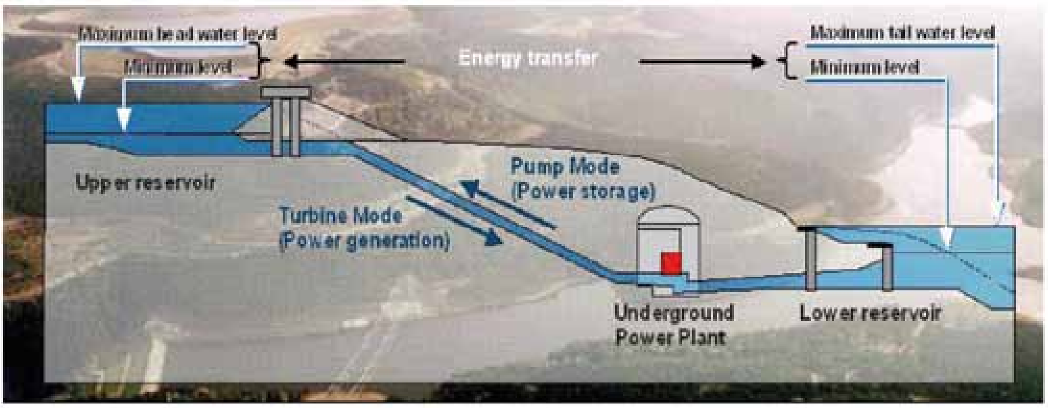


FIGURE 16 - Pumped storage power plant schematic

This technology can ramp up to full production capacity within minutes providing a quick response for peak-load energy supply and making it a useful tool to balance the grid during unplanned outages of other power plants.

There is about 1 000 GW of hydropower installed worldwide with an average annual production of about 3 500 TWh, where 480 TWh are produced in Europe from an installed capacity of 160 GW. The total energy storage in European reservoirs is about 170 TWh, where 85 TWh is located in Norway. IEA Technology Roadmap foresees a doubling of the global hydropower capacity up to almost 2 000 GW with an electricity generation of over 7 000 TWh by 2050. There is over 140 GW of pumped storage in operation worldwide. In response to the grid flexibility needs in Europe, North America and Asia, the pumped storage market is expected to grow 60% over the next four years, with an average of 6 GW of added pumped storage capacity to be ordered each year. We expect 50% of the market to come from China. In Europe, which accounts for approximately 25% of the market, opportunities are mostly focused around the alpine regions (Switzerland, Austria, Germany), Spain and Portugal. In the USA, where 45 plants currently in operation totalise 20,720 MW capacity, an additional 43 plants corresponding to 36,600 MW are currently in the licensing process.

Even though more than 50 per cent of the technical potential for hydropower in Europe is still not developed (IEA Hydropower Technology Roadmap 2012), the main R&D challenges are related to technical and other issues similar to or included in R&D challenges for pumped storage hydro. Therefore, the rest of this chapter is concentrated around pumped storage hydro.

Variable speed technology, latest innovation to further increase flexibility

Variable Speed is the latest major innovation in hydroelectricity. These machines have the capability to regulate their power both in pumping and production mode thanks to their capability to adapt their rotational speed whilst conventional machines can only regulate their power in production mode.

This means the variable speed plant owner can adjust the level of power needed when pumping excess energy, which in turn means that conventional thermal power plants that are operated for frequency adjustment can be stopped. This helps utilities operate their fleets more economically while reducing CO_2 emissions. Finally, the technology also allows utilities to earn revenues from balancing the network's frequency (ancillary services).

The variable speed element of the turbines and generators enables utilities to match supply to demand to the second, pumping when demand marginally drops, and releasing when demand marginally rises. This helps them reach maximum efficiency of their fuel portfolios and maximise revenues. It also means load balancing can be achieved using a clean, renewable energy source.

This increased flexibility is particularly useful when PSP are used to balance the variable production from renewables. This production has to be balanced at all times of the day, which includes the night hours used by PSP to pump up the water in the upper reservoir. Variable speed machines can achieve this operation and provide balancing service in the same time.

PHS fact sheet

TABLE 9 - PHS fact sheet

General Performances	50 to 500 MW *200 to 350 MW*	Output/Input *Most Typical values*
	>> 8 hours full load	Storage capacity
	10 to 2000 m. *~100 to ~ 600m*	Head Range *Single stage reversible Francis*
	> 80%	Cycle efficiency
Reaction Time	~15 s	50% to 100% Generation
	~ 2 min.	0% to 100% Generation
	~ 5 min.	0% to 100% Pumping
	~ 10 min.	100% Generation to 100% Pumping
Ancillary Services	40% to 100%	Production adjustment range
	70% to 100%	Pumping power adjustment range (Variable speed machines only)
	Reactive power	
	Black start capability	

Critical gaps between needs and present performance

Pumped Hydro provides highly flexible bulk storage. The key areas for improvement today are:

- Expand possibilities for installation of PHS:
  - Develop sea water PHS
  - Study development of underground reservoirs suitable for PHS in connection with surface reservoirs
  - Develop new concepts for PHS e.g. by moving solid mass like soil
  - Minimisation of environmental impacts e.g. by utilising existing reservoirs
  - Detailed studies of the Energy Island concept (a reservoir in the sea to build a low head PSP) with particular emphasis on economy and underground potentials in Europe. The dikes of the island can be used to install off shore wind mills. This will also necessitates specific very low head equipment developments
  - Establish smaller demonstration projects for new PSP concept (see e.g. Gravity Power and Energy Membrane (DK))
  - Expand possibilities to equip more complex sites: going to very high head with the development of multiple stage solutions and very low head with other types of turbines
- Increase flexibility of PHS by
  - Developing variable speed motor generator to allow regulation in pumping mode. Pilot projects are launched but the technology is very young and needs improvement to reduce cost and reduce technical limitations (speed/power,...)
  - Exploitation of the synergy between PHS technology and HVDC technology to develop large variable speed solution with power electronics on the stator
  - Increase the turbine flexibility. Present turbines are able to operate stably between

50/70% and 100% max power. Below this limit high vibration coming from hydraulic "turbulences" occur and they limit turbine lifetime. One needs to improve the turbine hydraulic design, and better understand the fluid-structure interactions. This requires developing simulation models and experimental analyses in order to study phenomena that are not mastered yet
› Increase the stability in the transition between the modes of reversible machine: present reversible pump-turbines present an instability operating zone in the transition between the two modes (s-curve). This requires developing simulation models and experimental analyses in order to study phenomena developing in this transition zone that are not mastered yet.
› Increase the pump stability at part loads: present reversible pump-turbines present instability at part loads. This requires developing simulation models and experimental analyses in order to study phenomena that are not mastered yet.
› Shortening start-up and transition times.

Technical development perspectives

Innovative pilots projects for new plant concepts allowing to reduce the geographic limitation of PHP development can be launched (island PSP, "moving mass" solution, underground reservoir PSP) so that the techno-economic feasibility is proven.

In term of turbine flexibility, the goal is to develop and validate simulation methods to be able to fully characterise all phenomena appearing at partial load so that the partial load impact on equipment lifetime can be fully understood.

The next decade will also see numerous variable speed plant developments, exploring the possibilities of both doubly fed and fully fed solutions.

Economic development perspectives

The market for new PHS is on average 6 GW/year in the world with 25% of the market in Europe. Today we see on average a 10%/year growth. Being conservative we can expect the European market will stabilise above 3GW/year in 2030. Taking an average value of 1000€/kW, this corresponds to a market of €3B/year on average. This is in relatively good agreement with a market analysis by Ecoprog (2011), which mentions that about 27 GW new PHS capacity will be installed throughout Europe in a ten years perspective.

Need for research

There is a strong need for applied science research on turbine to maximise their flexibility. It is not yet possible to simulate numerically all relevant phenomena occurring in turbines operating partial load and their impact on the equipment. The simulation capability increases with the progress of computing power but the industry needs also to have new simulation models in order to progress.

As it is necessary to increase the technology dissemination, studies on environmental impacts and public acceptation are key to the success of the technology.

Variable speed technology is constraint by the price and the losses of the power electronics. Progress is needed on them. New materials for motor generator would also be needed to reduce the technical limitation of the technology (going higher speed and higher power).

As pumped storage hydropower has relatively large capital costs (and very low operational costs), the development of business models that include pumped storage hydropower, grid connections and market models are probably crucial for future development of pumped storage hydropower. Today's market for balancing the production and demand for energy is concentrated only on short time scales like within-hour, intra-day or at most looking one day ahead. To fully utilise the potential for pumped storage hydropower, it is also important to develop business models and markets for longer time-horizons, as many pumped storage hydropower plants will be able to participate in multiple markets. A regulatory framework to handle multiple time-horizons and multiple markets may be needed.

Other issues of high importance in research and development are connected to environmental impacts of pumped storage hydropower and necessary grid connections, as well as societal acceptance. The siting of new pumped storage hydropower is then challenging, and we may see more use of seawater in pumped storage hydropower and underground storage in special cases.

General R&D needs

TABLE 10 - General R&D needs Hydro Energy Storage

	Total costs for a project	Total external funding needed for a project	Number of projects for the H.E. industry
Object of collaborative project			
Virtual test rig for enhanced and faster pump turbine understanding and development	3-5 M€	2-3 M€	3
New generation of more robust electromechanical equipment for ultra-flexible operation	5-10 M€	3-7 M€	4
Condition monitoring systems to allow wider operation while minimising wear and tear	2-5 M€	1-3 M€	4
Development of power converters suitable for large scale variable speed PHP: cost minimisation and efficiency improvement	5-10 M€	3-5 M€	3
Very low head pump turbines developments	5-10M€	2-5M€	4
Very high head pump turbines developments	5-10M€	2-5M€	4
Systematic investigation of unconventional sites	2-5 M€	1-3 M€	3
Development for new concept plants including equipment customisation and specific need related to the new concept technology	5-10M€	2-5M€	6
New turbines and generator technologies for upgrading existing conventional hydro into pumped hydro	5-10M€	2-5M€	3

Needs regarding "balance of plant"

Power electronics are key for the development of the variable speed technology.

To really benefit from all benefits of new technologies, the dispatching tools and TSO SCADA system needs to better integrate PHS features

European strongholds

European players are the leaders of PHS equipment industry. They have a market share above 50% and are the only players being present worldwide.

There is also a strong lead of European Civil Work Engineering Company able to design and coordinate the erection of a full plant.

Finally European utilities have the capability to globally develop their know-how on how to operate such plant and expand internationally.

This leadership will be soon challenged by Chinese players whose development is strongly supported by pro-active national policy and by a strong internal market. The European industry must keep its technological leadership to stay ahead of the competition.

Demo and pilot testing

The following Table 11 shows the estimated R&D needs for the period towards 2030:

TABLE 11 - estimated R&D needs Hydro Energy Storage towards 2030

Object of Collaborative Project	Total costs for a project	Total external funding needed for a project	Number of projects for the H.E. industry
Virtual test rig for enhanced and faster pump turbine understanding and development	3-5 M€	2-3 M€	3
New generation of more robust electromechanical equipment for ultra-flexible operation	5-10 M€	3-7 M€	4
Condition monitoring systems to allow wider operation while minimising wear and tear	2-5 M€	1-3 M€	4
Development of power converters suitable for large scale variable speed PHP: cost minimisation and efficiency improvement	5-10 M€	3-5 M€	3
Very low head pump turbines developments	5-10M€	2-5M€	4
Very high head pump turbines developments	5-10M€	2-5M€	4
Systematic investigation of unconventional sites	2-5 M€	1-3 M€	3
Development for new concept plants including equipment customisation and specific need related to the new concept technology	5-10M€	2-5M€	6
New turbines and generator technologies for upgrading existing conventional hydro into pumped hydro	5-10M€	2-5M€	3
Standardised pump/turbine design criteria		10 M€	2
Optimised control system		10 M€	2
New hydraulic cost-competitive pump/turbines		10 M€	2
Innovative solutions for reservoirs small scale and alternative small scale PHP		10 M€	2
Innovative compact solutions for small scale PHP		10 M€	2
New concept for turbine/generator set		10 M€	2
Environmental impacts in reservoirs used for flexible hydro operations and PHP		20 M€	10
Regulatory framework and business models PHP at multiple time scales		10 M€	5

Technologies				
Field	Subject	Innovation	Budget	No. of projects
Flexibility	Large power range Pump turbines		15 M€	3
	Cycles resistant units		15 M€	3
	Fast response units	Transition time minimisation	10 M€	2
		Ramp rate maximisation		
	Improved ICT technology: Information, intelligent and interactive	IEC 61850	10 M€	3
		CIM		
		Condition monitoring		
	New Regulation Adaptation	Water machinery directive	10 M€	1
		Grid code evolution compatibility		
	Ancillary services provision		10 M€	3
Cost-competitive small-scale PHP applications	Standardised pump/turbine design criteria		10 M€	2
	Optimised control system		10 M€	2
	New hydraulic cost-competitive pump/turbines		10 M€	2
	Innovative solutions for reservoirs		10 M€	2
	Innovative compact solutions		10 M€	2
	New concept for turbine/generator set		10 M€	2
Upgrade conventional Hydro into PSP	develop hydraulic solution + pilot project		50 M€	1
CO_2 emission minimisation for PSP equipment manufacturing			10M€	3
Environmental impacts in reservoirs used for flexible hydro operations and PHP			20 M€	10
Regulatory framework and business models PHP at multiple time scales			10 M€	5

For Demo and Pilot test projects it is estimated that each topic will require budgets in the range up to several hundred M€ with a need for funding of about one third.

Social and environmental issues

Regarding environmental impacts there are two fundamental differences in the magnitude of the environmental effects of pumped storage hydropower projects, depending on the project type:

- Creation of new dams and reservoirs for pumped storage hydropower
- Pumped storage hydropower plant construction using existing reservoirs

For both types, there are environmental impacts related to the construction of power houses (generally underground), water tunnels, access roads and power grid connection, as well as environmental impacts related to the operation of reservoirs and downstream rivers, lakes or estuaries. Even if PHP reservoirs are sized for only several hours storage and are therefore generally notably smaller than conventional hydropower reservoirs, creation of new dams and reservoirs might imply serious interference with nature in form of flooding terrestrial area, land use change, modification of natural stream flow regimes, and disruption of the river continuum and change of terrestrial and aquatic ecosystems. Flooding of land may also involve loss or change of biodiversity, and the net greenhouse gas and carbon budget may be changed when a reservoir is created. However, in most cases reservoirs in temperate and cold parts of Europe will not lead to drastic increase or decrease in greenhouse gas emissions or biodiversity.

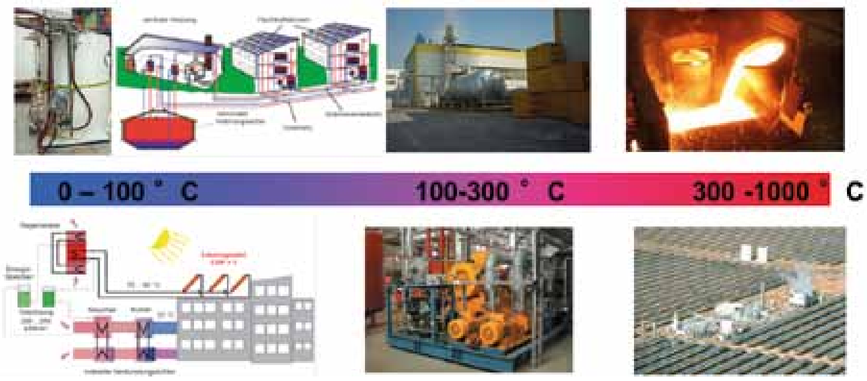
Modified stream flow regimes downstream of dams affect aquatic ecosystems by hydromorphological changes, alteration in water temperature patterns, habitat change, disruption of the lateral connectivity and changes in water quality. These impacts are the same as those occurring during the construction of reservoirs for hydropower or for other purposes. Through environmental impact assessments, extensive licensing processes, the application of the Water Framework Directive and other types of legislations, Europe has a long and strong history of maintaining functioning aquatic ecosystems and mitigating negative effects of reservoir creation and hydro operations. There is also a strong need to ensure public engagement and involvement early in new projects to find well-balanced solutions between energy and the environment.

ANNEX IV: THERMAL ENERGY STORAGE

Heat Storage Technology

Description and key property range

Thermal energy storage (TES) is a key element for effective and efficient generation and utilisation of heat where heat supply and heat demand do not match in time, space, temperature and power. This covers effective thermal management in the sectors heating and cooling, process heat and power generation as well as an increased utilisation of renewable energy systems (RES). A specific feature of thermal storage systems lies in their diversity with respect to applications that require different temperatures, energy/power levels and use of different heat transfer fluids. Each of these applications has its own specific operation parameters. Thus, availability of a broad portfolio of storage designs, media and methods is essential.



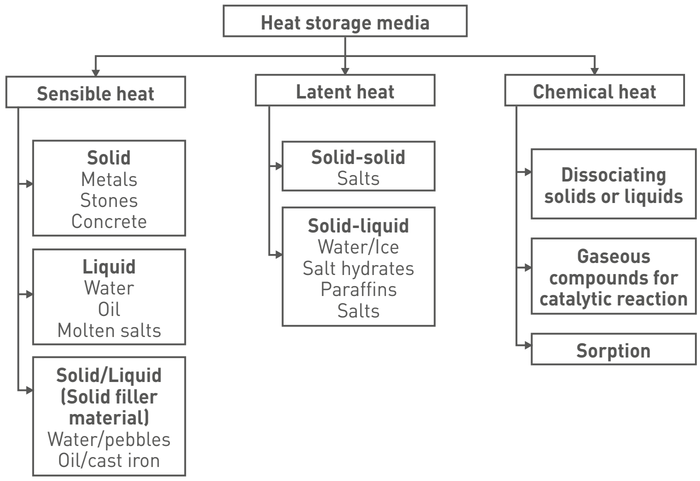
Regarding the physical principles TES can be classified into sensible, latent (also called as phase change material storage – PCM storage) and thermo-chemical heat storage.

Each storage concept has its best suited materials and these may occur in different physical phases: as solids, liquids, or via phase change. For example, the volumetric and gravimetric energy densities of the materials have a decisive impact on the capacity of the storage system.

The thermal conductivity of the materials is important for the charge and discharge power of the storage system. Furthermore, small density changes versus temperature minimise thermo-mechanical stress phenomena. A decisive criterion of a heat storage medium is its price and the costs that arise upon its utilisation. Long life and a high cycling stability are prerequisites for economic application, i.e., at a price competitive with existing storage facilities.

The charge and discharge powers of sensible and latent heat storage systems are determined mainly by heat transfer processes. For thermochemical storage, mass and heat transfer processes are the dominating physical effects.

The heat of the carrier fluid may be either transferred directly to the storage material as, for example, in a dry pebble bed with air flow, or a heat exchanger may be required as in a solar domestic hot water store where the water – antifreeze mixture flowing through a solar collector has to be separated from the hot water for consumption (indirect concept). For solar thermal electricity, a heat exchanger is also needed to transfer the heat from the carrier fluid circuit to the storage system, if this fluid is not the same. Other aspects of selecting a heat storage material may be operational advantages in energy supply systems or a larger flexibility in application. A survey of heat storage media is given in the following figure.



One possibility to store heat physically is the use of sensible heat, which results in an increase or decrease of the storage material temperature, stored energy is proportional to the temperature difference of the used materials. Today, liquids (mostly water), molten salts and solids may be used as heat storage media. The most common heat storage system is based on a sensible heat storage tank or (for Concentrated Solar Power) a configuration based on a two-tank storage system (sensible heat). These storage tanks can be classified in those for short-term and those for long-term applications. By use of underground thermal energy storage (UTES) systems, excess heat is stored in the ground during summer to be extracted during winter.

The use of energy storage media with sensible heat is limited. Parts of the input thermal energy end up as unavoidable heat losses. In order to minimise these losses, it is necessary to keep the ratio of the surface area to the volume of a heat storage tank as low as possible. This ratio decreases when the volume of a given geometry increases. In other words, the heat storage tank should be as large as possible.

Seasonal thermal energy storage is the umbrella term for storing heat or cold for periods of up to several months. This technology includes UTES systems where heat is stored e.g. in aquifers, the earth, boreholes and caverns. One typical application is a combination of a ground-source heat pump with aquifers for heating in winter and cooling in summer. Thermochemical storage systems which will be described below may also be used as seasonal thermal energy storage systems.

Long-term energy storage tanks or UTES systems in combination with solar collectors accumulate heat during the summer which is used in the winter time for space heating and for sanitary hot water generation. This technology is currently under thorough testing.

Liquids as heat storage material, such as water, organic liquids, molten salts and liquid metals have a wide range of properties:

- Temperature range -20 to 1800 °C
- Density 700 to 1800 kg/m^3
- Heat Capacity 1.3 to 4.2 kJ / (kg K)
- Thermal Conductivity 0.1 to 70 W / (m K).

Solid materials can be utilised in a wide temperature range and heated up to very high temperature (e.g. refractory bricks in Cowper regenerators to 1000 ºC). The density is between 1000 kg/m^3 and 2500 kg/m^3 (soil, bricks). The size of buffer tanks filled with water starts with about 100 litters for small applications. For large applications, there is no upper limit. Even a size of the buffer tank about 50.000 litters and more for very large applications is feasible.

Natural materials in the form of rocks and pebbles are abundant and cheap. For low temperatures, rock and soil can be used as ground storage. For high temperatures, the thermo-mechanical stability of the solids is important. Here, rocks such as granite, basalt and quartzite, as well as pebbles can have suitable properties.

Of the manufactured solid materials, various ceramics are widely used as heat storage materials. In the low temperature range, bricks act as a buffer for the acclimatisation of buildings. At higher temperatures, refractory bricks based on oxides (silica, alumina, magnesia and iron oxide - feolite), carbonates (e.g. magnesite) and their mixtures are commercially utilised in applications such as Cowper regenerators, night-storage heaters and tiled stoves.

Due to the potential to store thermal energy within a solar thermal power plant, heat storage is currently one of the hot topics to increase the share of solar thermal electricity generation in the future. The two-tank molten salt concept is proven and reliable. However, due to salt stability, the maximum operating temperature is limited to around 500°C. Therefore, new materials and concepts need to be developed to provide efficient and economic storage system when working at 600°C or beyond.

For solar thermal electricity, power plants currently in operation can store the heat for a typical 7.5 hour-period, thus feeding firm electricity to the grid during night time. A two-tank molten salt storage system coupled through a heat exchanger with a heat transfer fluid circuit is commonly used. The temperature reached in the state-of-art configuration is typically around 550 °C and the size of storage tank amounts 28 m3/MWhth for a regular 50 MW power plant in Spain. Thanks to R&D efforts to come great improvement in efficiency are expected in the near future.

A second possibility to store heat physically is the use of latent heat, which is connected with a phase transformation of the storage materials (phase change materials - PCM), typically changing their physical phase from solid to liquid and vice versa. The phase change is always coupled with the absorption or release of heat and occurs at a constant temperature. Thus, the heat added or released cannot be sensed and appears to be latent. Stored energy is equivalent to the heat (enthalpy) for melting and freezing. PCM can be classified into inorganic, organic, single phase materials or eutectics. Specific technological/physical properties are improved with composite PCM or encapsulated PCM.

The application range of PCMs is between 10 °C and 800 °C. The latent heat of PCM is between 100 and 500 kJ/kg. The density of PCM is in the area of 750 up to 2000 kg/m3 but is different between the solid and liquid phase. Latent heat storage materials should be inexpensive and be characterised by:

- a large phase-change enthalpy and a high density
- a large thermal diffusivity in the solid and liquid phase
- thermal stability and cycle stability with a low vapour pressure
- little or no sub-cooling during freezing and little or no super-saturation during melting
- a low thermal expansion, i.e., low volume change during melting

For refrigeration below 0°C, ice slurries using a solution of water-salt (brine) and water-glycol can be utilised. Applications are industrial processes and space cooling. Within the solution fine solid crystals are suspended. A major advantage of the slurries is that they can be pumped. Hence, they can act as both the heat carrier and the heat storage medium. The slurry has the advantage of a larger heat capacity compared to the solution.

There are several commercial PCM products without a heat carrier fluid (passive systems). In these applications the PCM increases the heat capacity of the system and the PCM stabilises the temperature of the system. Commercial PCM products are available in the areas of insulated transport containers (e.g. medical applications), the thermal management of electronic equipment, electric heating systems (e.g. floor heating) and human body comfort (e.g. pocket heater, clothes). Another area of commercial products is the space cooling of buildings. In particular in lightweight buildings with a low thermal mass, the PCM can reduce temperature fluctuation and cut peak temperatures. There are different ways to insert the PCM in the building. They include the additional use of boards and panels, such as gypsum plasterboard with microencapsulated paraffin and aluminium bags filled with salt hydrates. A second option is the integration of the PCM into the building material, such as plaster and concrete containing microencapsulated PCM. . A third option is the integration of PCM into the climatisation system of a building (in pipes and ducts, in the compression system, etc.)

For the heating and cooling of buildings, PCM systems with a heat carrier fluid, commonly water and air, have been researched. The advantage of these active systems is that they have a higher heat transfer rate (or shorter charge/discharge time) compared to passive systems. For buildings, the discharge of the PCM at night is a key issue. Cooling of the PCM in the building can be achieved by a cold forced convection stream of night air which passes the PCM unit. The PCM systems can be located in the floor, ceiling, wall or ventilation channels. In some cases the outside air is too warm at night and cooling with night air cannot be utilised. In this situation, water or brine as a heat carrier fluid and alternative cold sources can be used. The cold can be from natural sources (e.g. ground water and soil) or from artificial sources (e.g. absorption chiller). Typically, the water or brine flows through capillary tubes within the PCM panels or boards. The replacement of conventional hot water storage systems, mainly for space heating and tap water in households, is also of research interest. Typical storage temperatures range from 40 to 70 °C. The heat transfer is usually limited by the low thermal conductivity of the PCMs. Heat transfer designs include mainly indirect contact concepts (e.g. heat exchanger tubes with and without fins, as well as encapsulated-PCM in the water), but also other concepts (direct contact concepts, PCM slurries).

For the temperature range above 120 °C, organic PCMs have been proposed. Their critical aspects have been not fully assessed. They include the long-term thermal stability, the reactivity with air oxygen and the high vapour pressure. Some disadvantages can be overcome if hermetically sealed storage systems are utilised. The thermal stability of inorganic materials is inherently higher. For temperatures from 120 to 1000 °C inorganic anhydrous salts can be utilised. There are solid-solid and solid-liquid phase transitions of anhydrous salts which can be used. The cations are mainly alkali (e.g. Li, Na, K) and alkaline earth (e.g. Ca, Mg) metals. Anions which are considered include nitrates, nitrites, hydroxides, bromides, carbonates, chlorides, sulphates and fluorides. Many anhydrous salts are miscible and this results in a large variety of potential single salts and salt mixtures (binary and ternary systems).

In the temperature range 120 to 320 °C, steam storage systems based on PCMs have been developed. Applications of these PCM steam storage systems include the areas of solar thermal power generation, industrial process heat utilisation and combined heat and power generation.

A third possibility to store heat is thermochemical heat storage. The basic principle of these heat storages is the use of reversible chemical processes. The energy is stored in the form of chemical compounds created by an endothermic reaction and it is recovered again by recombining the compounds in an exothermic reaction. The heat stored and released is equivalent to the heat (enthalpy) of reaction. Thermo-chemical heat storage can be categorised in sorption heat storages and in heat storages with reversible chemical bindings which use the binding energy of a molecular state for storing energy. The latter can be classified into thermal dissociation reactions and catalytic reactions.

Thermo-chemical heat storage is a means for a nearly lossless way of storing energy when the chemical reaction partners are being stored separately. Energy densities between 200 to 500 kWh/m3 are feasible. Preferred properties of heat storage material substances are a large inner surface (high porosity) and a hygroscopic behaviour. Zeolite (aluminium silicates) and silica gel (based on silicon dioxide) are normally used. The operating range of zeolite is between 100 °C and 300 °C, the operating range of silica gel between 40 °C and 100 °C.

In the recent years a new family of composite adsorbent materials for heat storage has been invented and presented. Such materials, called SWS (Selective Water Sorbents), consist in an inorganic salt impregnated in a porous host matrix (silica gel). SWSs allow storing a double energy respect to other adsorbent materials. Range of application of this class of materials is suitable for low temperature solar heat storage (80 – 120 °C). Energy density is 500-2000 kJ/kg while bulk density is 800 – 900 kg/m3.

Other favourable reaction systems are based on solid or liquid compounds which can undergo dissociation reactions when they are heated. A gas is released while the depleted solid or liquid remains in the reactor (endothermic reaction, i.e., charging of the store). The reverse reaction will occur spontaneously if the equilibrium is changed by a temperature decrease or a pressure increase. Therefore, the dissociation products have to be separated and stored individually. For discharge, in the exothermic reaction, the gas is recombined with the solid or liquid. By varying the pressure of the gaseous reactants thermo-chemical heat storage can even be used for heat transformation.

In general there are various types of gas-solid reaction systems that can be used for thermochemical energy storage. Among them are:

- Dehydration of metal salt hydrates (application in the range of 40 – 260 °C)
- Dehydrogenation of metal hydrides (application in the range of 80 – 400 °C)
- Dehydration of metal hydroxides (application in the range of 250 – 800 °C)
- Decarboxylation of metal carbonates (application in the range of 100 – 950 °C)
- Thermal desoxygenation of metal oxides (application in the range of 600 – 1000 °C).

Critical gaps between needs and present performance

Currently commercially available TES systems are solely sensible heat storage systems to be used in connection with single phase heat transfer fluids. The predominant TES system is water storage mainly used in the domestic heating sector for instance, since the 60's in France 12 M€ of water heating equipment representing 20 TWh of annual consumption are in operation and contribute via a night and day tariff to smooth the national load curve. Seasonal storage tanks currently are profitable for 100 and more dwelling units. Due to the surface area – volume ratio, heat losses for smaller seasonal storage tanks are too high. Underground Thermal Energy Storage (UTES) for low temperature applications (at less than 40 °C) has been demonstrated and it's now available in some European markets, particularly in the Netherlands, Sweden and Germany.

There are only a few specialists on the market that are familiar with designing and producing complete latent storage systems. The technology of latent heat storage is today still more or less a subject of R&D.

There are many PCMs with disadvantages in their physical/chemical characteristics such as aggressive behaviour against the housing material of a storage tank.

Thermo-chemical heat storage is still in the laboratory stage. To exploit the potential for compact heat storage material as well as engineering aspects need to be solved. Harmlessness, a good heat transfer characteristic and a low market price are requested.

For a wide-spread use and market penetration of TES for RES, the available heat storage technologies show still too high investment costs. Therefore cost reduction of existing TES technologies as well as development of new cost effective TES concepts are the key issue to be solved. In addition, energy density and reliability are topics to be further improved.

Where are the most urgent needs for energy storage in 10-20 years?

Most urgent needs of TES systems cover the areas:

- Thermal energy storage for large scale solar thermal systems for heating and cooling, process heat and power generation;
- Thermal energy storage applications in the industrial process heat sector to be used as a heat management tool to increase efficiency and reduce specific energy consumption of industrial manufacturing processes;
- Thermal energy storage for power generation with thermal conversion processes – combustion engines, steam or gas turbines, ORC etc. – to make conventional power plants more flexible and to support CHP implementation, whereas heat production can be stored temporarily for subsequent use;
- Thermal energy storage for Adiabatic Compressed Air Energy Storage plants.

Where are the decisive challenges for meeting the needs in 10-20 years?

Challenges to realise a more wide-spread use and market penetration of TES technologies in the domestic, industrial and power generation sector are to reduce investment costs and to increase reliability and efficiency of existing and new TES systems. This needs more and continuous research as well as more pilot and demonstration plants.

To close this gap, material issues, design and heat transfer aspects, thermal process engineering and system integration of TES need to be further improved. Enhanced research activities as well as pilot installations are required to achieve further cost reduction.

Technical development perspectives

In addition to water storage additional sensible heat storage systems such as liquid salt storage, concrete storage and regenerator/packed bed storage are identified as being commercially deployed. Latent heat storage is expected to be commercially available and economic for selected applications. Thermo-chemical heat storage is in a pre-commercial state.

A promising approach is the combination of sensible heat storage tanks with compression heat pumps. Heat pumps might be a possibility for storing thermal energy during times of overcapacity of PV and / or wind energy production. The thermal energy can be stored in a buffer tank, in an under floor heating system or in the mass of a building. By that way, the combination of a heat storage tank and a heat pump makes a contribution to an electricity load management for using more energy from renewable sources. The heat pump is preferable running when electrical energy produced from PV and wind power is available. In other words, a balance between the demand of electric energy for the heat pump and the supply of electric energy generated by PV and / or wind has to be established via a bidirectional communication between the heat pump and the energy provider. Currently, field tests on that area are being performed and a communication standard is under development.

Currently, according to a study of TU Munich, a ground source heat pump saves 28 % of CO_2 emissions in comparison to gas heating supported by solar heating of sanitary water. As the share of renewables for the production of electric energy increases continuously, the CO_2 emissions for the operation of the heat pump keeps decreasing. These saves in CO_2 emissions are rising to 53 % in 2020 and even to 63 % in 2030 when the increase of the renewables progresses as forecast [30].

The use of absorption heat storage tanks as prototypes based on liquid storage media such as brine for air conditioning of buildings is currently under development.

30 Agentur für erneuerbare Energien: Intelligente Verknüfung von Strom- und Wärmemarkt. Ausgabe 59 / November 2012

High temperature heat storage might be a promising tool to use industrial waste heat and to improve thermal management of thermally driven processes. With integrated heat storage the waste heat can be reintegrated in the process or - if there is no heat demand – transported to external sites or used for power generation e.g. in connection with ORC (see figure below).

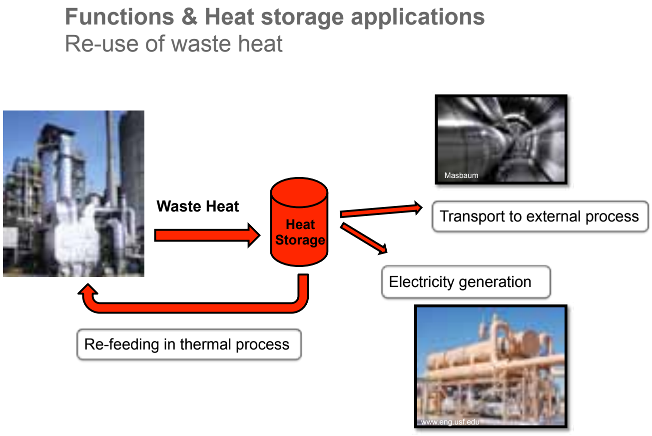


FIGURE 17 - Integrated heat storage

Economic development perspectives

In general,

- 85 % of the energy consumed by households is used for space heating and sanitary water heating [31].
- The prognosis is that the market tariff for electrical energy in the private sector will increase in the future. The result will be that the technology "Power to Heat" in this area constrains the developments integrating heat storage systems in combination with heat pumps or other electric driven heating equipment.
- PCM materials are still too expensive to be used as heat storage media on large scale applications.
- For CSP, reduction for storage investment costs is expected from 35 €/kWhth now to 15 €/kWhth by 2020.

Economic targets are:

- to reduce, in the short to medium term (till 2015), the specific investment cost of latent heat storage and sorption storage below 100 €/kWh and to identify niche applications for thermo-chemical storage
- to have, in the medium to long term (2020), a specific investment cost for compact latent heat and thermo-chemical storage below 50 €/kWh
- to have a long term vision that for a majority of applications, reliable and efficient heat storage technologies are available with a total life cycle costs (including manufacturing, O&M and decommissioning) below 5 € cents/kWh
- The future lies in application with thermo-chemical storage tanks for solar thermal power plants with operating temperatures over 400 °C to take advantage of a high energy storage density. On a medium term, the goal is to provide efficient energy storage tanks with specific investment costs of about 30 to 40 € / kWh[32].

31 Deutsche Energie-Agentur (dena) und Energiedaten BMWi, 12/2011
32 Pitz-Paal, R., et.al.: Solarthermische Kraftwerke – Integration von Strom und Brennstoffen in ein europäisches Verbundnetz. FVEE-Themen, 2010

Need for research

Scientific and technological challenges to be covered comprise:

- Increasing the energy density of storage materials relevant for all different heat storage types
- Reduction of thermal losses and therefore increasing the efficiency of the heat storage system
- R&D of adsorbent media for TES. A number of other potentially interesting dealuminated zeolites and zeotype materials like aluminophosphates (AlPOs) and silico-aluminophosphates (SAPOs) should be properly evaluated for possible application Thermal Storage.
- R&D on Selective Water Sorbent (SWS) materials to increase sorption capacity (up to 60 wt.%) and to reduce the desorption temperature.
- Development of improved UTES including microbiological issues, operation at higher temperature, component selection to prevent scaling and corrosion.
- Optimisation of hydraulics in advanced water stores, reduction of mixing and increased stratification.
- Integration of phase change materials storage materials in building envelope (walls, ceiling, roof).
- Combination of latent storage tanks and cogeneration plants with preferred production of electricity for smoothing the electrical power in the grid.
- Development of latent storage tanks for high temperature heat produced by solar thermal power plants.
- To develop latent heat thermal energy storage materials based on solid-liquid phase transitions, focusing on eutectic metal alloys
- Possibility to downsize the heat generation systems by integration of a heat storage tank.
- To develop advanced heat transfer fluids for thermal energy storage systems
- R&D of PCM-slurries as microencapsulated PCM (about 5 µm). These microcapsules are filled directly into the heat storage tank. Charging and discharging can take place via a suitable heat exchanger.
- R&D of macro encapsulated PCM. PCM can be encapsulated into modules that are filled into a heat storage tank. These capsules serve as kind of heat exchangers between the PCM and the surrounding heat transfer medium.
- Advanced materials research focused on inorganic encapsulation of different phase change materials, their development on ionic fluids for the generation of nanofluids, their improvement of corrosion resistance at high temperature combined with modelling techniques.
- Develop single tank solutions with excellent stratification between the hot and cold section in the tank for CSP
- Develop solid media storage solutions
- Develop new salt mixtures with lower freezing point and higher temperature stability.
- To improve relevant thermo-physical properties of storage materials
  - Special additives have to be added to the PCM basic substrate to achieve a well-defined melting and solidification process for the complete lifecycle of the PCM.
- To identify advanced heat transfer mechanism for charging and discharging
- To reduce thermal energy losses and exergy losses:
  - Increasing of the efficiency of long term heat storage systems with better insulation
  - Optimising the thermal layering in heat storage tanks
- To identify optimised method for system integration:
  - Communications and control systems for combination of heat pumps and heat storage tanks with the grid and other renewable energy systems.

- To research thoroughly environmental impacts of PCMs.
- Minimise storage cost by effective combination of several individual storages depending on temperature level and capacity.
- Development of control strategies for integrating heat storage into the Smart Grid.
- Simulation models of electric storage heaters in smart grids in combination of residential heating of buildings

General R&D Needs

- Development of and research for new materials as PCM and for thermo-chemical storage with optimised characteristics.
- Establishing simulation models for PCM based applications to predict their behaviour in certain conditions (heat transfer, fluid dynamics).
- Simulation models of thermal energy storage in combination with residential heating or industrial processes.
- Transient simulation of heat storage systems in combination with residential or industrial heat supply for optimisation of the design and therefore the efficiency of the total system.
- Reduction of the sensitivity of PCMs to additives.
- Evaluation of the storage capacity in Europe split into short term, middle term and long term applications.
- Develop and update comprehensive grid model to predict the value of dispatchable electricity in a future energy system.

Needs regarding "balance of plant"

Establishing a communication standard for the communication between energy producer and energy consumer

European strongholds

Building-PCM manufacturer in Europe:

- DuPont de Nemours (Luxembourg) S.à r.l., Rue General Patton, L-2984 Luxembourg
- Climator Sweden AB., Norregårdsvägen 18, SE-541 34 Skövde, Sweden
- PCM Products Ltd., Unit 32, Mere View Industrial Estate,Yaxley, Cambridgeshire, PE7 3HS, United Kingdom
- Rubitherm Technologies GmbH, Sperenberger Str. 5a, D-12277 Berlin, Germany.
- Capzo International BV, De Mors 112, NL-7631 AK Ootmarsum, Netherlands.
- BASF SE, Business Management Micronal® PCM, Marketing Polymer, Dispersions for Construction, 67056 Ludwigshafen, Germany.
- Dörken GmbH & Co. KG, Wetterstraße 58, D-58313 Herdecke, Germany
- Cristopia Energy Systems, 78, ch. du Moulin de la Clue, 06140 VENCE, FRANCE

Core research institutes representing the sub-programme thermal storage within EERA Storage

- AIT, Austrian Institute of Technology, Vienna, Austria
- CEA, Grenoble, France
- CNR-Institute of Science and Technology for Ceramics, FAENZA, Italy
- DLR, German Aerospace Center, Cologne, Stuttgart, Germany
- ENEA, Casaccia, Italy
- IMDEA Energía, Madrid, Spain
- UKERC, University of Leeds, UK
- VITO, Mol, Belgium

Hazards and Risks

There are some requirements using storage materials:

- Long term chemical stability
- No toxicity
- No fire risk, flammability
- Non corrosive
- Congruent melting, no sedimentation, no segregation, limited charge-discharge cycles (for PCM storage)
- No side reactions, no kinetic limitations (for thermo-chemical reactions)

Social acceptance

- Heat storage systems based on sensible heat using water as a heat storage medium are well established all over Europe in household applications and industrial applications.
- Large (larger than 5.000 liter) and very large (larger than 50.000 liter) storage tanks for sensible heat are still not established in the residential area. These tanks have to be integrated into a building or in its environment and therefore influence the appearance of that building or its environment.
- PCM based systems are currently still used in pilot projects and not integrated in household applications or industrial applications. The market price for such systems is still too high. A forecast in regard to their social acceptance is not possible.
- Thermo-chemical heat storage is in a very early stage of development. An assessment in regard to their social acceptance can only be made for a specific reaction system.

Market in focus – application areas and types

- Small scale heating and cooling in the private sector
- Large scale heating and cooling in the public and industrial building sector including administration buildings, hotels, schools and hospitals
- Seasonal heat storage
- Industrial waste heat storage
- Thermal management of thermal processes
- Heat storage for decentralised CHP systems
- Heat storage for solar thermal electricity generation

Electric Storage Heating

Description and key property range

An electric storage heater transforms electrical energy into useful heat. The electric storage heater consists of a core of bricks which is heated by electric heating elements. The bricks have grooves in them for containing heating elements and for allowing circulation of air through the bricks. The size, the shape and the material of the bricks ensure that they can be easily handled by one person. If the heating elements are switched on the electric energy is transformed into thermal energy by which the bricks are heated up. The core of the storage heater is surrounded by a layer of a very good insulating material to ensure that very little heat losses occur. The heat is released into the room by radiation and by convection. The convection takes place by air circulating through the air passages in the core. In a modern dynamic storage heater an electric fan blows warm air from the core of the storage heater into the room. A dynamic electric storage heater controls heat distribution more precisely according to the room temperature compared to a static storage heater without fan blower.

A controller automatically switches the electric charging off when the brick core sensor detects the predefined temperature. The electric fan is controlled by a room thermostat. The charge level is controlled by a charge controller and is dependent from the ambient temperature.

Originally electric storage heaters were designed to take the advantage that at certain times (in the night) the demand for electrical energy is significantly less than the supply of electrical energy. Electric storage heaters were programmed to use electrical energy at night. With that time demand shifting it is possible to load the electric storage heater during times when an overproduction of electrical energy is available.

The application range of dynamic electric storage heaters is typically between 2 and 7 kW. The storage capacity lies between 16 kWh and 56 kWh per charge cycle. The application range of static electric storage heaters is typically between 0.75 and 3 kW with a storage capacity between 8 kWh and 24 kWh. The maximum core temperature is about 700 oC.

Electric storage heaters use two different types of bricks as storage medium. One is called "magnesite" and the other "magnetite". The main component of magnesite is magnesium oxide (approx. 87 %) and of magnetite it is iron oxide (approx. 79 %). Table 12 summarises some important physical properties of bricks.

TABLE 12 - Physical properties of bricks

Property	Magnesite	Magnetite
Average specific heat	1.05 kJ/(kg K)	0.94 kJ/(kg K)
Average heat conductivity	5.8 W/(m K)	2.54 W/(m K)
Average density	2.85 kg/dm^3	3.85 kg/dm^3

Two different types of thermal insulation are used in electric storage heaters. Vermiculite consists of a mixture of silicium oxide, magnesium oxide, aluminium oxide and iron oxide with a maximum operating temperature of 1200 °C. Vermiculite has an average heat conductivity of 0.175 W/(m K). Mircoporous silica with a maximum operating temperature of 1700 °C has an average heat conductivity of 0.026 W/(m K).

As an example, a 6 kW electric storage heater has the dimensions 1200 x 700 x 250 mm (W x H x D) and a weight of approx. 250 kg. The energy storage density of a standard electric storage heater is approx. 2.5 106 kJ/m^3 bricks.

In many European countries, large capacities of electric storage heaters are already being installed. For example, in Germany the installed capacity is about 20 TWh per year.[33] In comparison, the often discussed hydro pump storage in Germany has an installed capacity of about 4 TWh per year.

Besides solar and photovoltaic heating equipment, electrical heating is the only way to have no environmental pollution near the place of use. Furthermore, electrical heating can be decentralised and flexible. For electrical heating, no additional installations are necessary, e. g. connecting pipes or tubes or a chimney.

Electrical storage heating is the only technology to use alternatively generated energy (green energy) for room heating without additional compilation losses.

Gaps between needs and present performance

- A dynamic electric storage heater should be remotely controllable to use electrical energy only at times when the generating capacity available is higher than the demand of electricity.
- The installed electric storage heaters may be loaded by remote control of the electric power company. Due to the fluctuation of the renewable energy source (Wind, PV), there has to be a feedback from all the electric storage heaters to the electric power company about their current heat demand (Demand Side Management, DSM).
- The state of the art does not allow the use of electric storage heaters in combination with a household PV system. The power demand of the electric storage heater has to be adapted to the electric power produced by PV. When the electric power of the PV is lower than the power demand of the electric storage, no operation is possible.
- Taking advantage of flexible tariffs is currently not possible.
- The grid infrastructure has to be adapted to an increased use of renewables as an energy source, especially wind power.
- For reducing net peaks from electrical energy generation from renewable sources, a large amount of storage systems is necessary.

Technical development perspectives

- A Demand Side Management (DSM) with a bidirectional communication between the electric storage heaters and the central control unit in the house switch board is not available today.
- Development of a universal electric storage heater for PV-self consumption and DSM.
- For adapting the electrical storage heater technology a development time frame from approx. 3 years should be necessary.
- A surplus of wind energy as a renewable energy source is available during the heating period. Therefore, it is the preferable energy source for electric storage heaters. To use that wind energy a sufficient expansion of the grid is necessary.

33 Verband der Elektrizitätswirtschaft-VDEW: Mitteilung der anteiligen Stromverbrauchs für Raumspeicherheizungen 2000. Berlin, 2005

Economic development perspectives

- To create fair and competitive conditions in comparison to fossil fuels, a reduction of fees / taxes on electricity for heating is necessary.
- Infrastructure for local energy generation has to be created (wind power plants, PV power plants).
- Average costs of an electric storage heater are between 50 and 125 € per installed kWh storage capacity. Additional costs are approx. 500 € for a single control and 150 € for the installation of each electric storage heater.

General R&D Needs

A simulation model of electric storage heaters in smart grids in combination with residential heating of the building envelope and the supply with electrical energy from the grid has to be developed.

The simulation is dependent of a lot of criteria:

- Characteristics of residential buildings (new / existing buildings, single family house / multiple dwelling, insulation)
- Control system of electric storage heater adapted to the use of renewable energy
- Time dependent load curve of renewable energy (wind and PV)
- Comfort demands of the house-occupants
- Existence and technique of ventilation system in the building
- Average climate conditions of the location, annual heating period

European strongholds

There are currently only few manufacturers.

- Brand "Stiebel Eltron": STIEBEL ELTRON GmbH & Co. KG, Dr.-Stiebel-Straße, 37603 Holzminden
- Brand "Dimplex": produced in Northern Ireland (Seagoe Technologies Limited, Portadown) and in Germany (Glen Dimplex Deutschland GmbH, Kulmbach)

Demo and pilot testing

Provision of the complete island Pellworm (North Frisian Island on the North Sea coast of Germany) with renewable sources. Among others electric storage heaters are used as heating appliances[34].

Grid integration

Electric storage heaters are typically used only during the winter period, whereas sanitary water heaters are used during the whole year. Both types of heaters have to be integrated into a smart home energy manager system. By that way, for residential buildings a complete provision with renewable energy can be achieved.

34 "Controlling - Pellworm Energy". Access February 12th, 2013. http://www.pellworm-energy.org/html/Control_de.html.

Hazards and Risks

- Very old electric storage heaters might be contaminated with asbestos.
- In electric storage heaters, an automated shutdown is integrated to prevent overheating.
- Electric storage heaters fall under the RoHS Directive and under the WEEE Directive. Therefore, modern electric storages do not contain the hazardous substances listed in the RoHS Directive.

Social acceptance

- Heating with electric energy is sometimes regarded as very inefficient. Nevertheless, the efficiency factor is close to 100 % at the storage heater itself. The low efficiency factor for electric storage heating systems results from the average power plant efficiency factor which is currently about 40 % EU wide. The average power plant efficiency factor will increased due to more generation of electricity by renewable energies in the future.
- Solution for end customers must be attractive; providing of load and time variable tariffs for demand side management is necessary
- Private households must be willing to invest into local infrastructure (PV, heat storage).
- Electric storage heaters are part of Lot 20 of the eco design directive referring to local room heating appliances. Currently, the characteristics of these appliances are summarised to gain a base for a delegated regulation.

Market in focus – application areas and types

- Strong markets in Germany (dynamic electric storage heaters) and UK (static electric storage heaters).
- Residential space heating for new and existing buildings.

ANNEX VI: MULTI– FUNCTIONALITY HYBRID ENERGY STORAGE SYSTEMS INCORPORATING SMES - A POTENTIALLY FUTURE APPLICABLE STORAGE TECHNOLOGY

Description and key property range

Superconducting magnetic energy storage has been of scientific interest for years and still needs a considerable development effort to demonstrate the practical potential. Long term rather basic R&D effort is required, but on the other hand the technology may hold a considerable potential.

In Superconducting Magnetic Energy Storage (SMES) systems the energy is stored in the magnetic field of one or more superconducting coils thereby exploiting the ultra-low losses of super-conductors. The SMES thus stores electrical energy directly as electricity without involving any electrochemical or electromechanical storage or conversion process. This allows a very fast delivery of high power at high cycle efficiency (>95%), even if the cooling is accounted for: SMES offer highest power but only low energies. Other key issues are a high robustness and a long lifetime with an almost unlimited number of cycles. The technical benefits of SMES have been well demonstrated with Low Temperature Superconductors, but the cost for the cryogenic infrastructure has prevented a broader utilisation. New superconductors which can be operated at higher temperatures and higher magnetic fields, now provide the perspective for new engineering designs. Moreover, if an already existing cryogenic stabilisation (e.g. for liquid hydrogen) can simultaneously be used for cooling the SMES, then the SMES has the concrete potential to become a fully cost-competitive new component in the grid.

A new multi-functionality hybrid energy storage system, LIQHYSMES (Figure 1), has been proposed which combines the use of LIQuid HYdrogen (LH_2) with SMES. The LIQHYSMES Storage Unit (LSU)[35] as the core element integrates the H_2 liquefaction part, the LH_2 storage tank and the SMES cooled by the LH_2 bath. This allows jointly utilising the cryogenic infrastructure and reducing the otherwise significant H_2 liquefaction losses by introducing a novel process with "cold recovery". Compared with compressed H_2 of 150-200 bar, LH_2 now offers similar storage losses (~ 10% of chemical energy), but a 6-fold higher volumetric energy density, and also increased operational safety. Today's cycle losses for the electrochemical re-electrification of H_2 are above 50%. To balance load and supply fluctuations also on time scales from (sub-) seconds to a few minutes is difficult with H_2 because of the response times of the flow control, and this part is taken over by the fast and efficient SMES.

The LIQHYSMES approach offers substantial gains with up-scaling both in terms of efficiency and cost reduction, and thus addresses especially the range of tens to hundreds of MW and GWh.

35 "LIQHYSMES Storage Unit – hybrid energy storage concept combining liquefied hydrogen with superconducting magnetic energy storage", M. Sander, R. Gehring, H. Neumann, T. Jordan, Int. J. of Hydrogen Energy 37 (2012) 14300

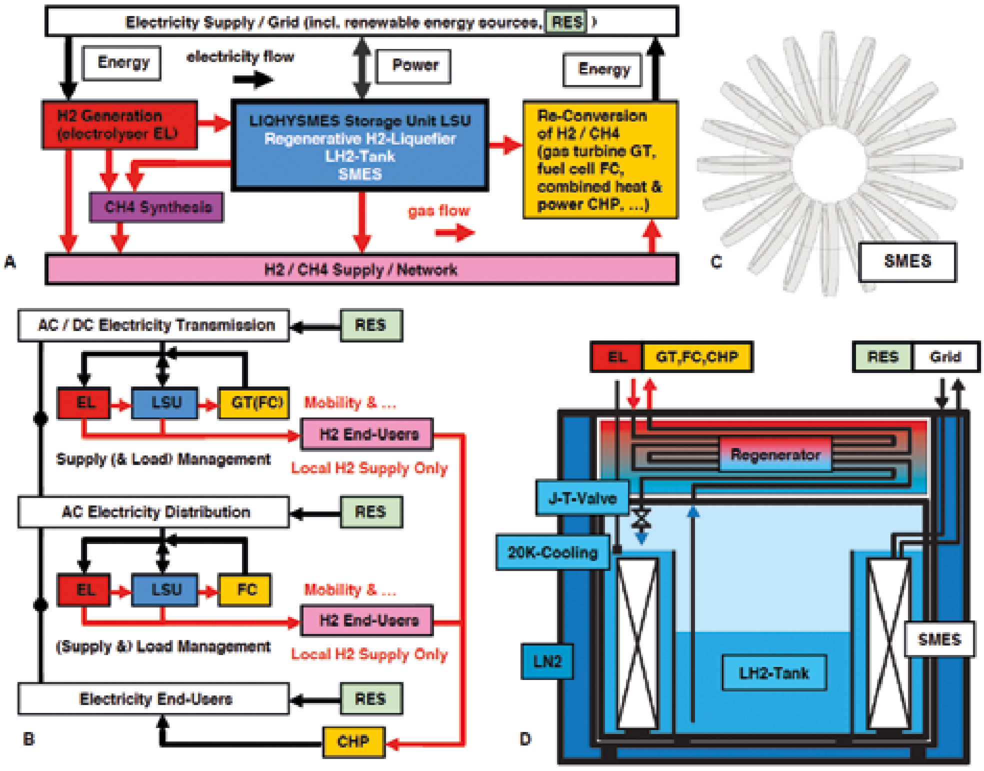


FIGURE 18 - General concept of LIQHYSMES

General concept of LIQHYSMES (A), several features are similar to the approaches described in the section on Chemical Energy Storage, Hydrogen, Synthetic Fuels and Chemicals), one potential grid integration scenario based on a preferably electric transport of variable renewable energies (RES) and local hydrogen supply (B), a view of a toroidal SMES configuration consisting of 20 solenoidal coils and offering low magnetic stray fields (C) and a conceptual design of the complete LIQHYSMES Storage Unit (LSU, (D))

LIQHYSMES contributes to the large scale grid integration of variable renewable energy sources (RES) as well as to the power quality & frequency control. It is open and applicable to ANY combination of electrolysers, gas turbines or fuel cells, to ANY H_2-based supply network (GH_2, LH_2 or H_2-rich compounds like methane) and to ANY centralised or spatially separated "virtual" (e.g. CHP) plant configuration.

Critical gaps between needs and present performance

Challenges as regards the SMES are both in the field of new superconducting materials and adapted novel designs & systems essentially based on modularity. The major H_2-related challenge of LIQHYSMES is the development of the regenerative liquefaction process with "cold recovery". Next, the integration of the H_2 liquefaction, H_2 storage and SMES, which reflects the basic synergy, needs to be developed for scalable LSU concepts. Many other H_2-related challenges are necessarily similar to those described in the section on Chemical Energy Storage, Hydrogen, Synthetic Fuels and Chemicals (restrictions with respect to location and public acceptance may be somewhat relaxed because H_2 is stored in a safe and more compact way). Finally, the integration of the LSU in a centralised or virtual plant configuration incl. the grid connection of the H_2 parts as well as the fast modular SMES requires further interdisciplinary attempts.

Technical development perspectives

Few technically successful SMES tests have already been made with bismuth-based, so-called first generation High Temperature Superconductors (1G-HTS), but the required silver sheath limits the perspectives for future cost reductions. 2G-HTS Coated Conductors are based on the class of 123-HTS (mostly YBaCuO) and show much better current-carrying capabilities in higher fields at LH_2 & higher temperatures than 1G-HTS and low temperature counterparts (LTS) . Programmes focusing on 2G-HTS-SMES for load levelling, frequency control or grid stabilisation are carried out in Japan, Korea and the U.S., but substantial developments, if not fundamental innovations are needed to reduce the AC losses which prohibit a fast ramping of strong magnetic fields. The materials are inexpensive, but the manufacturing cost for the km-length, well-oriented multilayer thin film structures is the issue. A strong development effort is being done in order to diminish the cost[36]. Although discovered more than a decade after 1G and 2G conductors, the manufacturing progress for round LTS MgB2 multi-filament wires in lengths of up to 3 km is already impressive. Due to the lower superconducting transition temperature of ~ 40 K, the fields accessible at LH_2 temperature are lower although improvements in the magnetic flux pinning behaviour are still foreseeable. The materials are readily available around the world, and the manufacturing cost is moderate. Today only cost projections for MgB2 wires come down to levels of a few €/kAm@4T,20K[37]. A programme on a hybrid energy storage system for RES combining an MgB2-SMES with LH_2 is pursued in Japan.

So far the focus of the research on LIQHYSMES was on various design studies and simulations related to SMES, H_2 liquefaction and the anticipated buffering capabilities of LIQHYSMES model plants. The major outcome of these studies is that no critical issue could be identified which would exclude a cost-effective realisation and grid integration of large scale LSUs. First steps towards building a corresponding LSU on a small laboratory scale have been made.

Economic development perspectives

The losses and the investment costs of complete LIQHYSMES plants are widely dominated by the electrochemical energy (re-)conversion, and the related developments, therefore, widely define the overall cost. Potential crossovers from electricity into the sectors of mobility and industry should help concerning earlier implementations. For the cryogenic parts of SMES and LSU both the investment cost and the operational losses per stored energy roughly scale with the inverse of the linear dimensions, thereby substantially increasing the cost-competitiveness for large systems. The major cost factor for the LSU is the SMES. In general, toroidal SMES designs offer low stray fields and also the most versatile application-specific scaling based on standardised and easy-to-manufacture components. A realistic target number for MgB2-SMES specific costs is 5 €/kAm@4T,20K which seems to be well within reach before 2020.

Realistic economic goals for the technology towards 2030

Realistic target numbers for the power- and energy-specific investment costs of the complete LSU are 500-750 €/kW and 2-3 €/kWh, based on the SMES power (w/o grid connection, deep discharge cycles > 1 Million) and the LH_2 energy (w/o electrochemical energy conversion)[38].

36 "Coated Conductors: From R&D to Manufacturing to Commercial Applications". Venkat Selvamanikam, EUCAS Conference, September 19-23 2011Den Haag, Holland, www.eurotapes.eu

37 "MgB2: an industrial viewpoint", G. Grasso, S. Berta et al., Workshop on Industrial Applications of Superconductivity, Sestri Levante (Genoa, Italy), October 4-5, 2010

38 "LIQHYSMES – a 48 GJ Toroidal MgB2-SMES for Buffering Minute and Second Fluctuations", M. Sander, R. Gehring, H. Neumann, http://www.ewh.ieee.org/tc/csc/europe/newsforum/pdf/ASC2012-4LG-05.pdf

Need for research

Research needs related to new concepts (not yet commercially explored)

Research on the LIQHYSMES approach so far concentrated on finite-element calculations of AC/ramping losses in different types of superconductors with higher operating temperatures, on comparisons of magnet designs for solenoidal and toroidal SMES configurations, on the modelling of regenerative H_2 liquefaction processes with "cold recovery", on the design of model plants thereby incorporating key parameters of the power conversion & control as well as of the electrochemical energy (re-) conversion, on simulations of the anticipated buffering capabilities of such plants with respect to strongly fluctuating imbalances between supply and load, on the related loss analyses and on various cost estimations.

R&D needs directly related to SMES

Material issues:

- Higher in-field current densities: Improving in field properties of relevant HTS materials (MgB2 and YBCO), wire architectures and superconducting joints allow the operation of a SMES at higher fields thereby (quadratically) increasing the volumetric energy density.
- Low AC loss conductors: Fast storage and energy release will cause AC loss in the superconductor, and this has to be limited to acceptable values with adequate wire concepts that need to be developed.
- Longer lengths of high quality HTS & MgB2 conductors: Longer lengths are a prerequisite for winding larger magnets because short piece lengths increase the number of required joints, the complexity of magnet systems and the losses.
- High amperage conductors: Large systems will probably require high amperage conductors (cables made of e.g. many individual multi-filament wires). Due to relaxed current density requirements in large systems, lower performance (and thus less costly) conductors may be used for these purposes.
- Cost reduction: Superconducting materials that can be operated in relevant magnetic fields at higher temperatures reduce the losses and the cost of cryogenics. This would be possible with tapes of 1G-HTS and 2G-HTS, but also with MgB2 wires which currently appear to be the most promising candidate for low cost conductors.

System Technology, Integration & Up-Scaling

- Loss reduction related to current leads: Current leads are still a major source of loss, and ideas and measures for improved current feeding & distribution schemes in large scale SMES systems should be found to reduce this loss.
- New concepts in coil design and fabrication based on higher temperature superconductors: Higher operating temperatures and higher magnetic fields require novel approaches both for the design and the manufacture of magnet systems.
- Modular approaches for more degrees of freedom for up-scaling: Standardised coils and new concepts for their integration and the design of larger SMES systems should allow the adaptation of systems to widely different application requirements.

R&D needs related to the LIQHYSMES hybrid energy storage concept

Components & System Technology, System Integration & Up-Scaling

- Loss reduction related to cryogenic components: Improvements concerning the complete cryogenic envelope incl. LN2 shield cooling, standardised processes for multi-layer insulations or conduction losses of mechanical support structures contribute to the efficiency of LIQHYSMES systems. Improvements on High current cable design .and cost optimisation of HTS materials
- Increase of the H_2 liquefaction efficiency due to regenerative (instead of the usual recuperative) liquefaction processes: The partial recovery of the refrigeration & condensation enthalpy of re-evaporated LH_2 (potentially further supported by the magnetic field of a SMES) reduces the losses for the intermediate storage down to a level fully comparable with compressed H_2 (at 150-200 bar).
- Standardised components and processes for the LSU: For commercial applications only large systems will be competitive. Their flexible and cost-effective adaptation to different stationary applications requires specific solutions for their manufacture and integration. A particular focus has to be on concepts for the use of pre-fabricated standardised modules for all plant components which can be transported on trailers and reduce costly on-site manufactures / assemblies.
- Electrochemical energy conversion: Both the losses and the cost of complete LIQHYSMES plants are dominated by electrolysers, gas turbines and fuel cells. The SMES-based short-term buffering already supports a widely steady operation which increases the efficiency, lifetime and operational safety of these devices, but adaptations or even new designs are required to become cost-effective for large scale stationary storage plants (see also the section on Chemical Energy Storage, Hydrogen, Synthetic Fuels and Chemicals).
- Power conversion & control (full power plant management): New power electronics topologies and devices will be required to simultaneously control all parts of the hybrid energy storage plant. Specific attention should be paid to fast and efficient quench detection and protection, the fast response of the modular SMES and the option to exchange both active and re-active power between SMES and grid.
- Applications studies: The techno-economical aspects of potentially attractive business cases need to be studied in more detail before starting with costly demonstration projects. Different services for distribution or transmission systems addressable by LIQHYSMES plants, different regional aspects of supply and load profiles as well as different penetration levels for RES and for H_2 supply need to be included.
- Demonstrations: A first proof of concept for an integrated functional model-LSU can be done in a laboratory environment. To convince potential customers, the potential impact on the energy system has to be clearly demonstrated in real long-term in-field demonstrations. If the LSU can be embedded in an already existing cryogenic infrastructure, then the cost for demonstrations could be reduced. The combination with liquefaction plants and/or storage tanks for liquefied He, H_2, N2 or even CH4, may show attractive locations for demonstrations and first business cases.

General R&D needs

Costs

The costs of the proposed multi-functionality hybrid energy storage systems are widely dominated by the electrochemical energy (re-) conversion, but lowering the cost for the cryogenic infrastructure and for the magnet system would strengthen this specific approach. This all requires substantial research on basic technologies in a strongly multi-disciplinary context.

Environmental issues (raw materials, sustainable utilisation of resources, recycling possibilities, internal and external environment, land use, emissions)

No LIQHYSMES-specific needs related to environmental issues could be identified so far:

For 2G conductors only rather small quantities of rare earth materials are needed for the thin film deposition technology, and for MgB2 wires the raw materials are readily available around the world.

Stray magnetic fields need to be taken into account when positioning large SMES systems. Toroidal magnet systems (see Figure 1C) have necessarily larger overall diameters and heights, but offer smaller radial and vertical distances for the heart pacemaker limit of 0.5 mT (although recently developed heart pacemakers seem to allow the operation also in fields of up to 1.5 T)

The LIQHYSMES approach itself is essentially greenhouse gas neutral, doesn't require any rare or precious (raw) materials (like nano-porous storage materials), doesn't require any specific geological formations (like salt caverns) and has minimum space requirements which allow flexible positioning e.g. an installation in cities.

Specific development needs (e.g. degradation, durability, temperature stability)

Apart from the needs addressed in the section on Chemical Energy Storage, Hydrogen, Synthetic Fuels and Chemicals, so far no specific development needs e.g. concerning the degradation, durability or temperature stability of the cryogenic LSU could be identified.

Needs regarding Balance of Plant

New topologies for the grid interfacing power electronics will be required to simultaneously control all parts of the hybrid energy storage plant, and, In particular, to take full advantage of the fast response of a fully modular SMES.

European strongholds

The European industry has a strong position in essentially all involved fields: power conversion, renewables, hydrogen (incl. liquefaction) and superconductivity: As regards the key issues for the LSU, cryogenics and superconductivity, European companies have currently a market share of roughly 50 % worldwide[39]. Concerted actions of different manufacturers and utilities will be required to extend existing strong positions also in this new strongly interdisciplinary field.

European economic and industrial potential (Current basis/starting point)

As addressed in the section on Chemical Energy Storage, Hydrogen, Synthetic Fuels and Chemicals, today there is no urgent need for the production and re-electrification of H_2, but it will first increase in regions with strongly increasing RES contributions and limited grid infrastructure.

39 http://conectus.org/market.html

The additional functionality of the SMES could accelerate this process and extend it into regions with currently sufficient conventional (thermal) control power for ensuring voltage and frequency stabilisation. In this respect the ancillary service of the SMES for an increasingly digitised society could help covering the "Second Reserve" (Primary Control: linear ramp-up to the power level of an incident i.e. a sudden increase / decrease of demand or supply within 30 sec, and 50% of it should be provided within about 5 seconds, according to ENTSO-E[40]) and optimising the operation of conventional power plants and grid components (in the beginning mainly related to load, not supply fluctuations).

Demo and pilot testing

A concrete European Lighthouse LIQHYSMES demonstration is envisaged: The SMES as a fast and high power device addresses the voltage and frequency stabilisation of the electrical grid. This stabilisation service will be combined with the long-term supply of electricity produced by variable RES and temporarily stored as liquefied H_2. Synergies with the mobility sector are envisaged.

Research group clustering potentials & joint use of research infrastructure in Europe

Europe's research also has a strong position in essentially all involved fields: power conversion, renewables, hydrogen (incl. liquefaction) and superconductivity, but an intensified exchange among the different stakeholders is needed:

- Establish a joint European characterisation and demonstration platform for SMES utilising superconducting materials with higher operating temperatures and modular SMES approaches.
- Establish a strongly interdisciplinary European platform for multi-functionality hybrid energy storage technology incorporating new SMES systems to initiate first grid-connected demonstrations on smaller scales.

Grid integration

The H_2 parts of the electrochemical energy (re-) conversion i.e. electrolysers, gas turbines or fuel cells may typically contribute to the buffering of imbalances between supply and load on time scales of minutes (depending on the specific type, it may be somewhat below a minute) up to days or weeks. The additional functionality of the SMES would not only cover the minute time scale, but could also help providing the "Second Reserve", contributing to voltage and frequency stabilisation and optimising the operation of conventional power plants and grid components.

Hazards (e.g. explosion, risk of toxic emissions)

No toxic materials are involved in the LSU.

The risks associated with the production and re-electrification of H_2 are addressed in the section on Chemical Energy Storage, Hydrogen, Synthetic Fuels and Chemicals. The risks associated with the intermediate storage of H_2 in liquefied form are somewhat relaxed compared with the storage in compressed form (much lower pressure and temperature).

40 https://www.entsoe.eu/publications/system-operations-reports/operation-handbook/

Social acceptance and engagement / social interfaces (incl. jobs creation)

Public acceptance issues associated with the production and re-electrification of H_2 are addressed in the section on Chemical Energy Storage, Hydrogen, Synthetic Fuels and Chemicals. Because of the reduced space requirements which allow a more flexible positioning of storage tanks for LH_2, it is anticipated that the concerns related to the storage of H_2 in liquefied form may be somewhat relaxed compared with those related to the preparation and operation of salt caverns for the storage of H_2 at e.g. 150-200 bar.

Markets in focus - application areas and types

Since LIQHYSMES plants do not depend on specific geological formations, they can be positioned everywhere, and consequently markets should be addressable everywhere in the world where ambitious plans for fluctuating RES and limitations of the grid infrastructure foster the introduction of large scale chemical energy storage. Highly industrialised regions characterised by a high level of digitisation and particular needs for high quality supply would then particularly benefit from the ancillary services of the SMES.

Potentially attractive locations in the electricity network might be those where the LIQHYSMES plant can be combined with other existing or foreseen grid components, e.g. with reactive power control, AC-DC / DC-AC conversion, transformers or circuit breakers, e.g.

- directly at variable RES power plants or near customers with varying high loads
- within the distribution network hosting different & widely distributed variable RES
- at the step-down transformation between transmission and distribution system
- nodes between existing AC grids and HVDC links e.g. to variable RES
- nodes between HV links connecting variable RES and/or central (e.g. pumped hydro) energy storage

Potentially attractive locations in a future H_2 supply network might be those where the LIQHYSMES plant can be combined with the production, storage and distribution of H_2, e.g.

- directly at large electrolyser facilities converting excess RES power into H_2
- at central hubs for H_2 fuelling stations (supplied as GH_2 or LH_2) for H_2-powered electric mobility which require high local storage capacities
- at storage nodes in central or more decentralised pipeline systems for locally buffering the H_2 supply & load e.g. related to Combined Heat & Power (CHP)

Particularly promising locations and markets would simultaneously utilise different functionalities of LIQHYSMES plants and thus provide additional benefits to customers.

Business cases

The first business cases will emerge where different functionalities of LIQHYSMES plants simultaneously provide different benefits i.e. simultaneously serving the mobility sector, ensuring voltage and frequency stabilisation and providing power quality for increasingly digitised societies.

Apart from (shorter term) niche markets such as islands, re-electrification of H_2 and thus also complete LIQHYSMES plants will become fully economical only in the mid to long term i.e. when the contributions of fluctuating RES exceed 50% of the overall electricity generation.

SWOT analysis in European context

Strengths: The European industry has a strong position in essentially all involved fields: power conversion, renewables, hydrogen incl. liquefaction, cryogenics in general and superconductivity in particular.

Weaknesses: A strongly interdisciplinary joint European characterisation and demonstration platform for multi-functionality hybrid energy storage systems involving different kinds of manufacturers and utilities is not yet established.

Opportunities: Right now, Europe is in the forefront of renewable energy, and the increasing contributions of fluctuating electricity provide excellent opportunities to also commercialise large scale energy storage.

Threats: Referring to East Asian countries, new technologies are considered as a cornerstone of social and economic development, and consequently the activities in Korea and China e.g. linking renewables and superconductivity, are strongly increasing.

Need for support/incentives

The development of multi-functionality hybrid energy storage systems involves fairly different technologies, and, therefore, there is a particularly high risk that one of the key components might not meet the economic goals which have to be achieved for successfully commercialising the complete systems.

The remuneration of the benefits of multi-functionality hybrid energy storage systems can only be dealt within the whole framework of new market design for energy storage.

Standards

The definition of new standards requires concerted efforts involving the on-going activities and stakeholders in the fields of hydrogen, grid connection and new superconductors.

ENERGY STORAGE TECHNOLOGY ROAD MAPPING

ROAD MAPPING EFFORTS IN OTHER REGIONS OF THE WORLD

Technology Road Mapping Status

All over the world Technology Road Mapping (TRM) is considered as an important strategic tool for collaborative technology planning and coordination for corporations as well as for entire industries. It is mainly used for the development of any new technology in an uncertain environment.

A first generic process description was elaborated by the US Sandia National Laboratories in 1997:

- "Fundamentals of Technology Road Mapping"

Similar processes were proposed by consultants and industrial companies.

In particular, TRM is used to define new energy technology policies able to fulfil the new low carbon requirements.

Therefore, the European Commission (EC) proposed its own view on TRM in 2009 for the Strategic Energy Technology Plan (SET Plan):

- "Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions on Investing in the Development of Low Carbon Technologies (SET-Plan): A Technology Roadmap"

All the European Industrial Initiatives (EII's) have already their TRM related to their specific field. There are 2 specific cases:

- EERA is requested to provide TRMs related to some specific research areas
- A generic Energy Materials TRM was elaborated by the EC with the support of some relevant stakeholders (EASE was involved for the Energy Storage (ES) materials). This Materials TRM is now taken in charge by EMIRI. EMIRI, the Energy Materials Industrial Research Initiative, aims through research, development and deployment of advanced materials, to enable the ambitious targets of the SET Plan.

In 2010, the International Energy Agency (IEA) defined a new TRM Guide in order to make it possible to elaborate good energy recommendations for different countries worldwide:

- Energy Technology Roadmaps: a guide to development and implementation

This TRM guide was used for developing all the IEA TRM related to a specific energy technology domain and is also expected to be used by different countries (such as India for example) for their own energy technology policies.

However, some countries used their own TRM process for defining their own energy technology policy:

- Japan: presented its 2008 "Cool Earth-Innovative Energy Technology Program" that incorporated several of Energy Technology Roadmaps
- China: a "Low Carbon Technology Development Roadmap" was drawn up in 2011 by the Energy Research Institute, National Development and Reform Commission
- US : some Energy TRM were and are being elaborated by most of the US states
- Most of the European countries are currently in the process of defining their own national Energy TRM.

Energy Storage Technology Road Mapping Issues

Even if it is possible to find numerous Energy Storage (ES) studies all over the world, the actual available ES TRM are very rare. However, most of the administrations, agencies or associations have put the ES TRM as a key objective of their respective work programme.

Indeed, if most of the relevant stakeholders are convinced that the ES is expected to represent a key grid flexibility solution (among other alternatives), they face a lot of difficulties to elaborate a ES TRM as ES needs and ES technologies depend on ES application and ES location on one hand and on its competitiveness against alternative solutions and on Grid Regulations on other hand.

It is the reason why the ES TRM should be elaborated in collaboration with other Energy technology TRM: it is especially the case for Japan, the EU and the IEA.

However, the development of some new clean transport systems (road, rail, marine or air) is expected to be based on some ES technologies (batteries and fuel/cell-H2 storage) and induces the setting of some specific ES TRM dedicated to the Transport issues. This situation outlines that some interferences are expected to happen between Transport and Stationary Energy.

Current Status of Energy Storage Technology Road Mapping

1. European Union (EU)

a. EC

In the Materials SET Plan presented by the EC in 2011 (Commission Staff Working Paper: Materials Roadmap Enabling Low Carbon Energy Technologies), a material ES Roadmap has been published: see below.

This material road map is based on the following segmentation:

- Energy oriented materials for lower costs, higher life span batteries
- Power oriented materials for electrochemical capacitors
- Materials for non-chemical energy storage
- Novel materials for Post-Li ion, Metal air, Li-S, Na ion

Read the report:
http://setis.ec.europa.eu/activities/materials-roadmap/Materials_Roadmap_EN.pdf/view

This material ES TRM is based on the performance targets of all the ES technologies that are expected to be involved in the Transport & Stationary Energy sectors.

EASE was involved in this exercise although it did not consider the ES needs and the ES challengers such as the ES value materialisation.

It means that the EASE/EERA TRM must not be limited to the technical issues that are partially addressed in this material TRM but must also go to the ES needs and to the identification of the gap between ES requirements and the available performances.

b. Member States

- France

A "Strategic Road Map (SRM)" on Energy Storage Systems was published by the French Environment Agency (ADEME) in 2011 in order to be able to launch some calls related to large projects on Energy Storage for Transport & Stationnary Applications.

For that purpose, this SRM identifies:

a. The main industrial, technological, environmental and societal issues;
b. Some coherent visions on technologies and socio-technical system;
c. The technological organisational and socio-economic barriers to overcome;
d. The needs in research, development and demonstrations related to the different energy storage technology.

Furthermore, the French Administration and some French stakeholders (EDF, GDF SUEZ, E.ON, Alstom, Saft,...) are currently funding a study of the ES potential market in France (PEPS) performed by a consortium of 3 consulting companies: Artelys (project leader), ENEA Consulting and G2Elab: in fact the PEPS study is a ES Technical Roadmap dedicated to the French situation.

Especially, this PEPS study intends to address the following issues:

- Assessment of the flexibility needs
- Analysis of the main ES technologies
- Assessment of the French potential ES needs
- Assessment of the different business models

- Germany

Even though some good ES German studies were recently published on the market point of view (VDE) and on the technical point of view (RWTH Aachen), no formal ES TRM has been published yet.

A new German ES association (BVES) was launched in September 2012 and the release of a German ES TRM is announced to be its first priority.

- UK

Some very good ES studies have recently been published and it is possible to consider 2 of them as a potential English TRM:

- "Pathways for energy storage in the UK" published by the Centre for Low Carbon future in 2011

Especially, this study identifies many different ES technologies at different stages of maturity and proposes some pathways for the deployment of centralised and decentralised ES systems

Read the report:
http://www.lowcarbonfutures.org/reports/research-reports

- The Energy Research Partnership Technology Report related to the future role for energy storage in the UK (June 2011)

This report presents the challenges to the UK energy system posed by increased wind and electrified space heating and explains how they can be met by ES technologies with indicative time and energy scales.

However, even though it is not an ES TRM, the Imperial College study on ES (Strategic Assessment of the Role and Value of Energy Storage Systems in the UK Low Carbon Energy Future) provides some key results about the ES potential in UK: In particular, this study proposes a quantified analysis related to the ES needs & benefits with a comparison of centralised and decentralised ES.

Read the report:
http://www.carbontrust.com/resources/reports/technology/energy-storage-systems-strategic-assessment-role-and-value

2. IEA

An IEA ES TRM was launched in 2012 and intends to answer to the following questions:

Where is technology today?

- GW installed capacity/kWh of savings
- Leading countries/regions
- Cost, efficiency
- What is the deployment pathway needed to achieve 2050 goals?
- Use IEA Energy Technology Perspectives 2 degree scenarios
- What are the priority near-term actions?
- R&D gaps and how to fill them
- Identify barriers and obstacles and how to overcome
- Market requirements and policy needs
- Technology diffusion/transfer and international collaboration needs

3. USA

a. DOE

Though some interesting ES US studies were recently published on the market point of view and on the technical point of view (Sandia, EPRI,…), no formal ES TRM seems to have been published yet at the federal level.

b. US states

- California

The "2020 Strategic Analysis of Energy Storage in California report" published in November 2011 assesses current energy storage technologies, discusses the diverse policies affecting deployment in California, and outlines critical technology gaps, future research needs, and policy reforms. It also provides a reference framework for the Energy Commission, CPUC, and other regulatory agencies to use as they develop solutions for how commercially ready energy storage technologies can be costÐeffectively applied in California to reduce costs to ratepayers, reduce emissions from fossil fuel generation, and enable and accelerate the implementation of more renewable generation and its integration in California's electricity system.

- New York

The New York Roadmap for Energy Storage was commissioned in 2012 by NY-BEST to assess the current landscape for energy storage technologies and to outline a strategy for increasing the energy storage industry in New York State. This industry encompasses a wide range of technologies including batteries, fuel cells, ultra capacitors, flywheels, pumped hydro, superconductors, and thermal storage. The Roadmap examines the roles of technology, industry and policy in the state and establishes key recommendations for each of these areas.

4. Japan

A High-Performance Power Storage TRM was published by the METI in 2008 in the frame of the "Cool EarthÐInnovative Energy Technology Program".

This TRM presents the Milestones and the direction of RD&D for 21 Innovative Technologies in the Energy field.

The following ES technologies are considered:
- SMES
- Power storage based on, super condensator, conventional & flow batteries
- Hyrogen storage

This TRM seems to focus mainly on transport issues and some new TRM are expected to be published in the aftermath of the nuclear accident.

5. China

No ES TRM is mentioned in the current Low Carbon Technology Development Roadmap for China but some works could be launched under the CNESA influence?

6. India

No ES TRM is mentioned in the current Energy documents but some works could be launched under the IESA influence?

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ABBREVIATIONS AND ACRONYMS

CAES	Compressed Air Energy Storage
CAPEX	Capital expenditures
CBA	Cost Benefit Analysis
CSP	Concentrated Solar Power
DESS	Decentralised Energy Storage Systems
DSO	Distribution System Operator
DOE	US Department of Energy
EC	European Commission
ECs	Electrochemical capacitors
EES	Electrical Energy Storage
EII	European Industrial Initiative
EMIRI	The Energy Materials Industrial Research Initiative
ENTSO-E	European Network of Transmission System Operators for Electricity
ES	Energy Storage
EV	Electrical Vehicle
IEA	International Energy Agency
LIQHYSMES	Long-term energy supply based on liquefied hydrogen
PCM	phase change materials
PHS	Pumped Hydro Storage
PV	Photovoltaic
R&D	Research & Development
RD&D	Research, Development & Demonstration
RE(S)	Renewable Energy (Sources)
SET Plan	Strategic Energy Technology Plan
TES	Thermal energy storage
TRM	Technology Road Mapping
TYNDP	Ten year network development plan performed by ENTSO-E
UPS	Uninterruptible Power Systems
UTES	Underground Thermal Energy Storage
VPP	Virtual Power Plant

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EASE
European Association for Storage of Energy

EERA
European Energy Research Alliance