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Technology Overview on Electricity Storage

Overview on the potential and on the deployment perspectives of electricity storage technologies

On behalf of

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Foreword

Electricity storage can be a key feature of a future decarbonized power system based on very high shares of renewables. This report provides a foundation for discussion tackling mainly two questions:

- Which functions can be served by electricity storage systems, and how can their different applications be classified?
- What is the state of development of different storage technologies, and their respective strengths and weaknesses?

The report offers an overview on storage technologies and a classification of their applications. It has been written for a public of non-technicians working on the energy transition.

Solar and wind energy play a decisive role in the energy transition. Their output is variable and not completely predictable. These challenges are not fundamentally new for Europe's power system, which has already in the past coped well with constantly fluctuating demand and with unforeseen contingencies.

However, the flexibility challenge is going to increase substantially. This is not only due to the increasing shares of variable generation, but also to the geographical reshaping of the power system: substantial shares of renewable generation will come from remote areas, while other substantial shares are embedded in the local low or medium-voltage distribution networks.

All these factors lead to a much higher need for flexibility in the power system. Broadly following the categorization of the International Energy Agency[1], four kinds of flexibility resources can be used to balance variability: dispatchable (or flexible) power plants, demand side management and demand response, energy storage facilities and increased interconnection with adjacent markets.

"Interconnection with adjacent markets" includes the upgrade and expansion of grid infrastructure and the integration of power markets to make best use of the interconnections. Demand response can be linked with storage opportunities in the heat (e.g. end-use heat storages) or in the transport (e.g. electric vehicles) sectors.

Flexibility sources are to some extent exchangeable: most flexibility services can be delivered by more than one of these sources. Thus, there are good reasons to assume that the transition to renewables can be achieved even if the deployment of one or the other flexibility source might be hindered for whatever reason.

The distinction between storage and other flexibility sources is not always clear-cut. For instance, hydropower reservoirs can be considered as "dispatchable generation" or as "storage". Similarly, end-use thermal storages (e.g. hot water storages linked to a heat pump or an electrical heater) can contribute to cost-effective balancing of the power system, if they are equipped with smart controls: this could be defined as "storage" or as a "demand response" solution. Detailed descriptions in this report are confined to those storage technologies able to re-convert the stored energy into electricity. For this reason, low temperature heat storages have not been considered, though they can play a very important role

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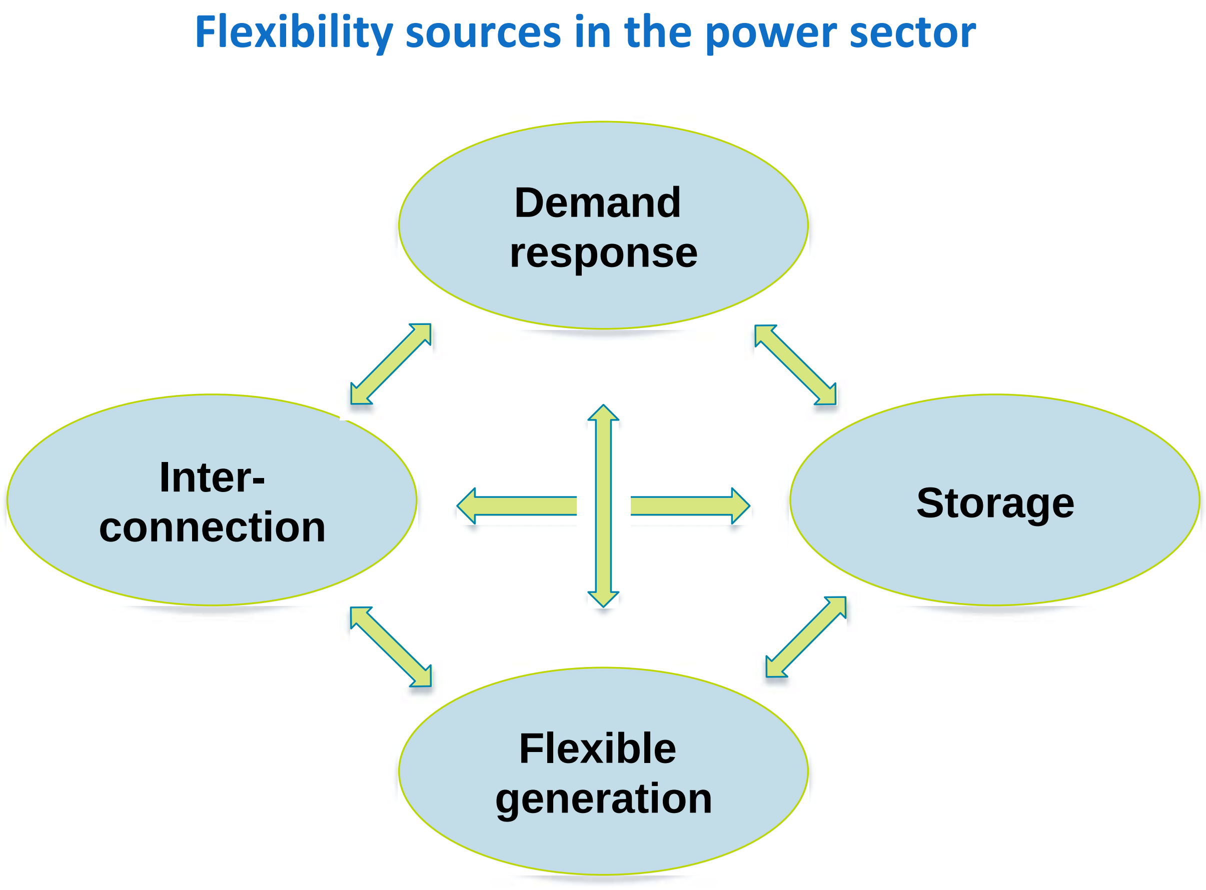
[1] Harnessing Variable Renewables – A Guide to the Balancing Challenge", International Energy Agency (2011).



to provide cost-efficient flexibility in many parts of Europe.

Taking a broader approach on flexibility as suggested above, the distinction between storage, generation, or demand response is not that important. The key issues of the energy transition in the power sector is the interaction between strongly increasing amounts of variable renewable electricity generation and the mix of flexibility resources to integrate them into the power system. On both sides, generation and flexibility, a broad portfolio of options makes sense. A robust mix is the best strategy to bring Europe onto a secure, resilient, rapid and cost-effective pathway towards high shares of renewables

Certainly, the interactions, trade-offs and competition between different flexibility sources and technologies will be a core aspect of energy policy and energy business choices in the next decades.

This report is intended to support the debate by informing on the technological aspects of one of the four flexibilities above. Neither the three other important sources for flexibility nor the non-technical factors for the deployment of flexibility like market design, environmental impact social and political acceptance are addressed.

SEFEP believes that enhancing dialogue on the various flexibility options is important to progress towards a power system predominantly based on renewables. This report is our first contribution to the storage part of the story. It reinforces, in a complementary fashion, our work on network development, on other flexibilities, and on a political framework supporting higher amounts of renewable generation.

We at SEFEP originally commissioned this report for our own internal use and strategy development. We asked experts for a short introduction to different storage technologies, to be written for a non-specialized public. In the end, the work became more substantial, and the authors contributed more insight and overview than originally anticipated. We therefore felt that this paper might be a useful introduction to electricity storage technologies to colleagues and partners, and thus we decided to share the results with the interested public. We thank the authors, who made this publication possible by their expertise and dedication to the issue.

Kristina Steenbock and Raffaele Piria

Contents

1. Introduction

The goal of this report is to provide a basic overview of electricity storage technologies and their potential applications, especially with regards to the transition to an electricity system with high shares of renewable energies.

Motivated by the threat of global warming and other environmental impacts of energy usage, security of energy supply and economic reasons, there is an international effort to increase the share of renewable power generation in the electricity supply. However, the two fastest growing renewable energy sources, wind and solar power, are naturally fluctuating due to weather conditions as well as diurnal and seasonal patterns. Furthermore, the best harvesting potential does often not coincide spatially with the centers of power consumption.

Therefore, the transition to a power system with high shares of renewable power generation requires a differently structured electricity grid with higher transmission capacity in order to bridge spatial distance between supply and demand. Additionally, the power system requires capabilities in order to bridge distance in time between supply and demand, which we may call flexibility. Flexibility is the ability of the power system to match fluctuating generation with - also fluctuating - demand. Sources of flexibility can be dispatchable generation (fossil, hydro or biomass), demand response, the curtailment of renewable generation and/or electricity storage.

In general, different sources or combinations thereof can provide flexibility. The choice will depend on economic factors, social acceptance, ecological considerations and other factors. This report focuses on storage technologies and specifically those that are able to absorb electricity from the system and reconvert it into electricity at a later time.

With increasing shares of renewable generation, the electricity system is in a transition from currently demand driven centralized and fossil-based generation, where flexibility is predominantly provided by dispatchable generation, towards more supply driven regenerative and distributed energy production where additional sources of flexibility will be required.

This also affects the operating principles and the system stability. Traditionally, the major conventional power plants supply energy and balancing power to the grid and the power flow is always directed from the higher voltage levels (location of power plants) to the lower voltage levels (location of consumers). Due to an increase in renewable electricity generation on the mid and low-voltage level (residential PV systems, onshore wind power) the power flow direction can be inversed. Furthermore, during times with high renewable energy feed-in the electricity demand can be covered completely by renewable generators. This leads to situations where new ways of guaranteeing system stability have to be found: either conventional power plants have to be run at minimal load with high specific emissions, or electricity storage systems, demand side response and the renewable energy generators themselves have to supply the necessary system services.

Besides the integration of renewable electricity generation the most active field of development for electricity storage systems is the electrification of the transport sector. The demand for especially lithium-ion battery systems rises rapidly due to the introduction of plug-in hybrid and full electric vehicles. This transition is also linked to the electricity sector for two reasons: Firstly, the increased demand fosters mass-production of batteries which causes decreasing battery prices which also helps to introduce storage systems in the electricity grid. Secondly, the battery storage systems of the traffic sector can also be used as grid storage during times when the vehicles are plugged-in for charging. The link between these two sectors causes major transitions in the traditional world of utilities as automobile manufacturers start to produce their one “green” electricity for their electric vehicle fleet. On the other hand utility companies start getting involved in the mobility sector as they deploy the charging infrastructure and develop business models for electricity supply for e-mobility. Both trends result in a closer link of these two important branches of industry.

In order to keep this report reasonably compact it was limited to the discussion of electricity storage systems. However, this is not to be mistaken as a statement of preference for electricity storage as a source of flexibility. In some cases electricity storage is unavoidable, however, for the time being all flexibility sources are to be considered as at the current state of development there is no single solution that serves all flexibility needs. One alternative to electricity storage is heat storage where heat is the final form of energy used. Especially low temperature heat in buildings and process heat in the industry have the potential to provide significant amounts flexibility. A short discussion of potentials and limitations is given in chapter 2.

All applications of electricity storage make it necessary to understand the technology options and their alternatives. As the cost of electricity storage strongly depends on the specifics of the application, this report cannot give general recommendations for the use of certain technologies for given applications. It is a first introduction into electricity storage systems and their possible applications. The report is structured as follows:

Chapter 2 gives an overview on selected applications for energy storage systems. This covers mainly electricity grid services but also other important systems like electromobility[2].

Chapter 3 gives an introduction into important parameters and terminologies. A systematic classification of storage technologies helps to better understand the different main characteristics.

Chapter 4 is the main part of this report and contains the description of important (technically and operationally proven) electricity storage technologies with their technical parameters and their deployment potential. Mechanical, electrical, chemical, thermal and electrochemical (batteries) storage systems are covered.

Chapter 0 discusses the potential role of the different storage technologies.

A comprehensive discussion of demand and cost of storage for the integration of renewable energy exceeds the scope of this report. The feasibility of different storage options, the amount of storage required at different shares of renewable energy and the related costs are being discussed among experts and in public. The main complications in the search for answers to these questions is the fact that demands for generation, transmission and flexibility are interlinked and can replace each other to some extent.

An estimate of the storage demand for the coming years therefore depends on the share of renewable energy, the fraction of the different renewable sources, the flexibility of the conventional generation portfolio and the transmission capacities, the cost structure of each component above and their development throughout Europe.

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[2] Proper English is electric mobility however, the term electromobility appears to be commonly used recently.

2. Applications

In this chapter various applications for electricity storage systems are introduced. The main focus is applications in the utility power system but also others like electromobility are described:

- Ancillary services
- Peak shaving
- Load leveling
- Long-term storage (weekly to monthly)
- Seasonal storage
- Island grids
- Other sectors

2.1 Ancillary Services

Slightly different definitions of ancillary services exist in the literature. In this report the definition of EURELECTRIC is used: “Ancillary services are all services required by the transmission or distribution system operator to enable them to maintain the integrity and stability of the transmission or distribution system as well as the power quality.”[3] In other words ancillary services are necessary for the stable operation of the electricity system. These services become more important with higher shares of renewable energies. The following ancillary services can be delivered by energy storage systems:

- Frequency control
- Voltage control
- Spinning reserve
- Standing reserve
- Black start capability

There are also ancillary services which cannot be delivered by storage systems, like “Remote generation control”, “Grid loss compensation” and “Emergency control actions”. However, these services are required for renewable and conventional power generation alike. In other words, renewable generation in combination with storage systems can deliver all services which conventional power generation provide today.

2.1.1 Frequency Control

In the electricity grid, demand and supply of energy have to be equal during all times. The system frequency (50 Hz in the European electricity grid) is a measure of balance between

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[3] Eurelectric: Ancillary Services (Unbundling Electricity Products – an Emerging Market), 2004

supply and demand of electricity. The frequency rises if generation is higher than demand and the frequency drops if demand is higher than generation. By charging energy storage systems, the demand of electricity can be increased and by discharging the storage systems generation can be increased. Therefore energy storage systems can balance generation and demand and by this supply frequency control. Different kinds of frequency control are distinguished:

Primary Frequency Control:

Primary control is the automatic response to frequency fluctuations which is activated some seconds after a frequency deviation from 50 Hz. This service is delivered by conventional power plants up to now. These power plants operate at slightly lower power output than rated maximum power to be able to ramp power up and down. In the future with high shares of renewables, primary control might be delivered by energy storage systems like batteries as it is not economic to operate conventional power plants exclusively for delivering primary frequency control.

Secondary Frequency Control:

Primary control is automatically replaced by secondary control after a certain time. This timeframe is different in different countries. Secondary control can also be supplied by energy storage systems like batteries.

Tertiary control (Minute Reserve):

Tertiary control, also called Minute Reserve, is additional to primary and secondary frequency control. The Transmission System Operators (TSO) must request it from the supplier. For this control, typically hydro pumped storage systems or gas power plants are used, as the delivery time is longer than for primary and secondary frequency control.

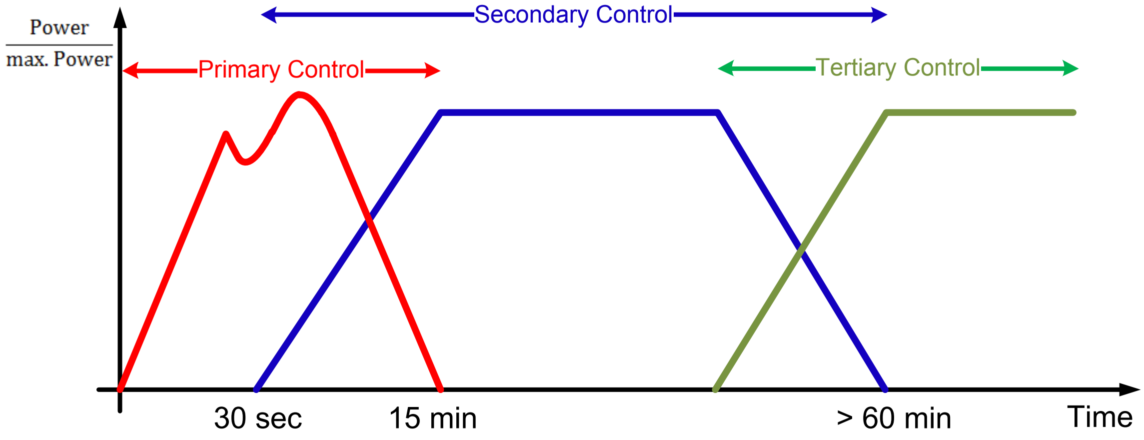

Figure 1: Time scale of frequency control (activating times are examples for Germany)

2.1.2 Voltage Control

The voltage on transmission and distribution lines has to be sustained within certain limits. Due to losses and other effects the voltage limits can be violated. One measure to control the voltage is the injection or absorption of reactive power. This can be supplied by systems which are solely installed for this purpose (SVC – Static Var Compensator) and also energy storage systems which can supply reactive power in addition to their primary purpose.

2.1.3 Spinning Reserve

Spinning reserve is the power generation capacity which can be activated on decision of the system operator and which is provided by devices that are synchronized to the grid and able to affect the active power. Spinning reserve is the standard means to provide secondary and tertiary frequency control today.[4] In order to do that, power plants have to be operated below maximum rated capacity. This causes reduced cost effectiveness and potentially an increase in specific emissions.

Strictly speaking Spinning Reserve is not an application of storage systems. However, the term is sometimes used synonymously for the services it provides. Storage systems are capable to deliver the same service as spinning reserve. Systematic evaluations of cost and emission effects are necessary. The authors have no knowledge of ongoing investigations of that kind.

In power systems with very high shares of renewables the tasks of spinning reserve can no longer be delivered by conventional power plants. Either renewable power generators operating below rated capacity or energy storage systems can be used instead.

2.1.4 Standing Reserve

Standing reserve is the power generation capacity which can be used to increase generation but which is not synchronously on-line. As spinning reserve, standing reserve is no real application but a method to provide control power. The same functionality can be provided by storage systems for medium and long term storage or reduction of consumption i.e. Demand Side Management. Also renewable generators which are kept offline can act as standing reserve.

2.1.5 Black Start Capability

This capability provides power and energy after a system failure. Many units of the power system are not able to restart after such an event. Energy storage systems can be used to provide energy to help other units restart and provide a reference frequency for synchronization of other generation units.

2.2 Peak Shaving

The distribution and transmission lines as well as generation capacity are dimensioned according to the peak power demand. This holds for the total capacities within a country or Europe but also for the local distribution grid for its respective loads. The cost for the overall power system but also the grid connection for the individual costumer is driven by the peak

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[4] In contrast primary frequency control is not provided by spinning reserve but rather the rotating masses of the active power plants. It is activated without operator interaction.

load. By the means of energy storage systems it is possible to reduce peaks in power demand and therefore reduce costs for seldom used generation and transmission capacities.

2.3 Load leveling

Load leveling reduces fluctuations in energy demand during one day. During times with low demand, energy is stored and during times with high demand, energy is fed back into the grid. The traditional operation of pumped hydro storage systems is the day to night shifting of energy demand which was necessary due to the constant power output of conventional power plants like nuclear and lignite. In power systems with high shares of renewables, the predictable pattern of shifting excess power from night hours to peak load times during the day will gradually disappear. However, load shifting for several hours will remain a typical application of storage systems. In regions with high fractions of PV-power a daily cycle of load leveling from peak production during the middle of the day to all other times of the day is expected to develop.

2.4 Long-term storage (weekly to monthly)

Long-term storage systems can deliver full power for typically up to three weeks. This kind of storage can be used to overcome the so called “dark calm[5]” periods, which are considered to be the most challenging weather condition for a power system with high shares of renewables in Central Europe: prolonged high pressure weather systems (reducing wind generation to a minimum) in winter time (high power demand, low solar generation) and in the worst case with widespread fog and/or snow cover (hindering solar generation). These weather situations typically do not last longer than three weeks.

2.5 Seasonal Storage

In a 100 % renewable scenario seasonal storage can compensate seasonal fluctuations in renewable power supply. In systems with only PV for example, excess energy can be stored in summer and supplied to the grid in winter. Seasonal storage of electricity is relatively costly, because the storage volume is only used one time per year. Seasonal storage will therefore become competitive only for few energy systems with very high fractions of certain types of renewable energy. Studies about future electricity supply show that for Central Europe the most economical solution is an over installation of generation capacity combined with long-term storage systems for up to three weeks.

2.6 Island Grids

In remote areas or on islands, the connection to an integrated power network is in many cases either not economical or technically impossible. Conventional island grids are therefore run with diesel generators, which cause high costs and emissions due to fuel consumption. Besides that frequent ramp ups and/or power variations result in distinctively

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[5] Dark calm refers to periods with low PV production (dark) and low wind power production (calm). In German the wording “Dunkle Flaute” is used.

higher fuel consumption and specific emissions as well as a higher wear compared to continuous operation. In such cases, energy storage systems can reduce the overall system costs, by smoothing load peaks allowing for operating the diesel generator with smaller power gradients and/or fewer power cycles.

In order to reduce fuel costs island grids are often supplemented with renewable power generators. However, the fluctuations cause additional costs due to flexible operation of the diesel backup. In this case, storage systems can adapt the strongly varying energy supply of wind and sun to the demand. These storage systems also cover the frequency regulation.

2.7 Other Sectors

Electromobility

The electrification of the transport sector is one main driver for the development of advanced energy storage technologies such as lithium-ion batteries. This mass market could also reduce battery prices significantly in the future due to economy-of-scale effects. Furthermore, the controlled charging or even discharging of electric vehicles offers a huge potential for supplying ancillary services in the seconds to hours timeframe. However, electric vehicles are not cost effective for balancing, for example, seasonal fluctuations of renewable energy supply.

Heat storage

High temperature heat storage can be used to increase flexibility of thermal power plants. Most prominently they are considered as flexibility option for solar power plants in order to be able to feed power into the grid also during times without sunshine. A section of this report describes this kind of heat storage.

Low temperature heat storage systems for end-use of thermal energy are widely used and have a great potential to provide flexibility to the power system. However, due to its limited scope, this report focuses only on storage technologies able to re-convert the stored energy into electricity. For this reason, low temperature heat storage technologies, are not described in detail in the next chapter, but only summarily sketched here.

Domestic heat storages can be fed by heat pump systems or direct electrical heaters, possibly supported by solar thermal systems. If these heating systems and the power system are equipped and designed accordingly, the electricity consumption of the heat generating unit can to some extent be shifted in time according to the flexibility requirements of the power system, while the heat storage guarantees the delivery of the heat service required by the end-user. Due to the limited size of domestic heat storages and to comfort requirements of the end-user, balancing services can only offered for relatively short periods, i.e minutes to hours for primary and secondary control and possibly several hours. Somewhat larger thermal masses, meaning larger energy capacity and therefore longer balancing times, are expected from heat pumps for domestic heating, which uses the thermal mass of the entire building. A great advantage of domestic heat storages is that they can contribute to balancing at the lowest voltage level, and thus can be used to integrate distributed renewable generation like PV.

Large-scale low-temperature heat storages are used in connection to district heating systems and heat consuming industrial processes. If part of the heat is produced electrically, for instance by heat pumps, also these heat storage facilities can be used to balance the power system.

Finally, seasonal heat storage is being developed, with some successful demonstration projects. One target application is to store solar thermal heat production during the summer and use it during the winter, both in individual buildings and in district heating system.

Residential energy storage for increased self-consumption of distributed electricity generation

Residential energy storage systems are able to increase the local self-consumption of electricity generated by distributed renewable generation; most of which are PV systems. During times when PV generation exceeds consumption the energy storage system is charged and during times when the consumption exceeds the PV generation the energy storage system is discharged. The general goal of increased self-consumption is to limit the effects of PV feed-in on the distribution grid. However, this is only achieved if the storage systems are configured and operated in a grid friendly way. For example a small battery may already be fully charged before noon and is therefore not available to limit the PV-production peak around noon, i.e. no relief of the local distribution grid is achieved.

So residential storage systems have the potential to reduce or defer investment in distribution grid structures, however, operation for maximal self-consumption does not automatically result in grid friendly operation. Residential storage systems also offer a big potential of delivering other grid services like frequency control which is not yet implemented in today’s systems.

Industrial energy storage

Storage systems for electrical energy can also be economical in industrial applications. The major drivers for this group of applications are protection against power drops (see section on UPS below), power quality (for example frequency stabilization for highly synchronous industrial drives), but also electricity cost reduction. In general multiple purposes can be served by one storage system, for example peak shaving and load shifting. Industrial consumers are usually billed independently for the peak power consumption in a year as well as the total energy. Depending on the load profile the peak-related costs can be significant. Storage systems can be used to reduce these costs.

Uninterruptible Power Supply (UPS)

UPS systems are always used when interruptions in power supply caused by e.g. faults in the electricity grid have to be mitigated. Examples for that are hospitals, IT centers or communication system stations. A UPS system can consist of a battery in combination with a generation unit like a diesel or gas generator or solely of a battery depending on the time which has to be bridged. Very large battery capacities are installed in the communication industry in Germany for example. These capacities could also be used for grid services in the seconds to hours range when appropriate control systems would be installed.

3. Terminology

3.1 Parameters

Energy *E* is the core entity of a power system. The very purpose of power systems is the generation (conversion), transmission, distribution, consumption (conversion again) of (electrical) energy. In general energy can be viewed as the capability to do work. Energy can take several forms during conversion such as thermal, mechanical, electrical and chemical. With respect to storage systems the term energy occurs as the capacity of a storage system as well as the amount of energy charged into a storage system or discharged from a storage system.

The unit of energy can be **Ws** (Watt second), **Nm** (Newton meter) or **J** (Joule). 1 Ws = 1 Nm = 1 J. 3600 Ws = 1 Wh.

Example	Energy E in kWh
gross demand for electrical energy in Germany (2010)	600,000,000,000
three-person household per year	4000
starter battery (lead-acid)	1
boil one liter water	0.1

Table 1: Comparison of typical energy values

Power *P* as physical value describes the rate of energy transfer per unit of time which can be supplied or consumed by a system. With respect to storage systems a high power storage system is capable to release (or store) its contained energy quickly. Low power storage systems take a longer time to charge and discharge. However, they are rather called high energy storage systems than low power systems, because they have a high energy/power ratio. The unit of power is Watt (**W)**. Table 2 lists different examples of power systems of different orders of magnitude.

Example	Power *P* in kW
average load in Germany (2010)	68,000,000
high speed train	16,000
automobile	100
average power consumption of three-person household	0.5

Table 2: Comparison of typical power values

Energy to Power Ratio (E2P) describes the ratio of installed capacity (energy) and installed power. Storage systems with a high E2P can deliver power for a longer time than storage systems with a small E2P. Longtime storage systems therefore have a high E2P; short time storage systems have a small E2P.

Energy Density *e* is the ratio of energy available from a storage system to its volume. The unit is e.g. **kWh/liter** or **kWh/m³**. Systems with lower energy density for example need more space for installation. High energy density is for example important in mobile applications as the volume for the energy storage system is limited. Table 3 shows examples for different storage technologies.

	Technology	Energy Density e in kWh/ m^3
Mechanical Energy Storage	potential energy (e.g. pumped hydro with 360 m height difference) (electrical energy)	1
	kinetic energy (e.g. flywheels) (electrical energy)	10
Electrical Energy Storage[6]	Electrostatic fields (Capacitors) (electrical energy)	10
	Electromagnetic fields (Coils) (electrical energy)	10
Electrochemical storage systems	Lead-acid battery (electrical energy)	100
	Lithium-ion battery (electrical energy)	500
Thermal Energy Storage	Sensible heat (e.g. Water $\Delta T = 100$ K) (thermal energy)	116
	Phase changes (e.g. water to steam) (thermal energy)	636
Chemical Energy Storage	Liquid hydrogen (thermal energy)	2.400
	Gasoline (thermal energy)	8.500

Table 3: Comparison of typical energy density values. Energy density is defined here by the usable energy after the conversion process.

Power Density *p* is the ratio of power available from a storage system to its volume. The unit is **W/liter** or **W/m³**. For high-power applications with short duration of power usage like in hybrid electric vehicles e.g. for acceleration purposes, a high power density is important to achieve low weight and volume of the storage system.

Specific Energy describes the ratio of energy delivered by the storage system to its weight. The unit is e.g. **kWh/kg**. High specific energy is important for applications with weight limitations and high energy demand (e.g. electric vehicles).

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[6] The terms *Electrical Energy Storage* and *Electricity Storage* are commonly used synonymously. For clarity in this report the term *Electrical Energy Storage* is used for the class of storage systems which store electrical energy directly in electrical fields. In contrast *Electricity Storage* is used for all forms of energy storage which are charged with electricity and generate electricity when they are discharged.

Specific Power describes the ratio of power delivered by the storage system to its weight. The unit is **W/kg**. A high specific power is important for applications with weight limitations and high power demand (e.g. hybrid electric vehicles).

The **Storage Capacity *C*** of an energy storage system is the amount of energy which can be stored by the system. The unit of the storage capacity is the same as for energy **kWh.**

Depth of Discharge (DOD) is the amount of discharged energy compared to the total storage capacity. The maximum amount of energy that can be discharged is 100 % DOD corresponding to a fully discharged system. It is important to mention in each case if 100% DOD correspond to the gross storage capacity or to the amount of usable storage capacity. Several storage technologies do not allow for technical reasons a full discharge of the storage system.

State of Charge (SOC) is the amount of energy still remaining in the system as a percentage of usable storage capacity. The maximum SOC is 100 % corresponding to a fully charged system. The SOC after discharging the usable storage capacity is 0%.

Efficiency η is the ratio of the output energy to the input energy. A high efficiency of the systems means low losses and therefore also low costs for the compensation of these losses. A high efficiency is important for systems with high cycle loads. Furthermore low efficiencies cause in several storage systems significant problems due to the generated heat.

Self-Discharge is the loss of energy content of a storage system due to internal processes. In pumped hydro storage plants self-discharge occurs due to evaporation and seepage.

Start-up time is the time period from a power request until the first power delivery.

Ramp-up time is the time from zero power to full power.

Ramp rate is the maximum power divided by the ramp-up time.

Deployment time or response time is the time to reach the full power of a system since it was requested. It is the sum from **Start-up** and **Ramp-up** time. The parameters are illustrated in Figure 2 below.

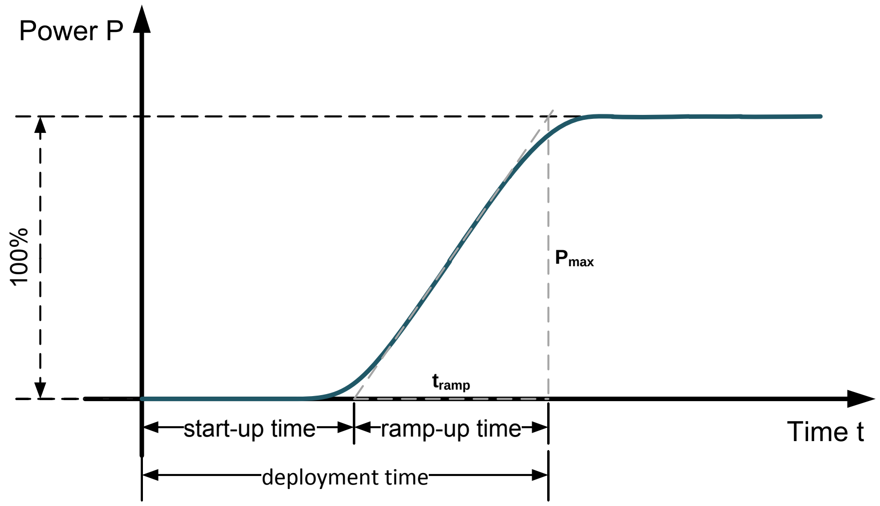

Figure 2: Response of a storage system

The deployment time for battery storage systems for example is in the range of milliseconds whereas the deployment time of gas power plants is in the range of 10 minutes.

Full Cycle is the complete discharging and charging process of a storage system. In the case of pumped hydro, this means a complete emptying and refilling of the upper reservoir between the predefined min and the max water levels (available capacity).

Equivalent Full Cycle is defined by the overall energy throughput (counting either only charge or only discharge direction) with any DOD per cycle divided by the available capacity.

Cycle Life is the number of full cycles which can be delivered by a storage system under specified conditions before it fails to meet specified criteria.

Calendar Life is the lifetime of a storage system when it is not used. A pumped hydro system for example also has a limited lifetime when it is not active. For example the lifetime of the dam is limited due to decomposition processes even if the plant is not operated.

3.2 Classification

Storage systems are in general able to supply positive and / or negative control power to the grid in different time scales. Positive power is equal to an increase in supply (e.g. discharging a battery). Negative control power is equal to an increase in demand (e.g. charging a battery). For that purpose a variety of different technologies can be used. Generally, supplying control power always causes costs and losses. Depending on the choice of technology the extent of costs and losses is different. Therefore, it is crucial to analyze the different options for storing energy in detail and to select appropriate technologies with regard to the demand. Storage systems in this report also include technologies beyond the classical storage systems, which take up electrical energy and supply electrical energy.

For the comparison of storage technologies from an economic and technical point of view it is important to define the application of storage technologies appropriately. Different classifications are necessary to specify the storage system application. Three different classifications with three classes each can be defined as shown in Table 4.

Class A differentiates the setup of the storage systems and the main objective for its installation. The three different types are:

A1 Modular storage systems with double use

A2 Modular storage for grid use only

A3 Centralized storage systems

“Modular storage” (for example batteries): describes systems, which are built up by relatively small basic units like battery modules. To form larger systems, these small basic units can be connected together. By increasing the storage system size neither the efficiency nor the specific costs are reduced significantly. Modular storage systems do not require special locations for installation.

“Modular storage systems with double use” are systems, which are built as described above, but their main purpose is not the supply of control power. The primary purpose can, for example, be mobility in the case of electric vehicles or increased self-consumption in the case of residential storage systems. Of course, this primary purpose has to be served first and their limited availability for control power has to be considered. The advantage of this class of storage systems is that they are financed already by their main application. They can therefore supply control power in addition to their main application and they must not refinance themselves from grid services only.

A. Type and location of storage system	A1 Modular storage systems with double use
	A2 Modular storage for grid use only
	A3 Centralized storage systems
B. Duration and frequency of power supply	B1 “seconds to minutes“ – short-term energy storage systems
	B2 “daily storage“ – medium-term energy storage systems
	B3 “weekly to monthly storage“ – long-term energy storage systems
C. Input and output type of energy to and from the storage system	C1 “Electricity to Electricity“ – positive and negative control energy
	C2 “Anything to electricity“ – positive control energy
	C3 “Electricity to anything“ – negative control energy

Table 4: Classification of storage technologies

“Centralized storage systems” (for example pumped hydro storage, compressed air, hydrogen storage) have to be located at specific sites. These sites have to fulfill requirements concerning e.g. geology. Furthermore, the system efficiency increases and the specific costs decrease with bigger installations. Typical systems have a power rating of 100 MW and more.

Class B refers to duration and frequency of power supply. It has the following sub-classes:

B1 “seconds to minutes“ – short-term energy storage systems

B2 “daily storage“ – medium-term energy storage systems

B3 “weekly to monthly storage“ – long-term energy storage systems

“Short-term energy storage systems” have to supply energy immediately after activation. Full power is already reached after a few seconds and the maximum duration of power delivery is about a quarter of an hour. Typical applications are the supply of primary and secondary frequency control and reactive power compensation. These energy storage systems have an energy to power ratio (installed capacity in kWh divided by the peak power in kW – E2P) of less than 0.25 hours. The charging and discharging rates are high and, depending on the application, they must deliver a huge number of charging/discharging cycles per day.

“Medium-term energy storage systems” have an E2P ratio of 1 to 10 hours. Therefore, the specific load on the storage systems is less than in class B1. The number of cycles per day hardly exceeds two full cycles. Classical applications are pumped hydro storage plants, which are already widespread and have been used for matching the day/night fluctuations of demand with inflexible nuclear and lignite power plants. With higher shares of renewables this night to day shifting becomes less important. Today and in the future these storage systems can be used for leveling errors between forecast of renewable generation and reality. They are not able to supply power during several days or weeks of low renewable generation.

For this purpose “long-term energy storage systems” have to be used, which have an E2P ratio of 50 to 500 hours. With that they are able to supply power for several days or weeks. Due to the high energy capacity and the relatively low power the number of full cycles per year is limited. This kind of storage can be used to overcome the “dark calm” periods, which are considered to be the most challenging weather constellation for a power system with high shares of renewables in Central Europe: prolonged high pressure weather systems (reducing wind generation to a minimum) in winter time (high power demand, low solar generation) and in the worst case with widespread fog and/or snow cover (hindering solar generation). Typically, such weather systems do not last longer than 3 weeks.

Due to the limited cycle numbers, very cheap storage media like salt caverns for hydrogen are required to achieve an economic operation. Due to the long storage time the self-discharge should be low.

Finally, the “Input and output type of energy to and from the storage system” can be categorized as follows:

C1 “Electricity to Electricity“ – positive and negative control energy

C2 “Anything to electricity“ – positive control energy

C3 “Electricity to anything“ – negative control energy

“Electricity to Electricity” systems can supply positive and negative control power by discharging and charging the system. These systems are typically called “storage systems”. This class contains for example battery storage systems and pumped hydro storage plants. However, positive or negative control power can also be served by other technologies, which are not the focus of this report (see section 0 for a discussion).

“Anything to electricity” technologies support the grid with positive control energy either by shutting down electrical loads (equivalent to an increase in power generation), or by supplying additional power to the grid from energy reserves stored otherwise. The latter category includes all conventional power plants which can supply positive control energy for different periods of time from fossil, nuclear, hydro or biomass fuels. Controlled shut down of loads can be supplied e.g. by demand side management strategies or by controlling the charging of electric vehicles.

“Electricity to anything” technologies use electrical energy and convert it into another type of energy that can be used at a later point of time. This can be the generation of heat from electricity or the generation of chemical fuels from electricity such as hydrogen or methane. The curtailment of a renewable power generator can also be considered as a functional equivalent of this class, with the difference that the energy is lost.

A combination of an “anything to electricity” and an “electricity to anything” storage technology can serve the same services to the grid as an “electricity to electricity” storage system.

The classification of storage applications is summarized in Table 5.

Energy to power ratio (E2P)[7]	"seconds to minutes" storage systems < 0,25 h	"daily" storage systems 1 – 10 h	"weekly to monthly" storage systems 50 – 500 h[8]
Applications:	- Primary/Secondary frequency control - Spinning reserve - Voltage control - Black start capability - Peak shaving - Island grids (with e.g. diesel generator) - Electromobility (Hybrid Electric Vehicle) - Uninterruptible power supply	- Tertiary frequency control - Standing reserve - Load leveling - Island grids - Electromobility (Full Electric Vehicle) - Residential storage systems - Uninterruptible power supply	- Storage for “Dark calm” periods - Island grids

Table 5: Classification of storage applications

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[7] The E2P ratios are typical values for the different storage classes; slightly other values can also occur in practice.

[8] Studies about the storage demand in future power grids show that long-term storage systems typically do not exceed E2P ratios of 500 h (3 weeks). Seasonal storage systems have E2P ratios above 500 h.

4. Technologies

Figure 3 shows a classification of different energy storage technologies categorized by their work principle and typical time scale of application. The time scale indicates the typical energy to power ratio of the technologies and corresponds to the typical time of charging and discharging. A short overview on the main characteristics and features of the different storage technologies is given in the following sections. Please note that the technical data for the different storage technologies is based on experience and is taken from several other studies or sources. The data is chosen by the authors by their best knowledge by analyzing the often quite diverging sources. Therefore, no literature sources are given for the data. The data is presented on a basis which allows the comparison of different technologies. Please note in addition, that in most cases products might be also available, which go beyond the given numbers for e.g. energy densities or lifetimes. However, we tried to present data in one table which are consistent. Higher performance might be available but this typically also results e.g. in higher costs. Costs are also varying with the size of the installation. The values given are for typical system sizes as they seem to fit for the markets today. Smaller or larger systems bear higher or lower costs.

In total, the given data should be used for comparing the various technologies rather than for final life cycle cost calculation. This requires a detailed analysis of the application and the technologies and should be done in an interactive consultancy process.

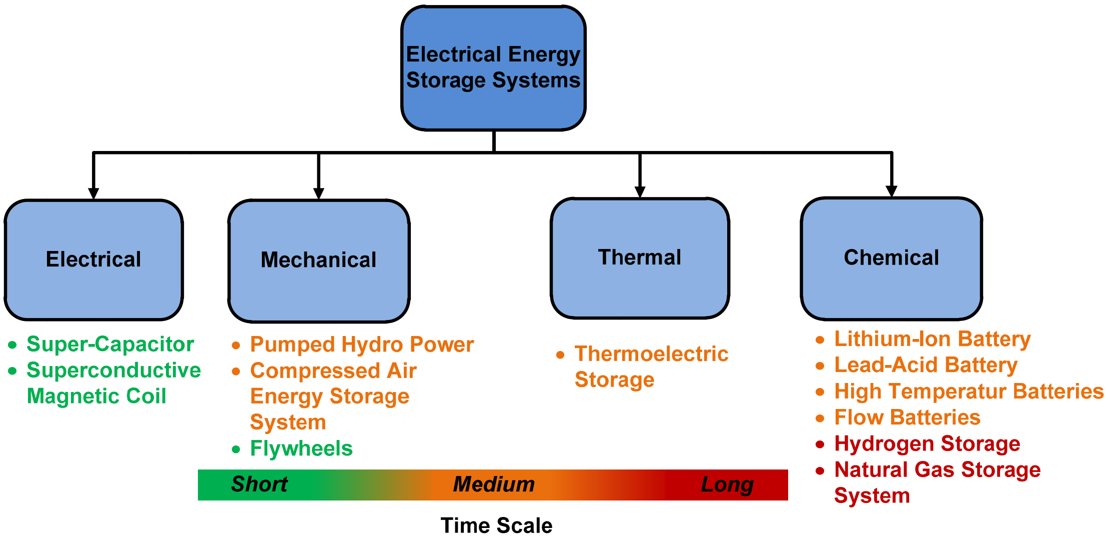

Figure 3: Energy storage technologies classification with examples for each type

4.1 Mechanical energy storage systems

4.1.1 Pumped Hydro

A pumped hydro energy storage system consists of two interconnected water reservoirs located at different heights such as a mountain lake and a valley lake. Penstocks connect the upper to the lower reservoir. An electrically-powered pump pumps up water from the lower to the upper reservoir during the charging process and a turbine is powered by falling water during the discharging process. The amount of stored energy is proportional to the product of the total mass of water and the altitude difference between the reservoirs.

Pumped hydro energy storage is the major storage technology worldwide with more than 127 GW installed power and has been used since the early 20th century. They are used as medium-term storage systems, i.e. typically 2 to 8 hours E2P-ratio. Technically no major improvements can be achieved as this technology is composed of well-known components and has matured over several decades. Slight improvements in efficiency and costs can be achieved with advanced turbine and generator designs.

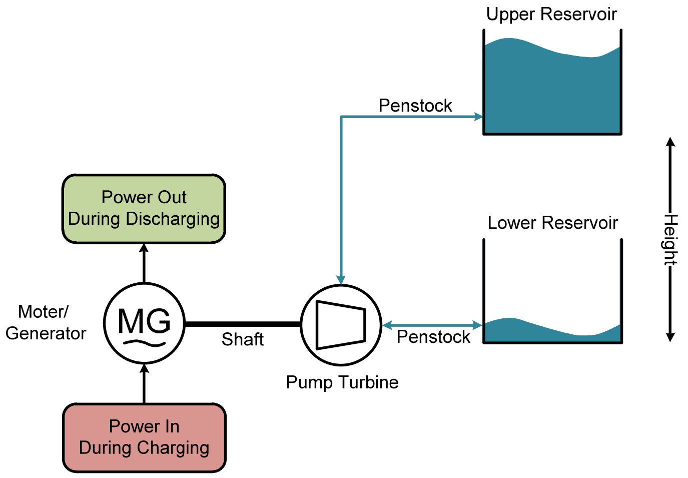

Figure 4: Schematic diagram of pumped hydro storage system

The deployment potential for new pumped hydro storage systems is limited in central Europe. There are only a few new sites under construction or in the planning phase. The biggest potential for growth of storage capacity in Europe is the refitting of hydro storage plants with pump sets. Hydro storage plants are hydro power plants at seasonal water reservoirs, which so far have no pumping option and in general no lower reservoir. Typically their Energy-to-Power-ratio (E2P) is large enough to provide power for several weeks or months. Their design goal was to collect water during the wet seasons and produce hydro power continuously throughout the year.

In order to enable these plants for energy storage they need to be equipped with pump sets. However, the biggest challenge is to find suitable spaces for lower reservoirs. Rivers cannot be used easily as dams have to be erected and the change in water level has an ecological impact. Nonetheless, hydro storage plants can serve as sources of flexibility even without pumping option if they can be equipped with larger turbines and are operated more dynamically to compensate renewable energy fluctuations. Also this option has some ecological impacts due to fluctuating flow rates downstream of the power plant.

Due to the proximity to the Northern Sea one very favorable option for the balancing of Northern Europe’s wind power is the use of the Scandinavian water storage systems. The documented storage capacity of Norwegian reservoirs alone is 84 TWh – approximately 2.000 times the storage capacity of all German pumped hydro power plants. However, as mentioned above ecological restrictions apply. Besides that the transmission capacity would have to be increased significantly.

Besides the technical and ecological challenges in the case of Scandinavia another aspect has to be considered. Due to a low-cost power generation from almost 100% hydro power

Norway has relatively low electricity prices compared with other European countries. Therefore, a strong energy intensive metallurgical industry has been established and electricity usage in the private sector e.g. for space heating is very common. The utilization of storage capacities in Norway as flexibility source for Central European renewable energy would imply according to today's energy market designs an integration of the Norwegian electricity market into the European electricity market. While the Norwegian power supply industry would strongly benefit from the additional markets, this would increase the electricity prices in Norway, conflicting with the interests of existing industries and private end-users.

Parameters for Pumped Hydro Power[9]	All numbers are indications and my vary significantly among different products and installations	
	Today	**2030**[10]
Round-trip efficiency	75 % to 82 % (for new systems, existing older systems often have lower efficiency)	
Energy density	0.27 Wh/ l (head 100 m) to 1.5 Wh/ l (head 550m) (taking into account only the upper water basin)	
Power density	n. a.	
Cycle life	n. a.	
Calendar Life	80 years	
Depth of discharge	80 to100 % (between predefined min and max water levels, natural lakes will have relative high min levels to assure the functioning of the eco system)	
Self-discharge	0.005 %/ day to 0.02 %/ day[11]	
Power installation cost	500 €/ kW to 1,000 €/ kW (higher costs due to difficult geological conditions have been reported)	
Energy installation cost	5 €/ kWh to 20 €/ kWh	
Deployment time	about 3 min.[12]	
Site requirements	Two reservoirs located at different heights. Significant height difference.	
Main applications	Frequency control (secondary reserve, minute reserve), Voltage control, Peak shaving, Load leveling, Standing reserve, Black start	

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[9] Typical values are given. These may vary in reality.

[10] Established technology, no significant cost-reduction potential

[11] Assumed data from an operator of several hydro power plants

[12] From maximum negative to maximum positive power output

A detailed analysis of the potential is beyond the scope of this work. Hohmeyer et.al. estimate a Scandinavian storage potential of several tens of TWh and several tens of GW.[13]

Pumped Hydro Power

	Strengths	Weaknesses
Internal	• Established technology • Very long life-time • Low self-discharge • Good efficiency	• Low energy density • Geographical restriction • High investment costs • Long return of investment (> 30 years) • Only large units connected to the transmission grid are economical
	Opportunities	**Threats**
External	• Very large additional potential in Norway and Sweden, some smaller potential elsewhere • Storage costs are very competitive compared with other storage technologies	• Lengthy approval processes • High environmental standards • Increasing competition from decentralized storage systems • Flexible use of hydropower represents even more competition • High power requires connection to the transmission grid and therefore cannot solve problems in the distribution grid • Pumped Hydro in Norway: Public and political acceptance critical due to the impact of trading on electricity prices.

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[13] Olav Hohmeyer, LichtBlick AG: 2050. Die Zukunft der Energie., Flensburg 2010

4.1.2 Compressed Air Energy Storage (CAES) Systems

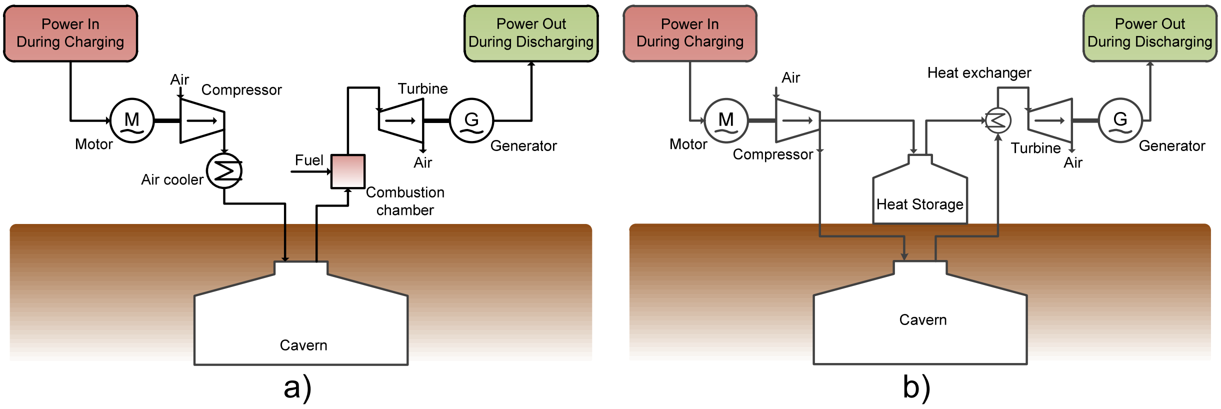

Figure 5: Schematic diagram of a) diabatic and b) adiabatic compressed air energy storage

During the charging process air gets compressed by a compressor which is driven by a motor. During the compression process the air heats up; the heat is removed by a radiator. The energy is stored as compressed air in a cavern. While discharging the air is expanded and therefore cools down. It has to be heated up by burning conventional fuel or biofuel and then drives a turbine/generator unit, which feeds power into the grid.

In an adiabatic CAES system the heat generated during the compression process is stored. During the discharging process the stored heat is used to heat up the air while expanding. By this the efficiency of the overall process can be increased by around 20% and the operation is then completely CO_2-free as no fuel is used.

CAES systems are used as medium-term energy storage and can be seen as an alternative to pumped hydro storage systems. Today there are only two CAES plants in operation worldwide. One plant is located in McIntosch, US (110 MW) and one in Huntorf, Germany (320 MW). The Huntorf plant is successfully operated by E.ON since 1978. These plants operate without heat storage and therefore use natural gas as heat source for the discharging process.

Currently, there are no adiabatic CAES of scale in operation. The main components for adiabatic CAES are already available. However, the necessary heat storage systems are currently still under development. The most promising solution seems to be solid state heat storage systems above ground. A possible alternative known from solar thermal power plant developments are molten salt storage systems. However, both technologies are not yet technically mature and/or commercially available. Therefore so far only systems on an experimental level exist which do not allow a realistic cost estimate.

CAES systems need certain geological requirements (e.g. salt caverns) for their installation which are limited worldwide. Potential locations in Europe are located in the Netherlands, northern Germany and the UK.

Parameters for Adiabatic Compressed Air Energy Storage[14]	All numbers are indications and my vary significantly among different products and installations	
	Today	2030
Round-trip efficiency	60 % to 70 %	
Energy density	3 Wh/ l (at 100 bar) to 6 Wh/ l (at 200bar)	
Power density	n. a.	
Cycle life	Not limiting	
Calendar Life	Ca. 25 years	
Depth of discharge	35 % to 50%	
Self-discharge incl. thermal storage	0.5 %/ day to 1 %/ day	
Power installation cost	1000 €/ kW	700 €/ kW
Energy installation cost incl. thermal storage	40 €/ kWh to 80 €/ kWh	
Deployment time	about 3 min. to 10 min.	
Site requirements	Possibility to build a cavern, e.g. salt cavern	
Main applications	Frequency control, Voltage control, Peak shaving, Load leveling, Standing reserve, Black start	

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[14] Please note that no adiabatic compressed air storage system has been build or operated until today (2012). Therefore all numbers are based on simulations and assumptions. However, despite the costs, it is very likely that the technical parameters can be achieved.

	Compressed Air Energy Storage System	
Internal	**Strengths**	**Weaknesses**
	• Relatively low cost for the energy storage (caverns) • Small footprint on surface due to underground storage • Long life of the air reservoir (cavern) and the power systems (compressors, turbine) • Low self-discharge of compressed air	• Certain geological restrictions necessary (pressure-tight cavern) • High investment costs • Only two (and old) diabatic pilot plants, no adiabatic power plants available yet • Thermal storage for adiabatic CAES not yet demonstrated in full scale • High self-discharge of the thermal storage • Low efficiency for diabatic CAES (< 55%) • Long return of investment (> 30 years) • Only large units connected to the transmission grid are economical
External	**Opportunities**	**Threats**
	• Successful demonstration of the technology could help a short time-to-market • Good regional correlation between caverns and high wind areas in Germany	• Limited number of suitable sites for caverns • Competition in the use of caverns (e.g. gas or oil storage) • Increasing competition from decentralized storage systems • Limited number of locations outside Germany • High power requires connection to the transmission grid and therefore cannot solve problems in the distribution grid

4.1.3 Flywheel

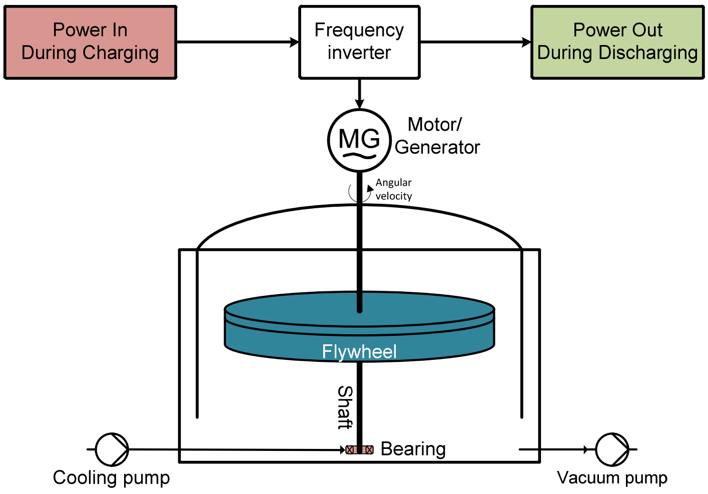

Figure 6: Schematic diagram of flywheel energy storage system

During the charging process a motor is used to accelerate a big rotating mass (flywheel). The energy is stored as the rotational kinetic energy of the flywheel. The disc has to remain spinning until energy is requested. By using vacuum and magnetic bearings the rotation resistance is kept as small as possible. During discharging the kinetic energy is extracted by a generator driven by the inertia of the flywheel resulting in a deceleration of the rotating mass.

Flywheels have very high cycle life and power density, however only an average energy density and a very high self-discharge rate (see table below). Therefore, flywheels perform well for applications, which demand very high power for only a short time with a high number of charging-discharging cycles and only short storing periods (neither charging nor discharging). They are used, for example, for grid stabilization purposes for trams and underground trains. They absorb energy during the regenerative braking phases and feed power back during acceleration phases. They can also be used for stabilization purposes in weak grids. Due to their high self-discharge rate they are not able to supply applications with longer storage times.

The use of magnetic bearings and high vacuum chambers can reduce the self-discharge rate of the systems. However, these measures also increase the investment and operation costs, for example, due to necessary cooling of super conductive magnets for bearings. The main technical challenge therefore is to develop cost-effective components with low additional energy demand.

There are two major trends of ongoing research. The development of high-speed flywheels is interesting due to lower losses and higher specific energy. There are also initiatives to develop low cost – high mass flywheels with a higher energy capacity.

For the integration of renewable energy in Europe flywheels have no major application known to the author.

Parameters for Flywheels	All numbers are indications and my vary significantly among different products and installations	
	Today	2030
Round-trip efficiency	80 % - 95 %	No numbers available
Energy density	80 Wh/ l to 200 Wh/ l[15]	
Power density	10 kW/ l[16]	
Cycle life	several millions	
Calendar Life	15 years	
Depth of discharge	75 %	
Self-discharge	5 to 15%/hour	
Power installation cost	300 €/ kW	
Energy installation cost (high speed flywheel)	1,000 €/ kWh	
Deployment time	about 10 ms	
Site requirements	None	
Main applications	Primary frequency control, voltage control, Peak shaving, UPS	

	Flywheel	
	Strengths	**Weaknesses**
Internal	Fast charge capability Low maintenance requirements Long life time Better composite materials may allow higher rotational speed and therefore increased energy density	Low energy density Vacuum chamber needed Safety reasons; crack occur due to dynamic loads, bearing failure on the supports, external shocks Cooling system for superconducting bearings Very high self-discharge
	Opportunities	**Threats**
External	First commercial plant built as recently as 2011 for large scale grid storage Well established in UPS systems Already used for frequency control	Cheaper technologies available Promised increase in efficiency is not reached

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[15] Takes into account only the rotating body, which is only one part of the storage system. The complete storage system also includes the shafts, the motor/engine, the frequency converter, the housing, or the vacuum pump.

[16] See Footnote 15

4.2 Electrical Energy Storage Systems

4.2.1 Super-Capacitors

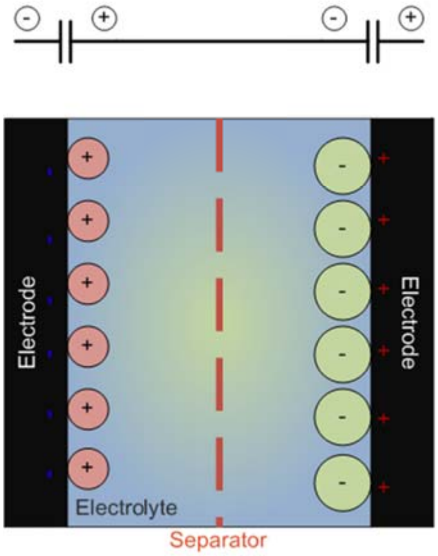

Figure 7: Schematic diagram of Super-Capacitor energy storage system

The electrical energy in a super-capacitor is stored in the static electric field between the electrodes and the ions in the electrolyte. During charging and discharging the ions move from one electrode to the other.

With respect to power density and energy density Super-Capacitors can be found between classical capacitors and batteries. Compared to batteries, they have a very high cycle life and power density but a much lower energy density. Therefore, they are used in short-term and high power storage systems. They are also used in hybrid storage systems with batteries in order to increase their lifetime. Furthermore, they for example used for stabilizing the voltage in on-board grids of cars and trains.

The main challenge in the development of super capacitors is their high costs, which, for example, could be decreased with the introduction of mass-production for the automobile industry (hybrid cars). Still, super-capacitors are going to remain a technology for the very special field of short-term storage in the range of up to 10 sec with very high cycle load.

A new technology in the class of super-capacitors is currently entering the market. This technology combines a carbon-based intercalation, electrolyte, and lithium salt for the negative electrode as used in lithium-ion batteries with a classical super-capacitor electrode as the positive electrode. This increases the energy density by a factor 2 to 3 while maintaining high power densities and cycle lifetimes as achieved.

Parameters for Super-Capacitors	All numbers are indications and my vary significantly among different products and installations	
	Today	2030
Round-trip efficiency	90 % to 94 %	No numbers available
Energy density	2 Wh/ l to 10 Wh/ l	
Power density	up to 15 kW/ l	
Cycle life	up to one million	
Calendar Life	15 years	
Depth of discharge	75 %	
Self-discharge	up to 25% in the first 48 hours, afterwards very low	
Power installation cost	10 €/ kW to 20 €/ kW	
Energy installation cost	10,000 €/ kWh to 20,000 €/ kWh	
Deployment time	< 10 ms	
Site requirements	None	
Main applications	Primary frequency control, voltage control, Peak shaving, UPS	

	Super-Capacitor	
	Strengths	**Weaknesses**
Internal	• High efficiency • High power capability • Long cycle lifetime	• Low energy density • High costs per installed energy
	Opportunities	**Threats**
External	• Applications with very high power demand and cycle load	• High power applications might be served by high power lithium-ion batteries

4.2.2 Superconductive Magnetic Energy Storage (SMES)

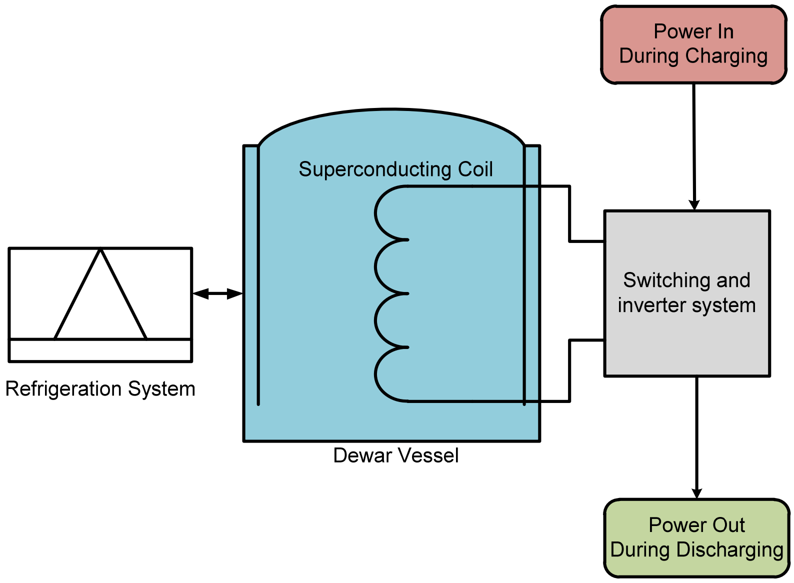

Figure 8: Schematic diagram of Superconductive Magnetic Energy Storage system

During the charging process the superconducting coil is fed with direct current from the inverter. The electric current induces a constant magnetic field in which the energy is stored. To be able to use the superconducting properties (no losses) of the coil, it has to be placed e.g. in liquid helium to guarantee temperatures below -260°C. The discharging process begins with connecting the coil to an external load by the switching system. The energy is then supplied by the magnetic field which drives a current. The magnetic energy and the current are decreased during discharging.

SMES systems are short-term storage systems for very short periods (power storage). They are only used in some demonstration and niche applications. They have very high standby losses due to the cooling demand. Currently, SMES systems with high-temperature superconductors are under research with the aim of reducing the cooling demand. Due to the limited application areas SMES systems will hardly become competitive with other technologies.

Parameters for Superconductive Magnetic Energy Storage[17]	All numbers are indications and my vary significantly among different products and installations	
	Today	**2030**
Round-trip efficiency	80 % to 90 %	Technology development of superconductors uncertain.
Energy density	0.5 Wh/ l to 10 Wh/ l	
Power density	1 kW/ l to 4 kW/ l	
Cycle life	Not limiting	
Calendar Life	20 years	
Depth of discharge	n. a.	
Self-discharge	10 %/ day to 15 %/ day	
Power installation cost	n.a.	
Energy installation cost	n.a.	
Deployment time	about 1 ms to 10 ms	
Site requirements	Refrigeration, switching and inverter system	
Main applications	Primary frequency control, voltage control, Peak shaving, UPS	

	Superconductive Magnetic Energy Storage	
	Strengths	**Weaknesses**
Internal	High power capability High cycle life	High cooling demand Expensive raw materials for superconductors Complicated inverter design and measurement circuits
	Opportunities	**Threats**
External	Innovative technology New superconductive materials	Security requirements due to very low temperatures and high magnetic fields Insufficiently validated technology

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[17] It is almost impossible to find well-approved data for this technology. Therefore the table is incomplete and the given data are only assumptions.

4.3 High Temperature Thermal Energy Storage Systems

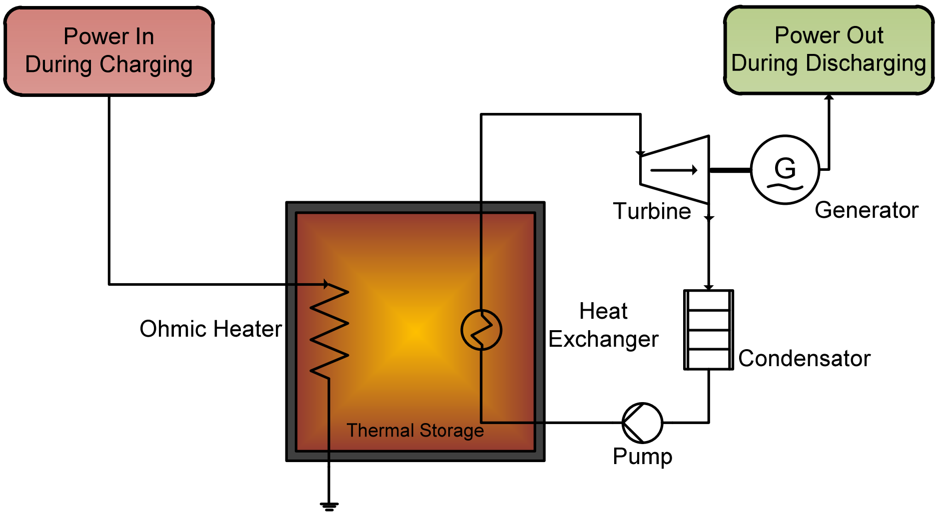

Figure 9: Schematic diagram of thermoelectric energy storage system

For storing electrical energy, also high temperature thermoelectric energy storage systems (TEES)[18] can be used. During the charging process high temperature heat at around 500°C is generated by an electrical heater. Alternatively, heat pumps can be used, which makes the systems more complex. The heat is stored in a thermal storage like magnesium oxide bricks or molten salt. In the discharging process the heat is extracted from the thermal storage and steam is generated which drives a turbine. The turbine feeds power into the electricity grid.

TEES systems are medium-term energy storage systems which operate in similar regions like pumped hydro and CAES systems. They are currently under research. As they are composed of more or less standard components, they could be market ready in 5 to 10 years. Only units in the MW-range can be cost-effective.

The main development effort has to be made in the field of cost-effective and adapted thermal storage systems and in the development of customized heat-pump processes. Furthermore, the thermo-economic optimization of TEES systems under different market conditions could be interesting.

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[18] Low temperature heat storage technologies are not described here, due to the limited scope of this report. See section 3.6. for a short discussion of their role.

Parameters for Thermoelectric Storage[19]	All numbers are indications and my vary significantly among different products and installations	
	Today	**2030**
Round-trip efficiency	Not available, as technology is in concept phase	
Energy density		
Power density		
Cycle life		
Calendar Life		
Depth of discharge		
Self-discharge		
Power installation cost		
Energy installation cost		
Deployment time		
Site requirements		
Main applications	Frequency control, Voltage control, Peak shaving, Load leveling, Standing reserve, Black start (expected)	

	Thermoelectric Storage System	
	Strengths	**Weaknesses**
Internal	• Option for large-scale storage • Energy density in the range of electrochemical batteries	• Thermal standby losses • Relatively low efficiency
	Opportunities	**Threats**
External	• No special site requirements • Many standard components from conventional power plant technology • Problems to find suitable sites for CAES and pumped hydro (alternative technology)	• No demonstration plant existing • Only large plants economically feasible

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[19] A few systems are being operated in CSP-plants in Spain, however representative data are not publically available.

4.4 Chemical Storage Systems

Chemical storage systems can be classified as illustrated in Figure 10 below:

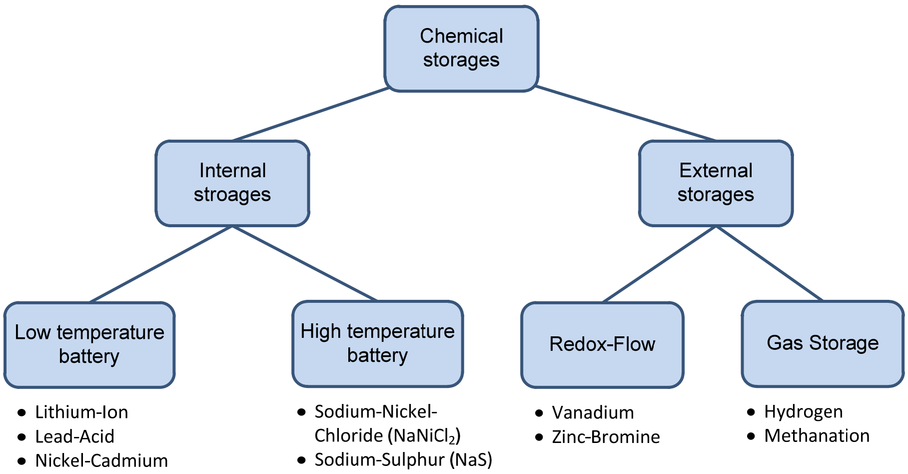

Figure 10: Classification of chemical storage systems (named technologies are only examples)

There are chemical storage systems with internal and external storages. Storage systems with external storage have the advantage that energy content and power capability can be designed separately. Important examples are hydrogen and methane storage as well as redox-flow batteries.

In systems with internal storage, energy content and power capability depend on each other: Higher energy content also means higher power capability. A distinction is made in low- and high-temperature batteries. Low temperature batteries operate at around room temperature whereas high temperature batteries operate at around 300°C.

4.4.1 Chemical storage systems with external storage

4.4.1.1 Hydrogen Storage System

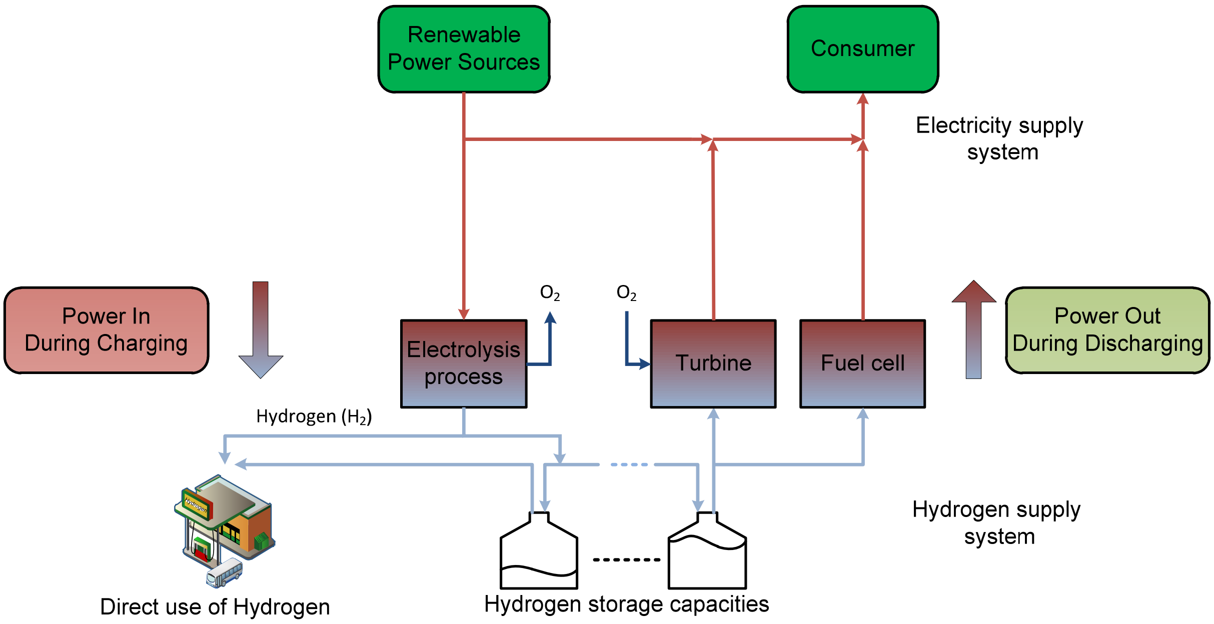

Figure 11: Schematic diagram of Hydrogen energy storage system

During the charging process hydrogen is produced by electricity through an electrolyzer. The produced hydrogen is compressed and stored e.g. in salt caverns or special tanks. During the discharging process hydrogen can be used to drive combustion turbines or fuel cells. Besides for power generation hydrogen can directly be used in hydrogen cars with fuel cells or special internal combustion engines or for heat generation.

Hydrogen energy storage systems are characterized by two extreme properties. Due to the high volumetric energy density of compressed hydrogen and the possibility to store large amounts of hydrogen in salt caverns, the specific costs of the storage itself are very low. However, the efficiency of the conversion chain is also very low, i.e. below 40% for one charge-discharge cycle. Besides that small and midsize hydrogen storage systems have significantly higher specific costs than salt caverns.

The major application in the context of renewable energy integration is large scale and long term energy storage (weekly, monthly, seasonal), where low cost for the storage capacity outweighs the inefficiency of conversion. Today there are no large scale hydrogen energy storage systems in operation because at the current level of renewable energy penetration conventional backup generation capacity or long distance transmission plus instant consumption are much cheaper. Hydrogen storage is expected to become more important for power systems with very high fractions of renewable energy e.g. 80-100%.

An alternative to hydrogen storage in caverns is the storage in the natural gas grid. According to current industry standard the permissible concentration of hydrogen is limited to a few percent today. Technically this level could be raised if the downstream processes are adjusted (e.g. cars for compressed natural gas (CNG)). The maximum possible share of hydrogen in the gas grid and the necessary adjustments to the infrastructure are currently a matter of debate among experts. However, even if limited to a few percent of volume this storage option constitutes a very large energy reservoir.

Although hydrogen energy storage systems are not expected to be installed in large capacity soon, the relevant components are well-known and commercially available: Electrolyzers are used in the chemical industry in large scale. Ongoing development efforts focus on increased efficiency and higher load flexibility at low cost. Hydrogen turbines are not commercially available but according to a large manufacturer can be build any time the market is there. The use of fuel cells for large-scale applications is still very costly but has the potential to improve the AC-to-AC-efficiency to about 50%.

Parameters for Hydrogen Storage	All numbers are indications and my vary significantly among different products and installations	
	Today	**2030**
Round-trip efficiency	34 % to 40 %	40 % to 50 %
Energy density	3 Wh/l (at normal pressure), 750 Wh/l (at 250 bar), 2400 Wh/l (liquid)	
Power density	n. a.	
Cycle life	n. a.	
Calendar Life	n. a.	
Depth of discharge	40% to 60 %	
Self-discharge	0.03 %/ day to 0.003 %/ day	
Power installation cost	1,500 €/ kW to 2,000 €/ kW	500 €/ kW to 800 €/k W
Energy installation cost	0.3 €/ kWh to 0.6 €/ kWh (cavern)	
Deployment time	10 min.[20]	
Site requirements	Underground cavern, storage in tanks expensive	
Main applications	Seasonal storage, Island grid	

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[20] Only valid for high-temperature or alkaline electrolyzers. PEM-electrolyzers are even able to supply frequency control.

	Hydrogen Storage System	
	Strengths	**Weaknesses**
Internal	• Low footprint, because of underground storage • Sufficient experience with hydrogen storage in caverns • Very large amounts of energy can be stored • Water in unlimited quantities available	• High costs for electrolyzers • Low efficiency (less relevant for long-term storage) • Storage density is about one-third lower than for methane • Hydrogen turbines for the reconversion is not yet available
	Opportunities	**Threats**
External	• The only realistic option for long term storage of electricity • Progress in the field of high-pressure electrolyzers is expected • Synergies with the development of new power plant processes which use hydrogen-rich gas • Hydrogen can also be used in other energy sectors	• Competition from long-term storage of energy in Norwegian pumped storage power plants • Competition in the use of suitable caverns • Operating costs strongly depend on price of the purchasing power due to low efficiency

4.4.1.2 Power to Gas: Methanation / Synthectic Natural Gas

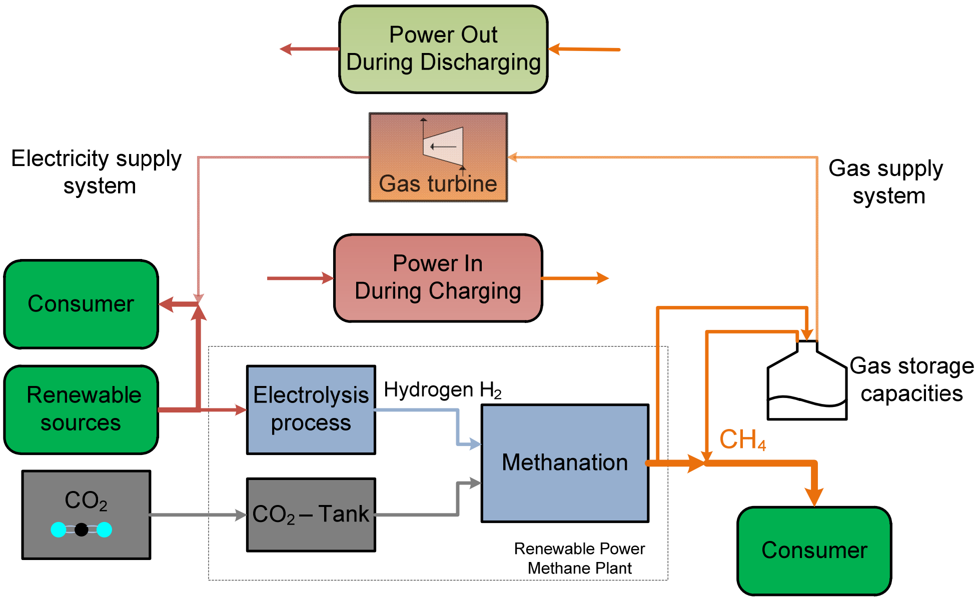

Figure 12: Schematic diagram of Power to Gas energy storage system

An alternative to the storage of hydrogen is the storage of synthetic natural gas. It can be produced from hydrogen and carbon dioxide by the so called “methanation”, an exothermic reaction also known as Fischer-Tropsch process. The end product, methane, is the main constituent of natural gas and therefore fully compatible with the existing infrastructure for natural gas. Therefore, it can be injected into the natural gas grid without restriction. The storage capacity of around 400 TWh (German gas grid) could then be used for medium- and long-term storage purposes.

The major advantage of methanation over direct use of hydrogen is exactly the full compatibility with the existing value chain of natural gas. The main drawback however, is the additional loss in efficiency and the added cost. Besides this, the process requires an external CO_2-source and produces waste heat. If this heat is not used for residential heating or industry processes the efficiency of the overall process is further decreased. As CO_2-source, conventional power plants or biogas plants can be used. However, periods of excess electricity for methanation and periods of CO_2-production from power plants do not coincide. This could result in burning carbon to generate energy and using electricity to generate methane at the same time. In other words, the carbon dioxide storage required creates additional cost.

Nevertheless, methanation provides the possibility to interconnect the electricity system with the heat and fuel market. Application schemes where electricity excess, CO_2-supply and heat demand coincide are being investigated. A first demonstration project of kW-scale has been built and operated in Germany and MW-scale demonstrations have been proposed.

Parameters for Power to Gas Storage	All numbers are indications and my vary significantly among different products and installations	
	Today	**2030**
Round-trip efficiency	30 % to 35 %	35 % to 40 %
Energy density	Approx. three times higher than hydrogen	
Power density	n. a.	
Cycle life	n. a.	
Calendar Life	n. a.	
Depth of discharge	40% to 60 %	
Self-discharge	0.03 %/ day to 0.003 %/ day	
Power installation cost	1,000 €/ kW to 2,000 €/ kW[21]	
Energy installation cost	No additional cost for storage in gas grid	
Deployment time	10 min.	
Site requirements	Underground cavern or gas grid access, external CO_2-source, heat demand	
Main applications	Seasonal storage, Island grid	

	Natural Gas Storage System	
	Strengths	**Weaknesses**
Internal	• Technology for long term storage of electricity • Compared to hydrogen storage in caverns cheaper kWh-related costs, as higher energy density • Additional buffer storage is the gas system (days)	• Basically, a technology that runs on hydrogen and thus still somewhat more expensive and less efficient than pure hydrogen storage systems • Low efficiency (<35% energy to electricity) • External source of CO_2 necessary or extraction from the air (further reduction in efficiency)
	Opportunities	**Threats**
External	• High storage capacity of the gas system can be used • Marketing effect of renewable natural gas • Alternative to biogas (land use by monocultures) • Use of methane not only for reconversion, but for other heat and power markets	• Direct incorporation of hydrogen into the gas grid can cause problems • Pumped storage projects for seasonal storage in Norway as competition • It makes sense only if all other means of networking and load management is exploited • Expected demand of technology on the market not before 2025

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[21] Target costs from Sterner, M. (2009): Bioenergy and renewable power methane in integrated 100% renewable energy systems. Limiting global warming by transforming energy systems. Kassel University, Dissertation

4.4.1.3 Flow Batteries

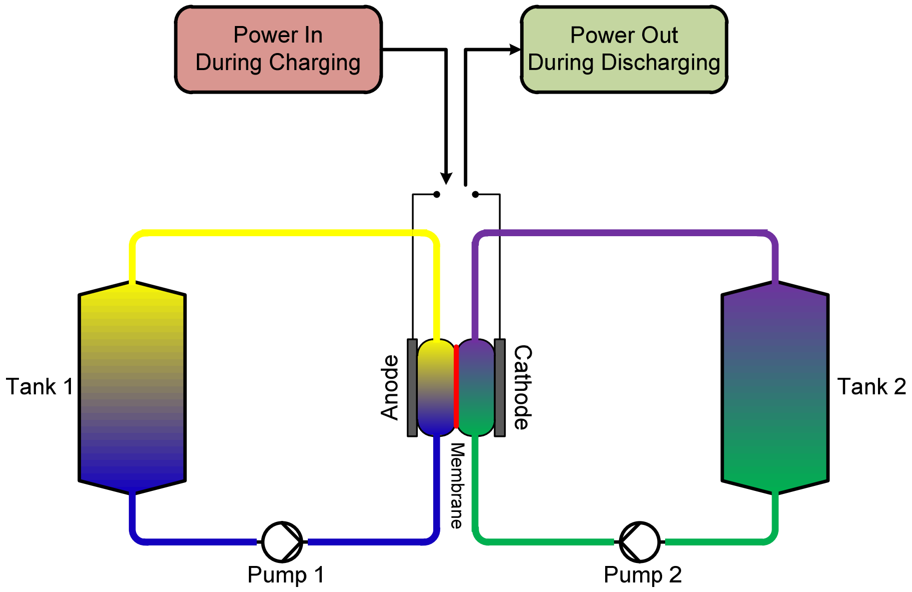

Figure 13: Design of a flow battery system

In flow batteries, the active material is made up of salt, which is dissolved in a fluid electrolyte. The electrolyte is stored in tanks. During charging and discharging the electrolyte is pumped through a central reaction unit where a current is applied or delivered. The size of the tank determines the energy capacity of the battery and the reaction unit (cell stack) determines the power of the battery.

Principally, this battery technology suits very well for a large- and medium-scale technical operation because the construction of bigger tanks can be done easily and effectively. It is a possible technology, which can bridge the gap between medium-term storage (1-10 hours) and long-term storage (several weeks), for example, to compensate weekly fluctuations of renewable power generation.

The most important commercially available type of flow battery is the Vanadium Redox-Flow Battery. This battery type is for example available from Cellstrom (Austria) and Prudent Energy (USA) with different modular scalable sizes. Several demonstration sites with this technology exist, particularly in Japan mainly for load-leveling purposes in the range of several 100 kW. Zinc-Bromine batteries are another type of flow battery, which is commercially available.

As the main advantage of this battery type is the independent scaling of power and energy, it offers a big potential for relatively cheap “weekly” storage. For this purpose, cost-effective redox-pairs have to be investigated, as vanadium and zinc/bromine are too expensive to make this technology competitive. Maintenance cost for flow batteries are still high due to leakage caused by the acidic liquids used. Another technical challenge is the up scaling of the cell stack to minimize the production costs.

Parameters for Flow Batteries	All numbers are indications and my vary significantly among different products and installations	
	Today	**2030**
Round-trip efficiency	60 % to 70 % (depending on chemistry)	65 % to 80 % (depending on chemistry)
Energy density	20 Wh/ l to 70 Wh/ l (depending on chemistry)	> 100 Wh/l
Power density	n. a.	
Cycle life	> 10,000	
>Calendar Life	10 years to 15 years	15 years to 25 years
Depth of discharge	100 %	
Self-discharge	0.1 % to 0.4 % per day	0.05 % to 0.2 % per day
Power installation cost	1000 €/ kW to 1,500 €/ kW	600 €/ kW to 1,000 €/ kW
Energy installation cost	300 €/ kWh to 500 €/ kWh	70 €/ kWh to 150 €/ kWh
Deployment time	seconds[22]	
Site requirements	None	
Main applications	Secondary/Tertiary frequency control, Long-term storage, Island grids	

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[22] Times for changing power depend very much on the actual operation condition of the redox-flow battery. E.g. if the battery is supplying high power the power can be changed to negative of the same power value without any delay. Only if the pumps are in stand-still it will take a few seconds until the power reaches full load in either charging or discharging direction.

	Flow Battery	
	Strengths	**Weaknesses**
Internal	• Energy and power independently scalable • High cycle life • Variety of possible redox couples possible	• Leakage caused by acidic fluids • Life of the cell stack is limited • Costs for vanadium-based redox solution is too high • Pumps and valves are prone to errors and costly maintenance
	Opportunities	**Threats**
External	• Cost reduction can be achieved due to larger cell stacks • No restrictions for storage location • No alternatives on the market that could operate economically for several days • Many patents expiring, so that new producers can increase the competitive pressure	• Legal approval problems for large systems with large amounts of acid • Present vanadium systems too expensive for storage periods of a few days • Vanadium is a limited resource • As storage for a few hours with no advantages over lead-acid- or high-temperature-batteries • A lot of R&D effort necessary to obtain favorable redox pairs

4.4.2 Chemical storage systems with internal storage

4.4.2.1 Lithium-ion (Li-ion) Battery

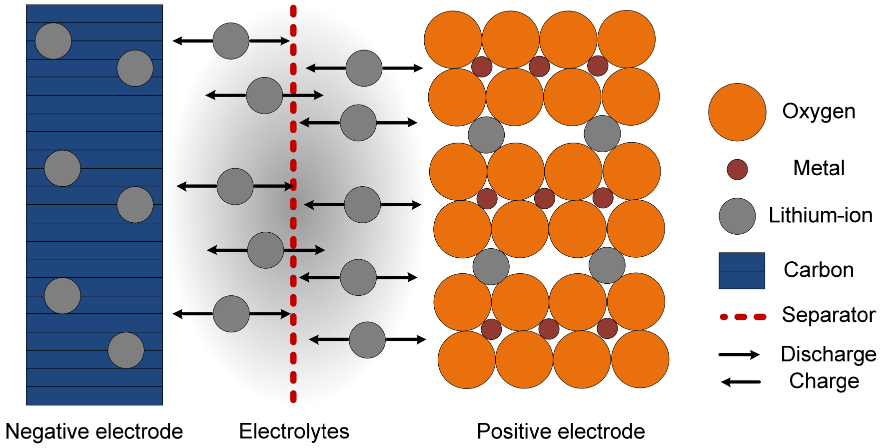

Figure 14: Principle of the discharge and charge process in a Lithium-Ion cell based on a $LiMeO_2$ cathode material and a carbon-based anode.

A state-of-the-art lithium-ion battery consists of a positive electrode made of lithiated metal oxide, and a negative electrode composed of layered graphitic carbon. The electrolyte is made of salts of lithium that have been dissolved in organic carbonates. During the charging process lithium-ions move from the positive to the negative electrode and are intercalated into the graphite layers. During discharge the lithium-ions move to the positive electrode, where they are intercalated into the crystal structure.

Lithium-ion batteries are mainly used as medium-term energy storage, but can also be used as short-term storage. They have become the most important storage technology in the area of portable applications (e.g. laptop, cell phone) during the last years. Also, in electric vehicles, mainly lithium-ion batteries are used. In stationary applications, they can be an interesting option too. Several demonstration projects with lithium-ion battery containers exist in Europe, while in the US lithium-ion battery storage containers are already used in weak grid areas.

In lithium-ion batteries a large number of electrolytes and combinations of electrodes materials, which lead to different characteristics, can be used. With the large number of possible material combinations, there are still high development activities and until today it is not clear, which concept will have the best combination of characteristics for the application in large storage systems, as well as in the area of electric traction.

The main challenge with lithium-ion batteries is to reach a significant cost reduction combined with acceptable lifetime and safety.

Parameters for Lithium-Ion Batteries	All numbers are indications and my vary significantly among different products and installations	
	Today	**2030**
Round-trip efficiency	83 % to 86 %	85 % to 92 %
Energy density	200 Wh/ l to 350 Wh/ l	250 Wh/ l to 550 Wh/ l
Power density	100 W/ l to 3500 W/ l[23]	100 W/l to 5000 W/l
Cycle life	1,000 to 5,000 (full cycles)[24]	3,000 to 10,000 (full cycles)
Calendar Life	5 years to 20 years (depending on temperature and SOC)	10 years to 30 years (depending on temperature and SOC)
Depth of discharge	Up to 100 %	Up to 100 %
Self-discharge	5 % per month	1 % per month
Power installation cost (converter)	150 €/ kW to 200 €/ kW	35 €/ kW to 65 €/ kW
Energy installation cost	300 €/ kWh to 800 €/ kWh	150 €/ kWh to 300 €/ kWh
Deployment time	3 ms to 5 ms	
Site requirements	None	
Main applications	Frequency control, Voltage control, Peak shaving, Load leveling, Electromobility, Residential storage systems	

	Lithium-Ion-Battery	
	Strengths	**Weaknesses**
Internal	• High energy density • Long lifetime • High performance	• No inherent security (thermal runaway) • Sophisticated battery management system required (single cell monitoring) • Packaging and cooling costly depending on the cell shape • High costs
	Opportunities	**Threats**
External	• High number of items in the automotive industry lead to faster cost reduction • No special requirements for storage location (no gassing)	• Social acceptance problems due to lithium mining in problematic countries possible • Lithium resources limited to only few countries • High energy and power densities represent a low added value in most stationary applications

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[23] Could also be higher if required.

[24] Significantly higher numbers have been reported as well. However, these batteries are not available in the cost range given in this table.

4.4.2.2 Lead-Acid Battery

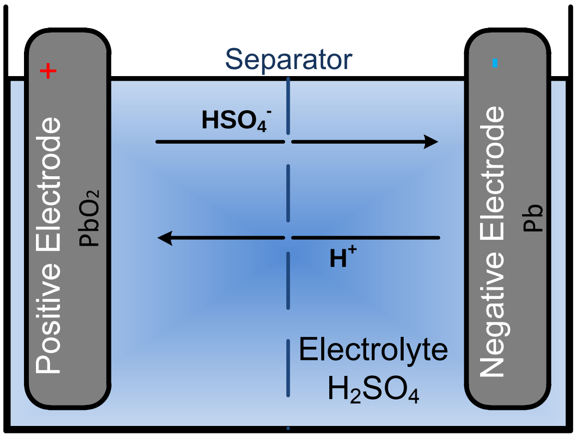

Figure 15: Principle of the discharge and charge process in a Lead-acid cell

Lead-acid batteries are one of the oldest and most developed battery technologies, which are mainly used in short-term and medium-term energy storage systems. It is the battery technology with the largest installed capacities. Many existing devices have been in operation for up to 20 years. One important and successful example is the grid storage plant of the former BEWAG in Berlin with 17 MW / 14 MWh, which was used for frequency control from 1986 onwards.

The biggest markets today are automotive starter batteries and UPS systems for telecommunications. Lead-acid batteries are also widely used in island grid systems.

Lead-acid batteries are commercially available from many different manufacturers. However, even if markets for stationary lead-acid batteries exist, they are not produced in large quantities compared to the automotive market. By introducing mass-production also for bigger stationary batteries, a significant cost reduction can be reached. By optimizing the cell design for the needs in stationary applications, a further cost-reduction and lifetime improvement can be reached.

Due to the limitations in the availability and the toxicity of lead, recycling of lead-acid batteries is of special importance. The recycling rate of this battery type is already very good and a high percentage of recycled lead is used for the production of new batteries.

Due to their low investment costs and relatively low life cycle costs lead-acid batteries are an important technology for the near- and mid-term future which is often not regarded in the public discussion due to the “hype” of lithium-ion batteries.

Parameters for Lead-Acid Batteries	All numbers are indications and my vary significantly among different products and installations	
	Today	**2030**
Round-trip efficiency	75 % to 80 %	78 % to 85 %
Energy density	50 Wh/ l to 100 Wh/ l	50 Wh/l to 130 Wh/l
Power density	10 W/ l to 500 W/ l	10 W/l to 1000 W/l
Cycle life	500 to 2000	1500 to 5000
Calendar Life	5 years to 15 years (depending on temperature and SOC)	10 years to 20 years (depending on temperature and SOC)
Depth of discharge	70 %	80 %
Self-discharge	0.1 % per day to 0.4 % per day	0.05 % to 0.2 % per day
Power installation cost (converter)	150 €/ kW to 200 €/ kW	35 €/ kW to 65 €/ kW
Energy installation cost	100 €/ kWh to 250 €/ kWh	50 €/ kWh to 80 €/ kWh
Deployment time	3 ms to 5 ms	
Site requirements	Ventilation due to gassing	
Main applications	Frequency control, Peak shaving, Load leveling, Island grids, Residential storage systems, Uninterruptible power supply	

	Lead-Acid-Battery	
Internal	**Strengths**	**Weaknesses**
	• Today already high number of items • Acceptable energy and power density for stationary applications • Inherent safety by controlled overcharge reaction • No complex cell management needed • Experience with large storage • Short amortization period and relatively low initial investment	• Charging and discharging ability are not symmetrical • Ventilation requirement • Restrictions to the location of the battery system • Limited cycle life • Industrial batteries are still not built with fully automatic systems
External	**Opportunities**	**Threats**
	• Significant cost savings through fully automated mass production possible • Location independence • Large number of manufacturers around the world	• Prohibition of the use of the heavy metal lead • Very strong cost reduction with lithium-ion batteries (the same application segment) • Limitations of the lead deposits • Insufficient R&D capabilities and experienced personal available • Social acceptance problems due to sulfur removal

4.4.2.3 High Temperature Batteries

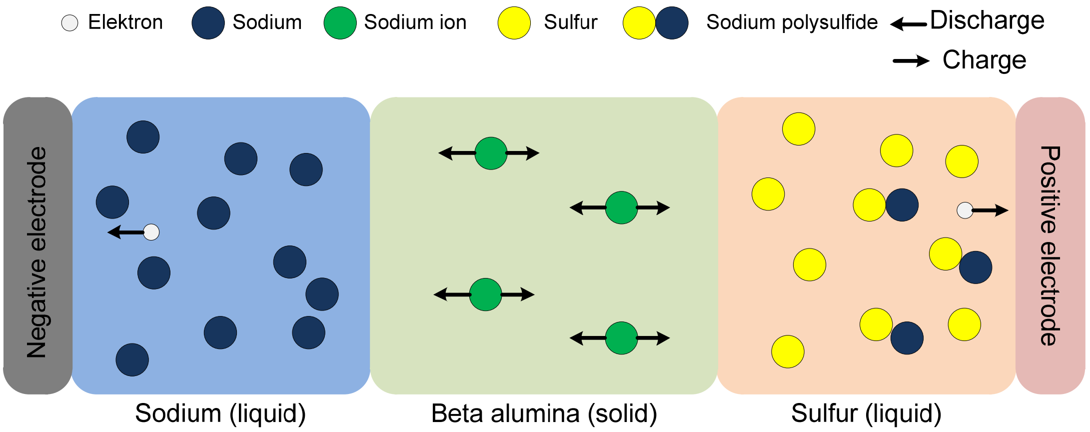

Figure 16: Schematic diagram of a NaS-battery

Sodium-Nickel-Chloride- ($NaNiCl_2$, also called Zebra-battery) and Sodium-Sulphur-batteries (NaS) have a solid state electrolyte instead of a fluid like other batteries. To get sufficiently high ion conductivity and to transfer the active masses into fluid condition, an operation temperature of 270 – 350°C is necessary. When the battery is cooled down, charging or discharging is not possible anymore and there is the danger of cracks in the ceramic electrolyte. For daily utilization, the temperature of the battery can be maintained by its own reaction heat with an appropriately dimensioned isolation. Thereby, these batteries qualify for applications with daily cycling, but are inappropriate for applications in uninterrupted power supply (UPS) with long standby times. They are typically medium-term energy storages.

Both types of high-temperature batteries are only available from one manufacturer. In Japan, NaS batteries are commercially available from NGK and are used in many stationary applications such as load leveling at wind farms, sometimes also including emergency power supply. Around 300 MWh of NaS-batteries are installed worldwide, mostly in Japan. $NaNiCl_2$ batteries are commercially available from Fiamm Sonick in Italy. Due to this single-supplier situation, they are not widely used. Typical areas of usage are electric cars and buses as well as stationary applications such as peak shaving and load shifting.

Due to cheaper raw materials NaS batteries seem to be better suited for a bigger deployment in the future. There are activities of companies in Europe to setup a NaS-battery production, which would most likely lead to an increased cost regression.

In the last months some safety concerns regarding NaS-batteries came up as a battery system caught fire, leading to the stoppage of the production of NaS-batteries. The biggest challenge now is to locate and eliminate the reason for this. It might be that a redesign of the battery system has to take place which can be time-consuming. This would cause a slower development of this promising technology.

Parameters for High Temperature Batteries (NaS)	All numbers are indications and my vary significantly among different products and installations	
	Today	**2030**
Round-trip efficiency	75 % to 80 %	80 % to 90 %
Energy density	150 Wh/ l to 250 Wh/ l	n. a.
Power density	n. a.	n. a.
Cycle life	5,000 to 10,000	5,000 to 10,000
Calendar Life	15 years to 20 years	20 years to 30 years
Depth of discharge	100 %	
Self-discharge	10 % per day (without operation for small systems)	n. a.
Power installation cost (converter)	150 €/ kW to 200 €/ kW	35 €/ kW to 65 €/ kW
Energy installation cost	500 €/ kWh to 700 €/ kWh	80 €/ kW to 150 €/ kW
Deployment time	3 ms to 5 ms	
Site requirements	None	
Main applications	Frequency control, Peak shaving, Load leveling, Island grids, Electromobility (Zebra), Uninterruptible power supply	

High Temperature-Battery

	Strengths	**Weaknesses**
Internal	• High specific energy • High cycle and calendar lifetime • Cheap raw materials (NaS) • Many stationary plants existing (NaS)	• High thermal standby losses • Hazard potential due to high operating temperature • High cost for Nickel-material in Zebra-batteries
	Opportunities	**Threats**
External	• Many patents expiring, so that new players come into the market • No special site requirements • No or almost no restrictions of availability of raw materials	• Only one manufacturer per technology • Competition with lead-acid and lithium-ion batteries • Safety issues especially with NaS-batteries (fire incident)

5. Potential role of different storage technologies

5.1 Selection of storage technologies for certain applications

In order to select the most economic technology for a specific application a careful analysis of the operation profile of the application and a comprehensive life cycle cost calculation have to be accomplished. The most relevant parameters are shown in Figure 17. By combining a storage technology parameter set with a set of parameters defining the application it is possible to calculate the total costs of ownership for supplying energy from the storage system as well as the costs per installed kW power. The technology parameters need to be chosen carefully with regard to the requirements in the specific application, as most storage technologies can be optimized according to the specific demands.

The methodology shown in Figure 17 is made for comparing storage technologies. Real costs of ownership might be higher due to costs which are not taken into account here. This includes for example the costs for connecting the storage system to the grid. These costs are assumed to be similar independent from the storage technology itself.

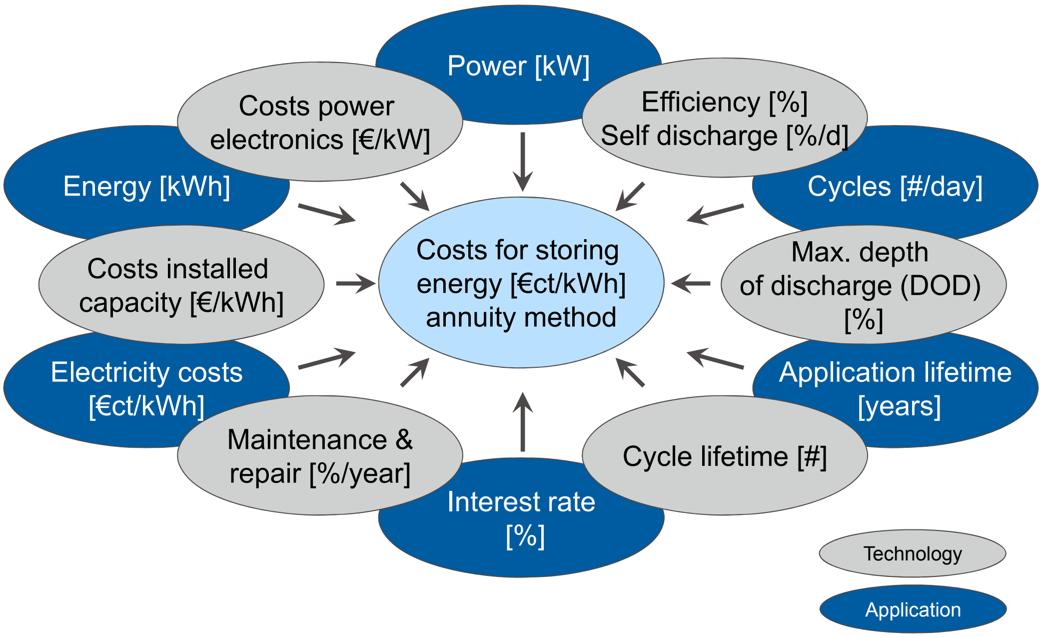

Figure 17: Cost calculation for storage systems

5.2 Classification of storage technologies and their applications

Due to the high number of application-specific parameters it is not possible to assign a certain storage technology exclusively to a certain application. The specific characteristics of the storage technologies only allow for a first classification, as shown below in

. The different applications for energy storage technologies are grouped according to the classification depending on the energy to power (E2P) ratio of the storage technologies (classification type B in section 3.2).

Short-term storage applications (“seconds to minutes”) are mainly served by electrical storage systems (Super-Capacitors, superconductive magnetic energy storage) and flywheels. These applications are characterized by their high cycle load and high power demand. For this reason especially, technologies with high power density and cycle stability are used. The most important applications in future power systems with high shares of renewables are primary frequency control and voltage control as these services were traditionally supplied by conventional power plants. With appropriate power electronic converters and control software all storage systems are able to supply these services. The activation (starting charge or discharge of storage systems) and billing of these units becomes more complex in the future, as the supply is distributed to a larger number of single units, whereas today it is concentrated to comparably few conventional power plants operated by utilities. Billing for example has to be made by calibrated systems and the transmission of billing values has to be encrypted.

For the application **“daily storage”** the biggest variety of technologies exists. All battery technologies as well as pumped hydro and compressed air energy storage plants can be used. Most important applications in this field for grid operation are secondary and tertiary control, and residential storage systems. Most “daily” storage systems are able to supply the “seconds to minutes” services as well.

The biggest markets for modular small and medium sized grid-connected storage systems today are uninterruptible power supply systems for telecommunication and data centers which are also expected to be growing sectors in the future. Today, large-scale storage systems for grid stabilization are almost completely realized by pumped-hydro power stations.

For both “seconds to minutes” as well as “daily” storage applications batteries in vehicles as well as batteries in residential energy storage systems can be used. The advantage of the double use of these systems is low additional costs for offering grid services as these systems are normally financed by their primary application (mobility or increased PV self-consumption). Therefore, these technologies can earn money in two markets.

Technology options for “**weekly to monthly” energy storage** are more limited. For the timeframe of one or two weeks, redox-flow systems may be used in the future. However, still a lot of research work has to be done, as the existing redox-pairs (mainly vanadium) are too expensive for applications with a higher energy to power ratio. For longer time periods, only large-scale hydro storage systems or water electrolysis for hydrogen production can be used. All other storage technologies, including compresses air energy storage (CAES), become extremely costly due to the capacity related costs (€/kWh) and the low utilization rate.

Hydrogen can be processed further to e.g. methane or methanol for different areas of use. However, the production of gases makes sense only if the gas can be stored very cheaply. This is possible in salt caverns, which are available in significant numbers in Germany and some other areas of Europe, but many countries do not have such easy access to gas storage options. On the other hand, large additional hydro power storage capacities are available in Scandinavia or in other mountain areas such as the Alps, the Massif Central, the Pyrenees, the Carpathians, the Balkan Peninsula and possibly Turkey.

In renewable energy systems “long-term storage” is used for compensating a loss in the energy supply from wind and solar in the so called “dark calm” periods. Historical wind data for Europe show that roughly once in a decade there is almost no wind for several weeks throughout entire Europe. That means that increasing electricity transmission capacity does not help in this situation. To maintain security of supply, these periods must be covered by long-term storage systems. In general, “long-term storage” systems must operate on the market for power plants with a very small number of operational hours per year, which makes them very costly. However, when the reservoirs are large enough, the same pumped hydro power storage systems and gas storage systems can be operated in parallel for long-term and daily storage.

Classification of storage systems and their applications

energy to power (E2P) ratio	"seconds to minutes" storage systems E2P: < 0,25 h	"daily" storage systems E2P: 1 – 10 h	"weekly to monthly" storage systems E2P: 50 – 500 h	typical power
Modular systems - dual use	- Plug-in hybrid and full electric vehicles with bidirectional charger - Grid-connected PV battery systems	- Plug-in hybrid and full electric vehicles with bidirectional charger - Grid-connected PV battery systems		1 kW – 1 MW
Modular technologies - grid control only	- Flywheels - Lithium-ion batteries - Super-Capacitors - Superconductive magnetic energy storage	- Lead-acid batteries - Lithium-ion batteries - Sodium-based high temperature batteries - Redox-flow batteries - other electrochemical storage systems	- Redox-flow batteries	1 kW – 100 MW
Centralized technologies		- Pumped hydro storage - Compressed air energy storage - Thermoelectric	- Hydrogen storage - Methanation - (Pumped) hydro storage (with large water reservoirs)	100 MW – 1 GW
Application	- Primary/Secondary frequency control - Spinning reserve - Peak shaving - Voltage control - Black start capability - Island grids (with e.g. diesel generator) - Electromobility (Hybrid Electric Vehicles) - Uninterruptible power supply	- Tertiary frequency control - Standing reserve - Load Leveling - Island grids (without e.g. diesel generator) - Electromobility (Full Electric Vehicles) - Residential storage systems - Uninterruptible power supply	- Storage for “dark calm” periods - Island grids	

Table 6: Classification of storage systems and their applications

5.3 Competition of technologies

In general, electricity storage systems are able to supply positive (feed-in of power into the grid) and negative (draw of power from the grid) control power to the grid. They are able to convert “electricity to electricity”. There are also alternatives that are able to generate the same behavior; systems that only supply positive control power converting “anything to electricity”. Examples are biogas power plants converting biogas into electricity or fossil-fired and nuclear power plants. Systems that only supply negative control power convert “electricity to anything”. The production of hydrogen and the use of electricity for heat production are examples within this group. A combination of these two types of systems can generate the same behavior as an “electricity to electricity” storage system. These competing technologies always have to be evaluated for the specific storage system application. Table 7 shows a summary of alternatives for daily storage systems.

The second dimension of competing technologies is the replacement of centralized technologies by a combination of modular systems (see Table 7). For example, it is possible to generate the same behavior as a pumped hydro storage plant with an aggregated set of 300,000 electric vehicles. The same is valid for a combination of residential storage systems. The main question within this field is the demand for communication and the management-overhead for a fleet of decentralized modular storage systems. With existing telecommunication infrastructure, their control seems possible. A new operator within electricity systems might arise: a storage system aggregator, which manages a large number of small storage systems to be able to operate in the existing energy and control power markets.

Today, we can identify 7 market segments where storage systems might be able to earn money in the existing market design. According to Table 8 the markets can be served by any storage technology belonging to the assigned class of storage technologies (“seconds to minutes”, “daily storage”, “weekly to monthly”).

As explained above, all technologies belonging to a certain class including the “anything to electricity” and “electricity to anything” technologies in appropriate combination are in direct competition to each other in these markets. This is true with one limitation: renewable power generators and storage systems are located in real-world grids with limited capacities to transfer power between different voltage levels, and with limited long-distance transmission capacities. Figure 18 shows a simplified representation of the power grid, the typical voltage levels at which wind turbines or wind parks and PV systems are connected to the grid, and a selection of appropriate storage technologies in the different voltage levels. For instance, large pumped hydro storage systems, which will be always connected to the transmission grid, hardly can contribute to balancing strong feed-in from PV systems connected to the low or medium voltage grid (distribution grid in any case). The grid will limit the ability to transfer this energy to the large scale storage systems, as long as the grid is not dramatically enhanced. However, this would require retrofits on all voltage levels and on a significant number of substations, which connect the power levels.

Therefore, it is not sufficient to discuss the needed storage capacities in general. It is also necessary to consider the needed storage capacities on different voltage levels in the grid. It is necessary to focus also on the issue of negative control power, since in 80% or 100% renewable energy scenarios, power generation capacities will by far exceed the power demand.

Daily storage systems

Class	"Electricity to electricity" (positive and negative control power)	"Anything to electricity" (positive control power)	"Electricity to anything" (negative control power)	typical power
Modular systems - dual use	- Plug-in hybrid and full electric vehicles with bidirectional charger - Grid-connected PV battery systems	- Combined heat and power (CHP) stations with thermal storage - Demand side management (shut down of loads)	- Heat pumps and electrically heated houses - Demand side management (enabling loads) - Cooling equipment - Plug-in hybrid and full electric vehicles with unidirectional charger	1 kW – 1 MW
Modular technologies - grid control only	- Lead-acid batteries - zinc-air batteries - zinc-bromine batteries - zinc-iron batteries - Lithium-ion batteries - High temperature batteries - Redox-flow batteries	- Biogas power plants	- Hydrogen for direct use (traffic sector) - Methane or methanol produced from hydrogen and CO2 - Shut-down of renewable generators	1 kW – 100 MW
Centralized technologies	- Pumped hydro storage - Compressed air energy storage	- hydro power plants - coal power plants - hydro storage plants - solar thermal power plants with thermal storage	- Hydrogen for direct use (traffic sector) - Methane or methanol produced from hydrogen and CO_2	100 MW – 1 GW

Table 7: Different options for "Daily storage systems" (incomplete list)

Market segment	**Class of storage systems**
Reactive power	"Seconds to minutes"
Primary frequency control	"Seconds to minutes"
Secondary frequency control	"Daily storage"
Tertiary frequency control	"Daily storage"
Spread in energy prices (energy trading)	"Daily storage"
Power plant scheduling[25]	"Weekly to monthly"

Table 8: Allocation of existing market segments to classes of storage systems.

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[25] Power plant scheduling (German „Kraftwerkseinsatzplanung“): As a result of the merit order process at the EEX a generation schedule is fixed for the power plants that won a contract 24h ahead of delivery. Only "weekly to monthly" storage systems can deliver energy for extended periods in time. "Daily storage" systems can be used to compensate deviations from the generation schedule.

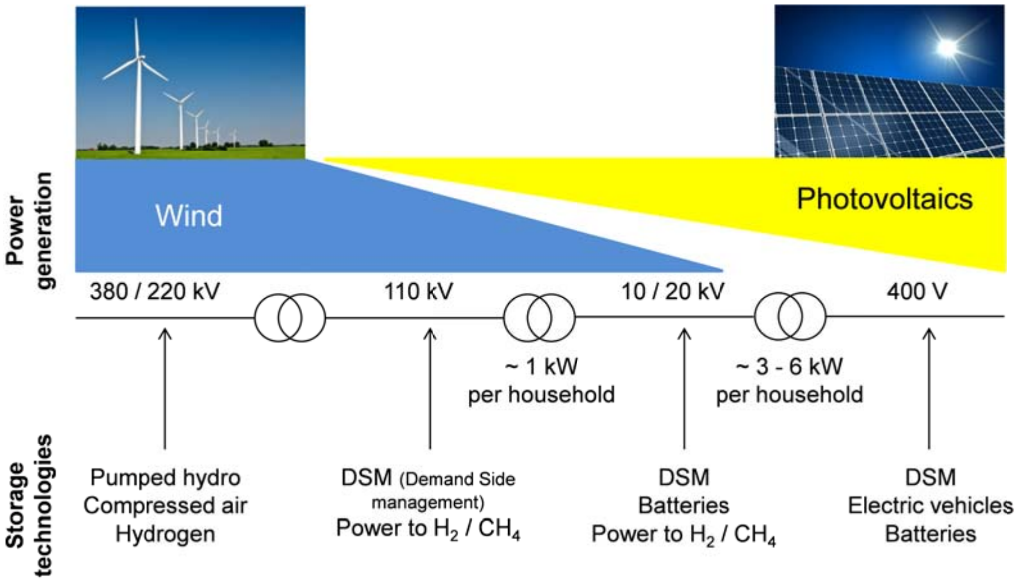

Figure 18: Simplified representation of the grid structure, location of installed wind turbine and PV systems, and appropriate storage technologies in different voltage levels.

Besides creating value for the electricity grid, storage systems can also generate local value, e.g. in terms of uninterruptible power supplies, peak shaving for a company to reduce the maximum power demand, optimization of self-consumption of energy from own power generators (e.g. a photovoltaic system), or electric vehicles by means of storage systems. Most of these applications are also served by storage technologies from the class "daily storage" system.

Especially these systems ("modular storage systems with double use") need to be recognized as severe competitors for storage systems designed only to serve the power markets ("modular storage technologies for grid control only" and "centralized storage technologies"). The "double use" systems have the big advantage of being able to rely on two sources for income with the primary use being the "private market". In case of a storage system in a house with an own PV system, the storage systems are often designed to optimize self-consumption, which becomes interesting when the feed-in tariff is below the electricity price.

A battery in an electric vehicle provides primarily mobility. People will buy and install such storage systems to provide this private use. However, once the storage systems are there, it will be relatively easy in the near future (providing that the regulatory framework is appropriate) to use these storage systems in addition like a virtual large scale storage system with distributed components in the power markets according to Table 8. Because they have been installed for other reasons than trading in the power market, the installed storage capacity is not "controlled" by the market mechanisms of the power market. "Storage systems for grid control only" will be financed only if the market prices allow refinancing of the storage systems, but this is not part of the investment decision for the "private market" storage systems. Therefore, their number and capacity can increase "uncontrolled" and therefore they are a real threat to the "Storage systems for grid control only" due to decreasing market prices. The "double use" systems can offer their service at differential costs near zero, because their investment would have been done anyway and any earnings from power markets is additional income.

From an economical point of view it would be desirable to supply grid services with “double use” systems as they decreases the overall investment in energy storage systems. However, there are considerable uncertainties about the volume and growth rate in the private storage market. Enabling technologies like a cost-efficient communication infrastructure for billing and activating these systems must be available. Furthermore, technologies and business models have to be developed and make sure that the primary use (e.g. mobility or increase self-consumption of PV energy) of the storage system is guaranteed also in a double-use scenario. The competition of double-use and grid-only systems will take place only in the markets for “seconds to minutes” and “daily” storage systems. There are no known “private markets” which require long-term storage systems.

Therefore, it is very difficult today to predict the demand for additional storage systems besides the capacities that can be provided by the “double use” systems incl. demand side management. Full electric vehicles (EV) or plug-in hybrid electric vehicles (PHEV), storage systems in PV systems, and demand side management, for example, using electrical space heating systems based on heat pumps, can provide large amounts of additional control capacities in the coming decades. For Germany, a transition of 50% of todays’ vehicle fleet to EVs or PHEVs and using a 3.7 kW bi-directional charger would result in an installed balancing power capacity of more than 80 GW. If only 50% of the vehicles are available for balancing at a certain point in time, this is still 40 GW for at least one hour. The big problem is, these capacities are not here yet and they will not be available in significant volume in the coming 15 to 20 years.

Nevertheless, this is a severe threat for all storage technologies with long return of investment periods such as pumped hydro or compressed air storage systems. From today’s perspective it is totally unclear if they can earn the money needed for refinancing the investment. Pumped hydro power stations typically need 10 years for planning and construction and at least another 30 years of operation to refinance the investments. Therefore, the investors need to know the demand for these storage systems already today and the available prices for grid services until beyond 2050.

From the authors’ point of view, it will be very difficult to operate storage systems economically in the market segments “seconds to minutes” and “daily storage” that are installed for “grid control only” beyond 2030. Storage systems will need a double use or their installation must be motivated by private use. The main question is how to bridge the gap until approx. 2030. From the authors point of view this gap can be filled by using battery storage technologies, because planning and construction needs less than two years and after 10 to 20 years the batteries are at their end of lifetime anyway. On the other hand it is not clear yet to what extend storage technologies are needed until 2030 at all, because until than we will still have a significant installed capacity of conventional power plants and as long as they are there they also can deliver, most probably, the required balancing power.

Things are very different with regard to the long-term storage systems. As mentioned above there is no competition with “private use” systems. In any scenario with very high share of renewable energies (>> 80%) the need for long-term storage will rise because it will be necessary to bridge extended periods of low wind or low solar radiation. The available technologies for these purposes are very large hydro power systems (not available e.g. in Germany) or hydrogen storage systems. Hydrogen here is a synonym for further use of hydrogen e.g. by methanation to produce methane. The technology can be used to make use also from the peak power generation that cannot be absorbed by the grid and the loads.

Once the long-term storage systems exist they can also provide balancing power for only few days with a lack of power generation. Furthermore, this is the link between the electrical power supply system and the remaining energy market. Producing methane from hydrogen makes sense if methane is used to supply other energy sectors such as transport, combined heat and power (CHP) or general heat generation in industry or private households. If electricity is required the hydrogen should be stored directly to reuse it in fuel cells or hydrogen turbines to avoid additional losses of roughly 20% for the generation of methane from hydrogen.

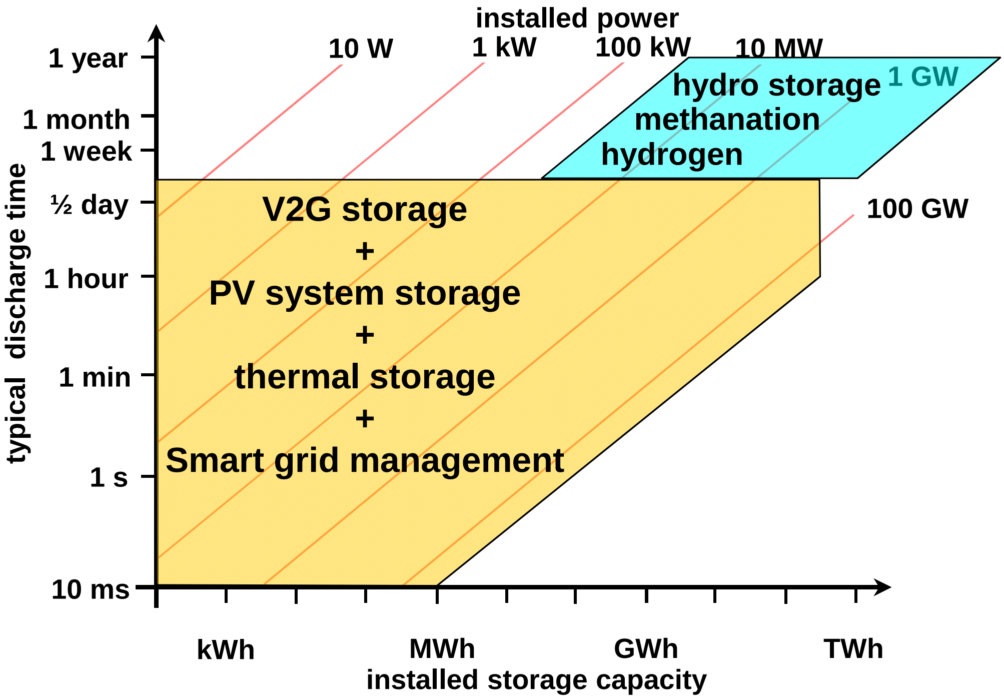

Figure 19: Landscape of storage market beyond 2030

Overall, the authors assume that the landscape for balancing power beyond 2030 (Figure 19) will be dominated for the "seconds to minutes" and the "daily" storage markets by decentralized "double use" storage systems and demand side management. The "long-term" storage market in Europe will be dominated by hydrogen stored in salt caverns and the use of Scandinavian and other (pumped) hydro storage systems. The link between power generation and other energy markets will be provided by the methanation of hydrogen. This also will allow making use of at least a significant percentage of the power generation capacities that go beyond the capacities of the grid and the loads for other fields of energy consumption. It is necessary to keep in mind that in countries such as Germany, currently, only one third of the energy is consumed in the electricity sector. To achieve the CO_2 reduction goals for 2050 it will be necessary, besides significant energy savings, to serve many other fields of energy consumption with electricity or derivatives produced from electricity. Therefore, large scale hydrogen production will be necessary in the medium-term future in any case. However, this should start only, once all options for direct use of electricity through long-ranging power transmission lines and demand-side management are used.

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