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Facilitating energy storage to allow high penetration of intermittent renewable energy

D2.1
Report summarizing the current Status, Role and Costs of Energy Storage Technologies

(Source: RenewableEnergyWorld.com)

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The work for this report has been coordinated by Energy Economics Group (EEG)

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List of Abbreviations

AA-CAES	…	(Advanced-) Adiabatic Compressed Air Energy Storage
AFC	…	Alkaline Fuel Cell
CAES	…	Compressed Air Energy Storage
CCGT	…	Combined Cycle Gas Turbine
CCS	…	Carbon Capture and Storage
$C_{generate}$	…	Electricity cost during generation
CH_4	…	Methane
CO_2	…	Carbon dioxide
C_{store}	…	Electricity cost during storage
EST	…	Energy Storage Technology
GW	…	Giga Watt
GWh	…	Giga Watt hour
H_2	…	Hydrogen
HES	…	Hydro Energy Storage (dam- or barrage-hydro power plant)
HFCSS	…	Hydrogen Fuel Cell Storage System
Hz	…	Hertz
kW	…	kilo Watt
kWh	…	kilo Watt hour
LAES	…	Liquefied Air Energy Storage
Li-Ion	…	Lithium-Ion
MCFC	…	Molten Carbonate Fuel Cell
MW	…	Mega Watt
NaS	…	Sodium-Sulphur
NiCd	…	Nickel Cadmium
NiMH	…	Nickel Metal Hybrid
O&M	…	Operation and Maintenance
PAFC	…	Phosphoric Acid Fuel Cell
$PbSO_4$	…	Lead-Acid
PEMFC	…	Proton Exchange Membrane Fuel Cell
PHES	…	Pumped Hydro Energy Storage
PV	…	Photovoltaics
RES-E	…	Renewable Energy Sources for Electricity generation
SMES	…	Super Magnetic Energy Storage
SOFC	…	Solid Oxide Fuel Cell
TSO	…	Transmission System Operator

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VRB	…	Vanadium Redox flow Battery
yr	…	Year
Zn-Br	…	Zinc-Bromine
η	…	Efficiency

Executive Summary

This document, Deliverable 2.1 (D2.1), provides and overview of the state-of-the-art and the expected future development of key technology and economic parameters (like typical rated power, energy intensity, charge / discharge time and frequency, capital and operation cost, etc.) of the two main bulk energy storage technologies (EST) pumped hydro energy storage (PHES) and compressed air energy storage (CAES). Furthermore, this document gives a brief introduction into typical applications of these candidates of bulk energy storage technologies in the electricity market, most notably those known in the field of generation and reserve capacity provision services.

Remaining energy storage technologies (like the long-term future option of hydrogen on bulk / transmission level and several other energy storage technologies on lower voltage levels like battery systems for future e-mobility applications, flywheels, etc.) are out of scope of the core objective of the stoRE project. Therefore, they are included in the document in a small section only where a brief overview of the latest developments in this segment is conducted in order to provide a complete picture of the entire technology portfolio on future energy storage options.

Work presented in this document is mainly based on already existing literature / references, whereas a critically review and update has been conducted where necessary. The references are cited throughout the document correspondingly. As well, they are listed at the end of this document.

As already outlined above, the first part of this document is dealing with the key technology parameters of the two main bulk energy storage technologies PHES and CAES.

PHES systems have been the main economic option for storing large amounts of electrical energy already for a long time. In PHES systems water stored in an upper reservoir is processed in a turbine to recover its potential energy in form of mechanical (kinetic) energy. Unlike dam- or run-of-river hydro power plants, the processed water does not just drain off; it is captured in a lower reservoir. In times of low electricity demand / low electricity prices (or excess electricity supply due to high electricity generation of renewable energy sources (RES-E)) the water is raised again to the upper reservoir by a pump which is powered by an electrical motor. There are many different subtypes of PHES, like, for example, sea water PHES, which use the sea as lower reservoir (one existing today in Japan), or underground PHES, which use deep mining structures for one or both reservoirs (concept). Generally, PHES power plants are operated in turbine mode (electricity generation) during peak-times while off-peak times, especially in the night, are used for “storing” electricity (pumping mode, electricity demand).

Power ratings of PHES systems reach from several MW up to 2 GW with discharge times up to 100 hours depending on the storage volume of the reservoirs. One-cycle efficiencies of up to 85 % are reached. PHES systems are among the oldest and most widely used energy storage options and therefore fully commercialised. Currently there are more than 90 GW of PHES systems (with power rating >100 MW) installed worldwide, representing approximately 3 % of global generation capacity. However, their deployment potential is constraint across Europe, since PHES systems are strongly dependent on certain geographic requirements and topographical conditions. Therefore, most of the currently proposed new PHES plants are either extensions or upgrades / repowering of existing storage and / or PHES power plants.

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CAES systems, the second major bulk energy storage technology, compress a gas (usually air) to high pressures (70 to 100+ Bar) and inject it into either an underground structure (e.g. cavern, aquifer, or abandoned mine) or an above ground system of tanks or pipes to store energy. To generate electricity the gas is mixed with an additional fuel (e.g. natural gas), burned and expanded through a conventional or gas-fired turbine which runs a generator. Besides conventional CAES (also called “diabatic” CAES) there exists an advanced CAES concept, “adiabatic” CAES (AA-CAES), which does not need to use an additional (fossil) fuel to “restore” the stored energy (but need an additional heat storage) and also have a higher overall efficiency. Also various other subtypes of CAES exist, like, for example, liquefied air energy storage (LAES), which uses liquefied gas as energy storage medium.

CAES systems are operated similar to PHES plants, i.e. shifting power generation from off-peak to on-peak times. Also in terms of their key technology parameters, they are very similar to PHES systems, but have shorter lifetimes and also slower response times. So far, only two commercial CAES systems have been built worldwide (one in Huntorf, Germany and the other one in McIntosh, USA). Even though they are in use since many years, further technological developments are needed in order to reach higher overall efficiencies (currently CAES systems have an efficiency of about 55 %, with a potential to reach up to 70 % in the future) and to eliminate the need for using additional fossil fuels (i.e. AA-CAES). The future utilization potential of CAES systems is also dependent on the availability of appropriate underground air storage capacities, especially salt caverns. However, the competing utilization of underground caverns for storing natural gas or CO_2 (carbon capture and storage, CCS) and accordingly hydrogen in the future, could decrease the availability of underground caverns for storing compressed air.

In this report, furthermore, other (non-bulk) EST such as batteries, supercapacitors and flywheels are also briefly described; however, no in-depth analyses is conducted since they are outside the scope of the stoRE project. Their major role in future electricity systems with high shares of variable / intermittent RES-E generation will be in short-time applications, e.g. output smoothing within seconds etc. and applications on low voltage levels. These applications, where bulk EST like PHES and CAES cannot be used - because of their high response times or high voltage level - will form a niche market for other non-bulk EST. However, hydrogen fuel cell storage systems also have the potential to become bulk EST in the future, but currently suffer from low efficiency.

Then, an overview about the economic situation (capital and variable cost) of the main bulk energy storage technologies, PHES and CAES is presented and discussed.

Typically, PHES plants are characterised by long asset life (typically 50 – 100 years), high capital cost and low operation and maintenance (O&M) cost. Project costs for PHES systems are very site specific with some quoted costs varying from of 450 – 2500 €/kW. Additionally capital costs depend not only on the installed power but also on the energy storage (reservoirs) and power rating at any given site. Since PHES is a mature technology, its capital cost is not expected to change substantially in the future.

Both existing CAES power plants had about the same specific investment costs of ~ 400 €/kW. Current investment costs are estimated to be between 450 – 1000 €/kW, strongly dependent on the structural conditions of the site, e.g. cavern condition, form and volume. Since no AA-CAES plant has been realised to date, investment cost estimations are more uncertain. However, current assessments state a bandwidth of 600 – 1200 €/kW, where the lower boundary represents the estimated cost in the medium term due to technological learning / economies of scale.

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However, the key issues determining economics of the bulk energy storage technologies are the charging cost as well as the price spread between charging and discharging in general. Especially cost of the charging current has a big influence on the overall electricity generation cost of the bulk EST. PHES systems are currently the most cost effective solution for daily as well as long-term storages. CAES systems suffer from the additional cost factor for fossil fuel (and also for CO_2), but get increasingly interesting with increasing charging electricity price. AA-CAES plants may be good (future) alternatives for PHES systems, however, their costs are still uncertain since no AA-CAES plant has been built today.

In the third part of this document, before concluding, a structured overview (incl. some illustrative examples) of typical applications of energy storage technologies in the electricity market is given. In particular, several of the different capacity provision services of bulk energy storage technologies on different time scales are briefly introduced and discussed, as there are e.g. black start capability, area control and frequency response (secondary and tertiary control), standing and / or energy imbalance reserve, load levelling and seasonal energy storage. The major application for bulk energy storage technologies like PHES and CAES is expected to be output smoothening of variable / intermittent RES-E generation on multiple time scales and energy arbitrage, i.e. storing RES-E generation in off-peak hours and restoring it again in on-peak hours. Also the provision of secondary and tertiary control reserve is a possible and profitable application for bulk energy storage technologies.

It is important to note, however, that the presentation of the typical applications of energy storage technologies in the electricity market have to be interpreted as a brief introduction only; an in-depth consideration of electricity market-driven applications on different time scales is covered by Deliverable 2.2 (D2.2) of the stoRE project.

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1 Introduction

1.1 General

The information and discussions presented in this report are part of the European project stoRE (www.store-project.eu). stoRE aims to facilitate the realization of the ambitious objectives for high penetration of variable / intermittent renewable energies in the European grid by 2020 and beyond by unblocking the potential for energy storage technology implementation. Energy storage, as part of an integrated approach including grid infrastructure reinforcement and demand management, brings advantages to existing and future electricity systems. Moreover, it helps accommodate higher percentages of variable / intermittent renewable energy by balancing supply and demand and improving power quality.

Within work-package 2 (WP2) of the stoRE project, a collection, evaluation and update of information about the status and future potential of energy storage technologies takes place, setting the foundations for the work to be carried out in the rest of the project stoRE.

This document, Deliverable 2.1 (D2.1), summarizes the current status, role and costs of energy storage technologies (with special focus on bulk energy storage). After a brief introduction into (bulk) energy storage and their interrelationship with the integration of renewable energies for electricity generation (RES-E), this report is then structured into three main parts:

- Section 2 of this report provides an overview of the state-of-the-art and the expected future development of energy storage technologies (EST) and their key technology parameters; special focus is drawn to the two main bulk EST pumped hydro energy storage (PHES) and compressed air energy storage (CAES).
- Section 3 discusses the capital and variable costs of the main bulk energy storage technologies, PHES and CAES.
- Section 4 finally presents an introduction into possible different applications of EST (incl. some illustrative examples).

1.2 Bulk Energy Storage & Renewable Energies

In electricity systems, supply and demand have to be balanced in real time. Therefore, every electricity system requires sufficient power (plants)[1] to be able to meet maximum electricity demand. Electricity demand, furthermore, fluctuates on a temporally basis and maximum demand is only reached some hours per year (average demand ~60 % of maximum demand). To overcome these fluctuations, flexible generation (gas turbines, combined-cycle gas turbine (CCGT), etc.) and load management technologies in combination with (indirect)[2] electricity storages, such as pumped hydro energy storage (PHES), have been used to balance the electricity system.

[1] And / or sufficient interconnection capacities to other electricity systems with enough power surplus
[2] c.f. Figure 1

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The growth of distributed generation in general, and the increasing deployment of variable / intermittent renewable electricity generation technologies like wind and solar photovoltaic (PV) in the electricity system in particular, is changing the way electricity systems have to be operated and managed in the future. Due to high shares of variable / intermittent RES-E (mainly wind) generation, future electricity systems will be increasingly “stressed” on several time scales in both dimensions “amplitude” and “frequency” of extreme events in electricity system operation.

Bulk energy storage technologies are expected to be one of the key enabling technologies for the integration of large amounts of variable / intermittent RES-E generation. In particular, the ability to quickly discharge large amounts of stored electric energy or to reduce loads during certain points in time throughout a day (i.e. output smoothing) can mitigate many challenges which arise with high shares of variable / intermittent RES-E generation in the electricity system. Further on, bulk EST could play an important role in optimising the physical and financial functioning of electricity markets and the corresponding commercial energy trading activities.

In task 2.2 of the stoRE project (Deliverable 2.2), several of these new, market-driven requirements / needs of bulk energy storage technologies (PHES and CAES) on different time scales (intra-daily, daily, weekly, monthly and seasonal energy trading and balancing) will be studied and reported in detail.

1.3 Other Energy Storage Technologies

In the stoRE project the focus of analysis and discussions is set predominantly on bulk energy storage technologies. It is, however, worth mentioning, that also the deployment and development of other (non-bulk) energy storage technologies, like battery systems and flywheels, induces benefits for the electricity system. Though, since their electricity storage capacities are technically and / or economically determined[3] in future electricity systems with high shares of variable / intermittent RES-E generation their major role will be in short-time applications (e.g. output smoothing within seconds etc.) and applications on low voltage levels. These applications, where bulk EST can not be used due to their relatively high response times or high voltage levels, will form a niche market for other EST.

Though, in order to provide a complete picture of energy storage options, this report also provides a brief overview of other (non-bulk) EST that are outside the scope of the stoRE project.

[3] Whereas hydrogen fuel cell systems and electric vehicles (see sections 2.4.1 and 2.4.2) may also be future options for large-scale electricity storage

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2 Key Technology Parameters of Bulk Energy Storage Technologies

2.1 Introduction

There is a broad variety of electricity storage technologies (EST) in use today. In order to get an overview, Figure 1 shows the most well-established EST. Generally, EST can be divided into direct storage and indirect storage technologies. In direct EST the electricity is stored in the magnetic or electrical field of a capacitor or inductor. In case of indirect EST the electricity is stored in mechanical (potential, kinetic etc.) or chemical energy and is converted back into electricity when needed. (Mariyappan et al, 2004)

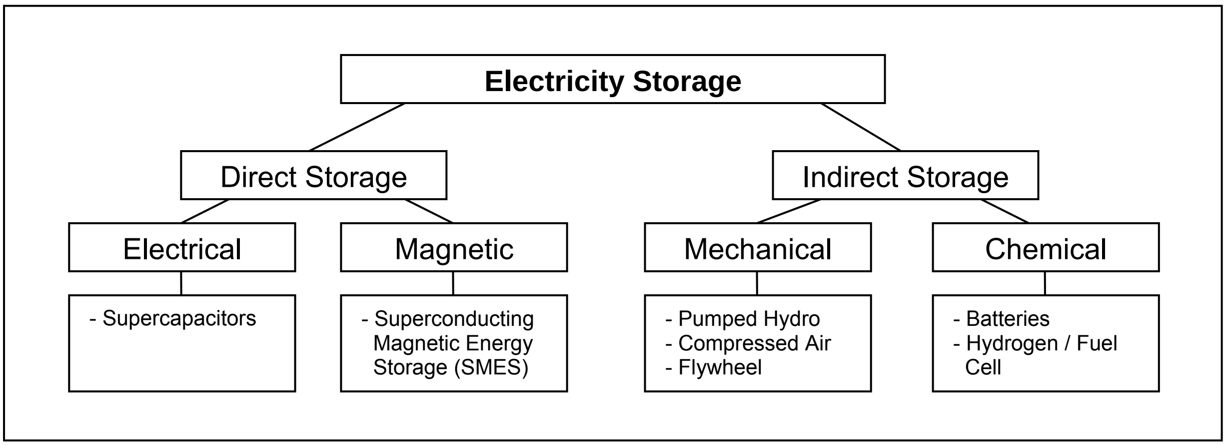

Figure 1: Overview of electricity storage systems (Source: Mariyappan et al, 2004)

Because of their high costs and inherent technology limitations, direct EST like supercapacitors and superconducting magnetic energy storage (SMES) are currently only used for applications where small amounts of electricity need to be stored. At the moment, indirect EST are the most widely used storage technologies. Especially pumped hydro and battery systems have been applied for many years and are the most mature EST. However, in recent years also compressed air and hydrogen energy storage gained more attention in research and development, since these technologies also (might) have the potential to store large amounts of (renewable) electricity in the future.

Since the stoRE project focuses on large-scale EST, in the following chapters 2.2 and 2.3 the two main bulk EST available today, pumped hydro energy storage (PHES) and compressed air energy storage (CAES), will be described in more detail. Chapter 2.4 gives a brief overview of other EST, which are outside the scope of the main objective of the stoRE project, i.e. batteries, hydrogen, flywheels, supercapacitors and SMES.

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2.2 Pumped Hydro Energy Storage

2.2.1 Basic Functional Principle

Pumped Hydro Energy Storage (PHES) systems have been the main economic option for storing large amounts of electrical energy already for a long time.

Figure 2 shows the basic functional principle of a PHES. Water stored in an upper reservoir is processed in a turbine to recover its potential energy in form of mechanical (kinetic) energy. The turbine runs a generator which converts the mechanical energy into electrical energy, which is fed into the electricity grid (turbine mode).

Unlike dam- or run-of-river hydro power plants, the processed water does not just drain off; it is captured in a lower reservoir. In times of low electricity demand / low electricity prices (or excess electricity supply due to high RES-E) the water is raised again to the upper reservoir by a pump which is powered by an electrical motor (pumping mode). Therefore, in the pumping mode the PHES is a load in the electricity system.

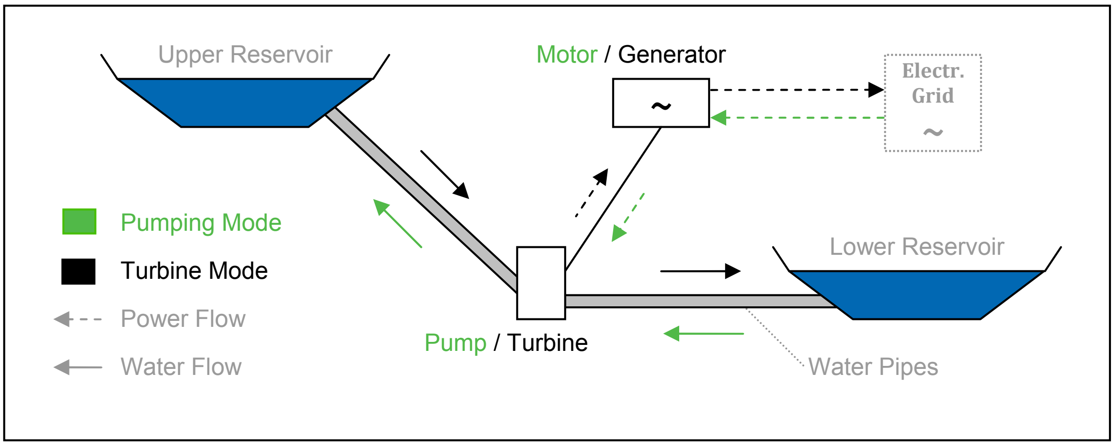

Figure 2: Schematic diagram of a PHES system (Source: EEG)

2.2.2 Subtypes of PHES

PHES systems can be classified into different subtypes concerning their water management[4]:

- "Closed-loop" PHES systems consists of two reservoirs neither of which is connected to a river system. Both reservoirs may either be artificial or modified existing lakes. The most common layout is that one reservoir is artificial and the other is a modified existing lake. A typical example of a closed loop system is Turlough Hill, Ireland, where the lower reservoir is a modified lake and the upper reservoir is artificial.
- "Semi-open" PHES systems have one artificial reservoir; the other reservoir has natural inflow or is part of a river system. An example of this type is Goldisthal, Germany, where the upper reservoir is artificial and the lower reservoir is part of a river system.

[4] See Appendix for additional details and figures

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- In an “open system” PHES both reservoirs have natural inflow or are part of a river system. The most common subtype of a “open system” PHES is the "pump-back" PHES system which is a combination of pumped storage and conventional hydro power plant that uses natural stream-flow

“Sea water” PHES are a special case of a semi-open PHES system, which use the sea as lower reservoir. This has the advantage to allow for larger and more economical schemes without the need to use valuable and limited freshwater resources but also has the problem of a more corrosive environment. Currently only one sea water PHES exists, the 30 MW Okinawa Yanbaru PHES built in 1999 in Japan.

An interesting concept is PHES in open cast mining structures. Here quarries with large volumes are planned to be used for the construction of a PHES after the coal production is finished. Depending on the area, coal layer quarries with depths between 120 to 300 m remain (see Figure 3). On one side of the mine is natural ground, on the other side geological unstable mining waste. The side with the natural ground can be used for the installation of a dam for the upper reservoir, while the ground of the coal mine can be used as the lower reservoir (see Figure 4). The main advantage of this setup is the existence of the lower reservoir and also the higher environmental acceptability, since the installation could also be part the rehabilitation process of the coal mine. (Do Thanh et al, 2010)

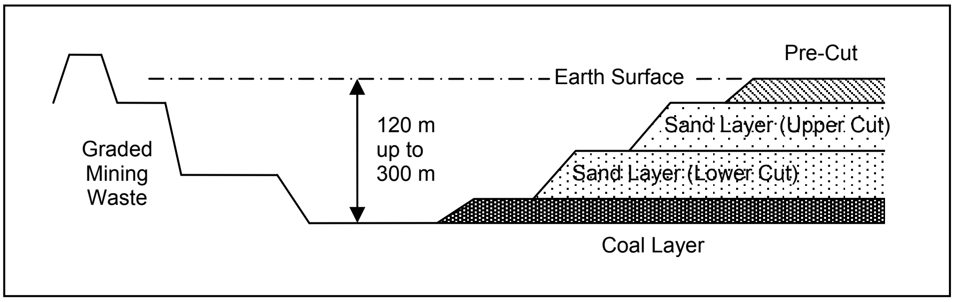

Figure 3: Cross-section of an open mining structure (Source: Do Thanh et al, 2010)

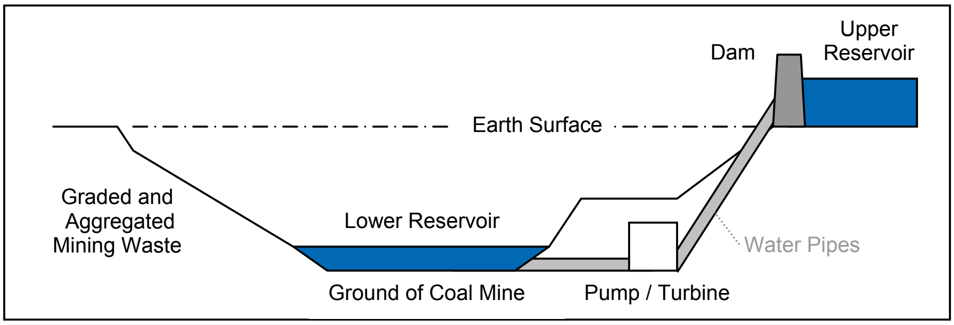

Figure 4: Cross-section of a PHES system installed in an open mining structure (Source: Do Thanh et al, 2010)

Similar to open cast mining structures, deep mining structures could also be used for the installation of a PHES system. In this innovative concept discontinued deep mining structures are expanded with additional caverns for the upper / lower reservoir and the pump / turbine (also hybrid solutions are possible, where the upper reservoir is on the surface). Further on up to three additional mine shafts have to be constructed for the operation of the plant, which also contribute

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to a higher installation cost compared to "conventional" PHES systems. The main advantage of a PHES in deep mining structures is that the plants are nearly invisible and allow an additional development potential for PHES. (Erlei et al, 2011)

Generally, the power house for a PHES system can be constructed in an underground cavern or in an open shaft near the lower reservoir. For the cavern configuration the power house is located deep inside the mountain with vehicular and personnel access through a tunnel. The penstock and tailrace pipes are both tunnelled. In a shaft configuration the power house is constructed in an open excavation close to the lower reservoir. This is normally only possible where the active range of the water in the lower reservoir is only a few meters. The tailrace forms an integral part of the power house. For the shaft configuration the penstock pipe can be an overground pipe, a buried pipe or a tunnel.

PHES can also be classified according to their machine setup. Two main technical setups exist (also a combination of both in one PHES plant is possible):

- Turbine and pump are separate units, which can be connected to the generator/motor alternately; this system is more complex, but has a higher efficiency, since the units can be fluidically optimised separately
- Turbine and pump are a single reversible unit, which is directly connected to the generator/motor; this layout significantly reduces the construction cost (up to 30 %) but has around 2 % lower efficiency

In case turbine and pump are separate units, they can be directly connected with each other through a pressure water pipe ("hydraulic shortcut") to allow a faster switching between pumping and turbining mode. Furthermore, this also enables the pump to be "controllable": turbine and pump units run simultaneously so that the energy demand of the pump can be varied with the turbine, i.e. the pump is partly powered by the turbine of the plant and partly by the connected electricity system. An example for such a PHES system is the Austrian "Kopswerk 2" of the Vorarlberger Illwerke AG. (Erben et al, 2008)

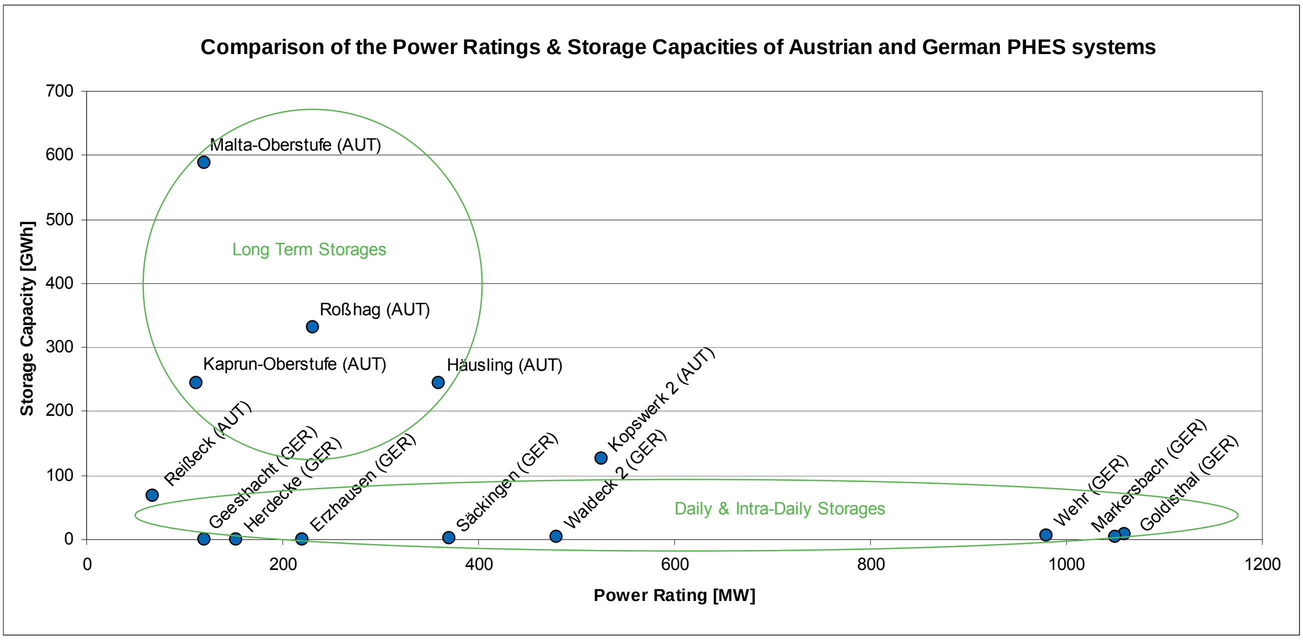

Figure 5: Comparison of the power ratings and storage capacities of Austrian and German PHES systems (Source: EEG)

Generally, PHES systems can be designed for daily, weekly, monthly or even annual / seasonal storage. The storage capacity of a PHES system is dependent on the reservoir capacity and also on the difference in elevation between upper and lower reservoirs.

Figure 5 shows a comparison of the power ratings and storage capacities of some selected Austrian and German PHES systems and illustrates the difference in the rating between daily and long term storage power plants. While daily storage systems have large power ratings but only low storage capacities, long term storage systems have high storage capacities. Whereas daily storages can also be built in comparatively flat landscapes with low drop heights and small reservoirs, long term storages generally need to rely on certain geographical preconditions, which can be found especially in mountainous areas, e.g. the Alps. This can also be seen in Figure 5, while most German PHES systems (and also the majority of PHES systems in the world) are designed as daily or intra-daily storages (low storage capacities), most Austrian PHES systems offer higher storage capacities.

2.2.3 PHES Operation

In general, the operational capability of PHES[5] systems is strongly dependent on the available water resources, e.g. from natural inflow and snow water, in the reservoirs. When looking at the monthly storage capacities, for instance for Austria in Figure 6[6], a typical sinusoidal-like development can be seen over a year, with the lowest available storage capacities around March / April and the highest available storage capacities in August / September.

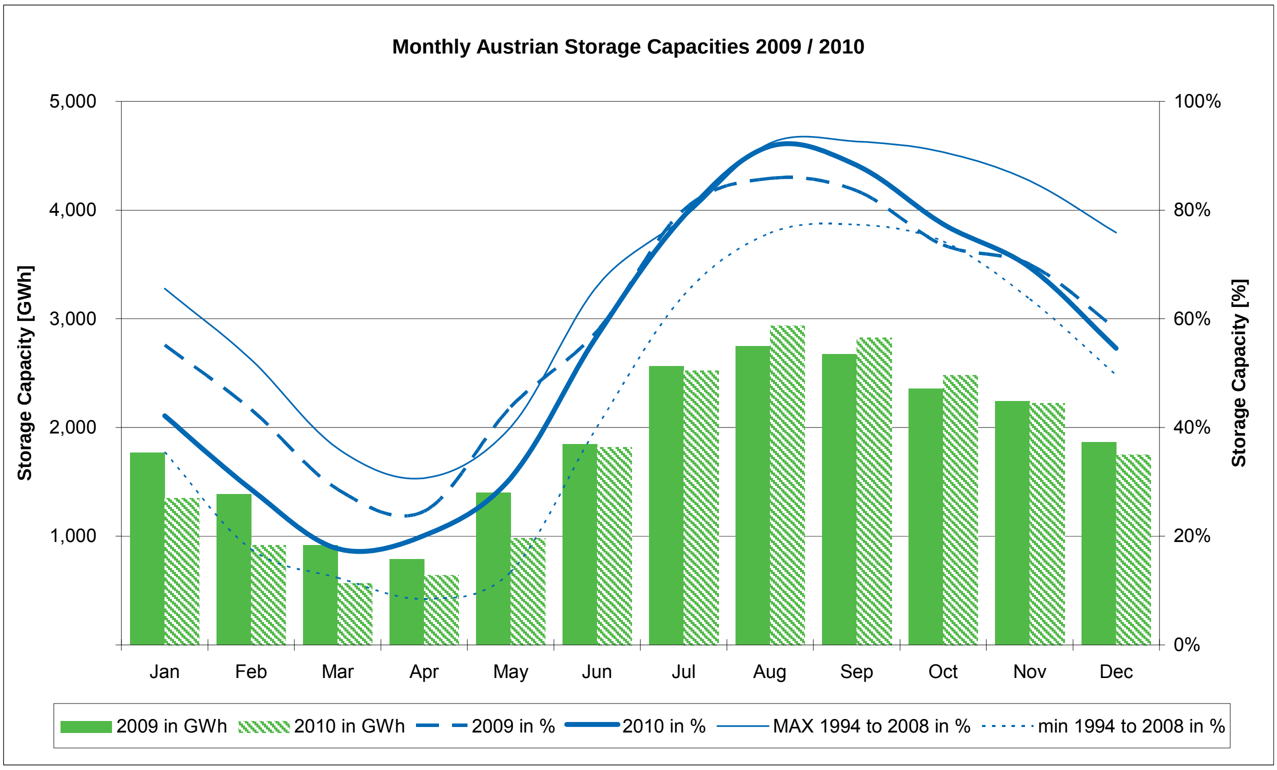

Figure 6: Comparison of the monthly Austrian storage capacities in 2009 and 2010 (Source: E-Control, 2011)

[5] Exception here are closed-loop PHES systems
[6] Storage capacities of Austrian PHES and regular hydro energy storage power plants (HES)

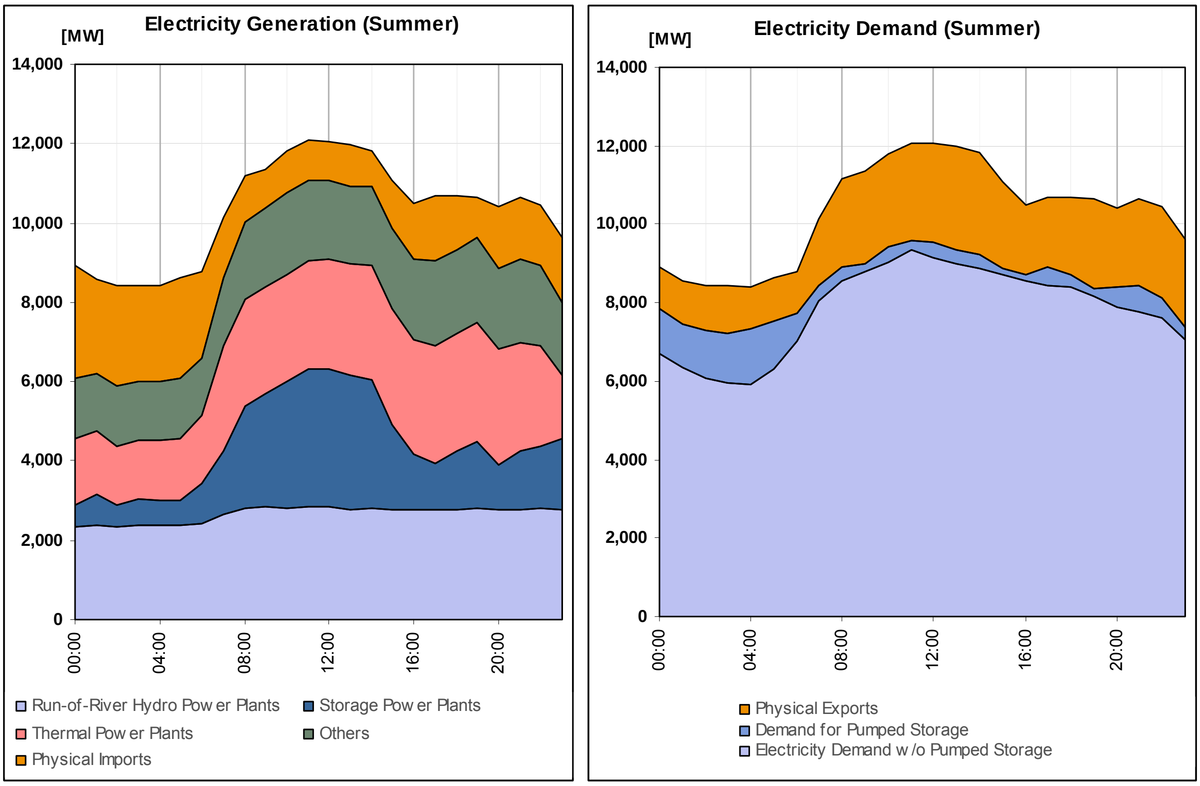

Figure 7: Austrian electricity generation (left) and demand (right) on typical summer day (20th July 2011), (Source: E-Control, 2011)

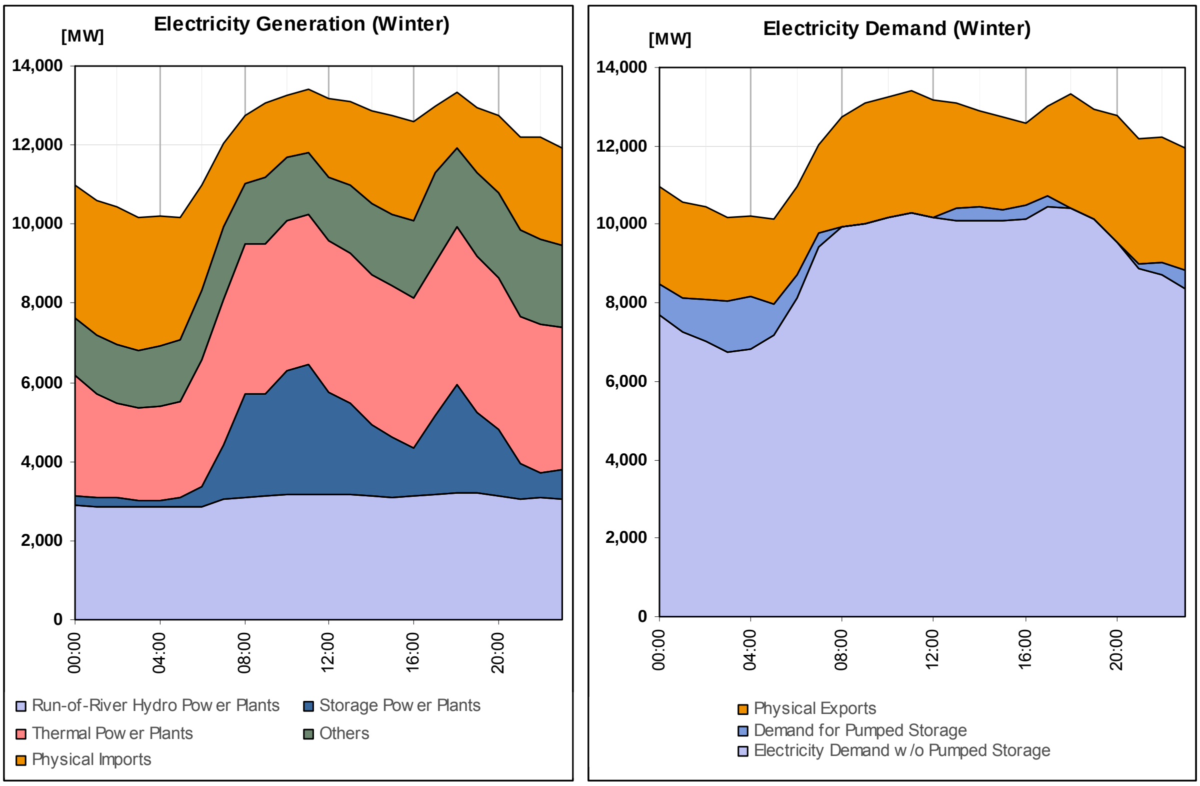

Figure 8: Austrian electricity generation (left) and demand (right) on typical winter day (19th January 2011), (Source: E-Control, 2011)

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The Figure 7 and Figure 8 show the Austrian electricity generation and demand on a typical summer / winter day in the year 2011. It can be seen that in the Austrian electricity system the (pumped-) hydro storage power plants are operated to follow the electricity demand, while the other generation technologies form more or less stable generation-bands. Generally, large amounts of (pumped-) hydro storage power plants are operated in turbine mode (electricity generation) during peak-times while off-peak times, especially in the night, are used for “storing” electricity (pumping mode, electricity demand). Both days show a similar development of the generation with slightly shifted peaks towards later hours on the summer day. The summer day also sees a higher overall generation level of storage generation plants.

The storage operational mode described here represents the “conventional” operation of PHES systems, as applied in current electricity systems. In the Deliverable 2.2 of the stoRE project the requirements of bulk EST in future electricity systems with high penetration of variable / intermittent RES-E generation will be discussed in detail.

2.2.4 Development Status of PHES

PHES systems are among the oldest and most widely used energy storage options and therefore fully commercialised. Figure 9 shows the chronological development of PHES plant installations in Europe starting from 1940 until today. It can be seen that the majority of PHES plants have been built from the 1960’s to the late 1980’s. This has partly been influenced by the energy crisis in the 1970’s and the rush for energy security. In the period from 1990 until now, only a few plants have been built because, on the one hand, most of the best available potential sites are already implemented. On the other hand, the introduction of the electricity market liberalisation has made the costly construction of new PHES plants less attractive. (Deane et al, 2010)

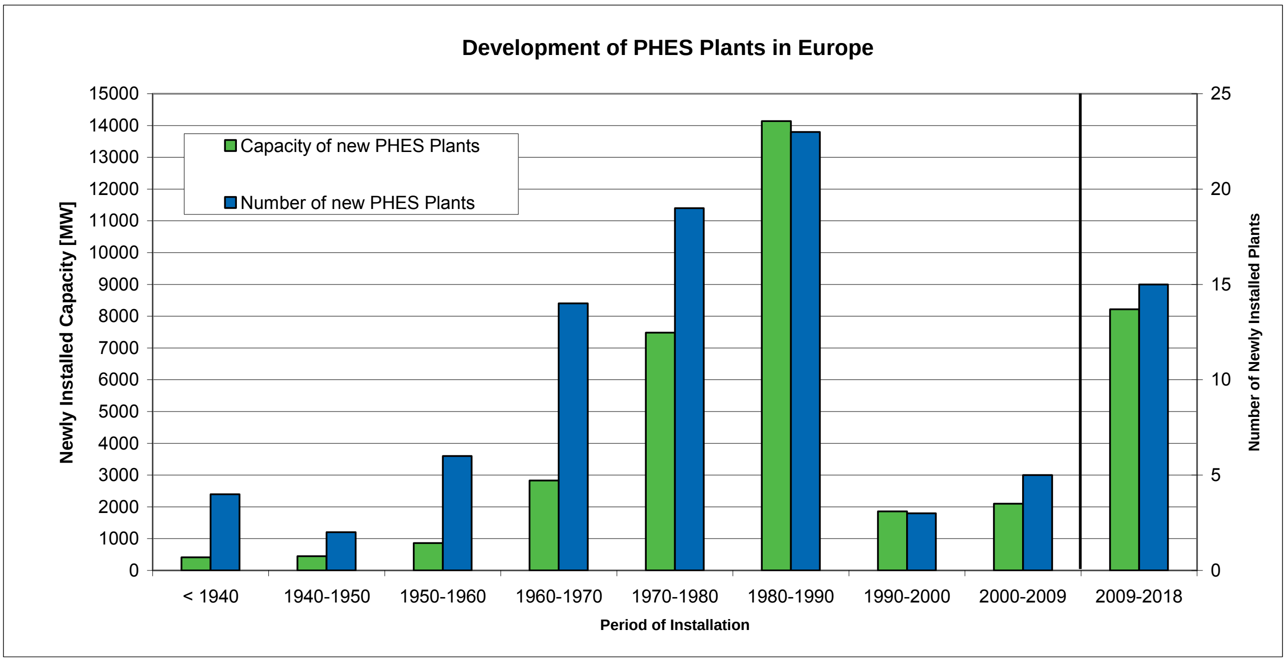

Figure 9: Chronological development of PHES plant installations in Europe (based on Deane et al, 2010)

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Currently there are more than 90 GW of PHES systems (with power rating >100 MW) installed worldwide, representing approximately 3 % of global generation capacity. Additionally there are a number of others presently in the construction and planning phase (compare Figure 9). The majority of these roughly 8,2 GW of proposed PHES systems in Europe is planned in Switzerland (2,9 GW)[7], followed by Portugal (~2 GW) and Austria (1,4 GW). (Deane et al, 2010)

According to (EURELECTRIC, 2011) further PHES systems with a total installed pump capacity of 19,3 GW are in early planning stage (no licence yet) in Europe.

Since PHES systems require very specific site conditions to make a project viable (i.e. high head, favourable topography, good geotechnical conditions, water availability, etc.)[8] and because of increasing environmental concerns, the development potential of conventional PHES systems in Europe is relatively restricted. (Deane et al, 2010)

However, alternative PHES schemes (e.g. sea water, underground PHES, etc.)[9] and also the extension of existing PHES or conversion of existing HES (c.f. JRC, 2011) offer additional development potential for PHES.

[7] Nant de Drance 900 MW, Linthal 1 GW (extension, total capacity will be 1,8 GW), Lago Bianco 1 GW
[8] Most essential of these conditions are access to water and great heights of fall
[9] Another example for alternative PHES schemes is the use of existing reservoirs for artificial snow making in alpine ski resorts within PHES systems when not needed for artificial snow making (c.f. Crettenand, 2011 and Mader et al, 2010)

2.3 Compressed Air Energy Storage

2.3.1 Basic Functional Principle

Principally, a compressed air energy storage (CAES) system compresses a gas (usually air) to high pressures (70 to 100+ Bar) and injects it into either an underground structure (e.g. cavern, aquifer, or abandoned mine) or an above ground system of tanks or pipes to store energy (see Figure 10). To generate electricity the gas is mixed with a fuel (e.g. natural gas), burned and expanded through a conventional or gas-fired turbine which runs a generator. A recuperator can be used to preheat the gas before burning to get higher efficiencies.

Since conventional CAES systems need an additional fossil fuel to recover the stored electricity, CAES systems are not “pure” electricity storage, but hybrid systems. In a conventional gas turbine, roughly two thirds of the power produced is needed to pressurise the air before combustion. CAES systems generate the same amount of electricity as a conventional gas turbine power plant using less than 40 % of the fuel.

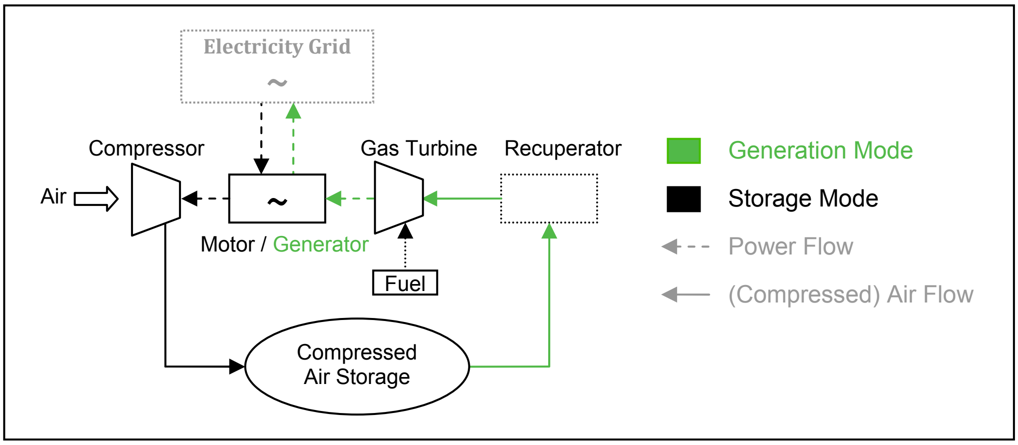

Figure 10: Schematic diagram of a CAES system (Source: EEG)

While the power ratings for storage and generation mode are determined by the number and power of the compressor(s) and turbine(s), the storage capacity of a CAES system is defined by the volume of the compressed air storage and its pressure level.

2.3.2 Subtypes of CAES

Besides conventional CAES (also called “diabatic” CAES) described above there exists an advanced CAES concept, “adiabatic” CAES (AA-CAES). In conventional CAES systems the gas, which heats up during compression, must first be cooled down to the ambient temperature before it can be stored. For discharging, the stored gas must be reheated again (with additional use of a fossil fuel) since it cools strongly when expanding in a turbine for power generation. AA-CAES systems retain the heat produced by the gas compression within a heat storage and return it to the gas when the gas is expanded through an air turbine to generate power (see Figure 11). The heat storage medium can be either a solid (e.g. concrete or stone), or a fluid such as hot oil or molten salt solutions. Therefore, in comparison to diabatic CAES, AA-CAES systems do not need to use an additional (fossil) fuel to “restore” the stored energy and also have a higher overall efficiency. (RWE Power, 2011)

There is also another AA-CAES concept in development, the “un-cooled” AA-CAES, which uses a combined heat and compressed air energy storage. However, this concept has considerably higher storage losses. (Wolf et al, 2009)

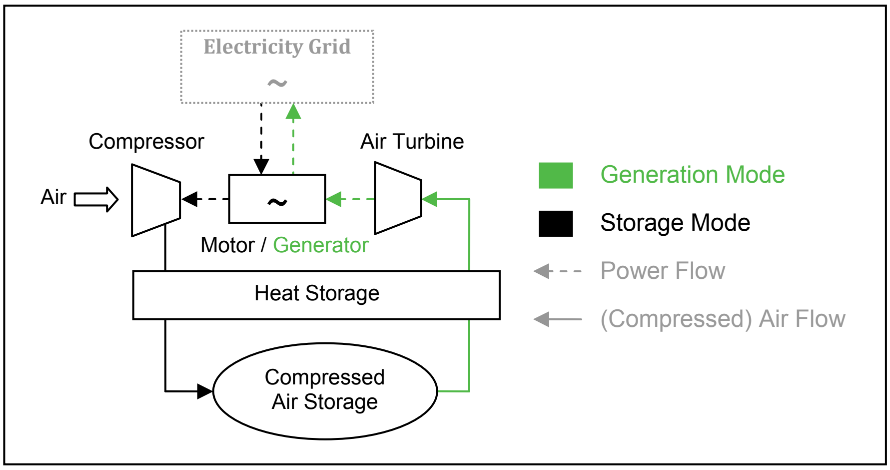

Figure 11: Schematic diagram of an AA-CAES system (Source: EEG)

Currently there exist many different subtypes/concepts from different manufacturers of CAES system, which differ only in minor technical details (used turbines, w/ or w/o air injection, bottom cycles etc.). Also CAES systems which use air as storage medium and oil as working fluid, so-called “hydropneumatic” CAES, are under development. (Wolf et al, 2009)

Another interesting subtype is the Ambient Heat CAES (AH-CAES). AH-CAES systems feed the heat of the compression process directly into the thermal heat grid. During electricity generation the ambient heat is used to expand the stored compressed air in an isothermal process. (IVE, 2011)

Instead of using costly high-pressure vessels or underground (salt) caverns, a new development foresees inexpensive, flexible containments (so called “energy bags”) held down on the sea bed in deep ocean water as compressed air storage. Here the sea/lake acts as the pressure vessel, where, at depths of around 600 m, the pressure is enough to store around 70 MWh in one 20 m diameter bag. (Thin Red Line Aerospace, 2011)

Liquid air energy storage (LAES) systems employ proven cryogenic processes that use liquid air as the energy storage instead of compressed air. The LAES systems operate by using electrical energy to drive an air liquefier and storing the resultant liquid air (~ - 196 °C) in an insulated tank at atmospheric pressure. To recover the stored energy, the liquid air is released from the storage tank, pumped in its liquid form to high pressure, vapourised and heated to ambient temperature by using either ambient heat or waste heat. The resultant high pressure gaseous air is used to drive an expansion turbine and generate electricity. The round-trip efficiency of the LAES system is projected to be between ~ 50 % and 70 %. However, only one pilot plant exists today. (Highview Power Storage, 2012)

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2.3.3 CAES Operation

CAES systems are operated similar to PHES plants, i.e. shifting power generation from off-peak to on-peak times. Figure 12 shows an example for the power generation / consumption and cavern pressure of a CAES plant during a single day. In off-peak times the CAES plant consumes power to pressurize the air in the compressed air storage (e.g. cavern), while in on-peak times this process is reversed and the pressure of the cavern decreases.

The CAES plant in Huntorf (see section 2.3.4) is typically used as a tertiary control reserve[10]: medium load power stations (coal) take 3 – 4 hours to generate full capacity before they are capable of providing short-term power – the intervening time is preferably covered by the CAES plant. (Crotogino et al, 2001)

The Huntorf plant has been operated successfully for over 33 years now. Figure 13 shows the number of starts of the compressor / gas turbine per year from 1977 until 2008. The number of starts made by the plant has fluctuated widely during this operational period, which is attributable on the one hand to the connection to a larger network in 1985 which added pumped hydro capacity. On the other hand, the CAES plant plays the primary role of an emergency reserve in case of unplanned failure of other power plants and also serves as an alternative option to purchasing expensive peak load from outside suppliers. (Crotogino et al, 2001)

2.3.4 Development Status of CAES

The worldwide first commercial CAES power plant went online in 1978 in Huntorf near Bremen in Germany. This 290 MW CAES system uses two dry salt rock caves at a depth between 650 and 800 m and a volume of around 310.000 m^3 as compressed air storage. The storage capacity is enough for two hours of full-load. In 2007 the plant was retrofitted and upgraded to 321 MW. (Radgen, 2009)

After a long period of inactivity in the CAES sector, a second CAES system was built in 1991 in McIntosh, Alabama, USA. This 110 MW CAES plant has storage volume of 560.000 m^3 (enough for 24 hour of full-load) and also uses a recuperator.

Currently there are several projects announced especially in the USA, though some have been in the planning phase since many years now, e.g. the Norton CAES Facility has already been announced in the year 2001 and has not entered its construction phase yet. (SNL, 2001)

So far no AA-CAES system has been built; RWE aims to construct the first AA-CAES plant by 2016 in Germany, called the “ADELE” project. (RWE Power, 2011)

However, the future utilization potential of CAES systems is also dependent on the availability of appropriate underground air storage capacities, especially salt caverns. Even though the availability of such caverns is generally estimated to be good in Europe, site specific geologic characteristics have to be taken under consideration. (VDE, 2008)

Also the competing utilization of underground caverns for storing natural gas or CO_2 (carbon capture and storage, CCS)[11] and accordingly hydrogen in the future, could decrease the availability of underground caverns for storing compressed air. (Gatzen, 2009)

[10] Also called minute reserve, see section 4.3.3 for details

[11] *CAES requires a cushion gas that compresses to store energy when air is injected into the reservoir and then expands to force out the compressed air during withdrawal*. There is also the possibility to use CO_2 as cushion gas instead of air for CAES applications; CO_2 offers greater compressibility which yields to more

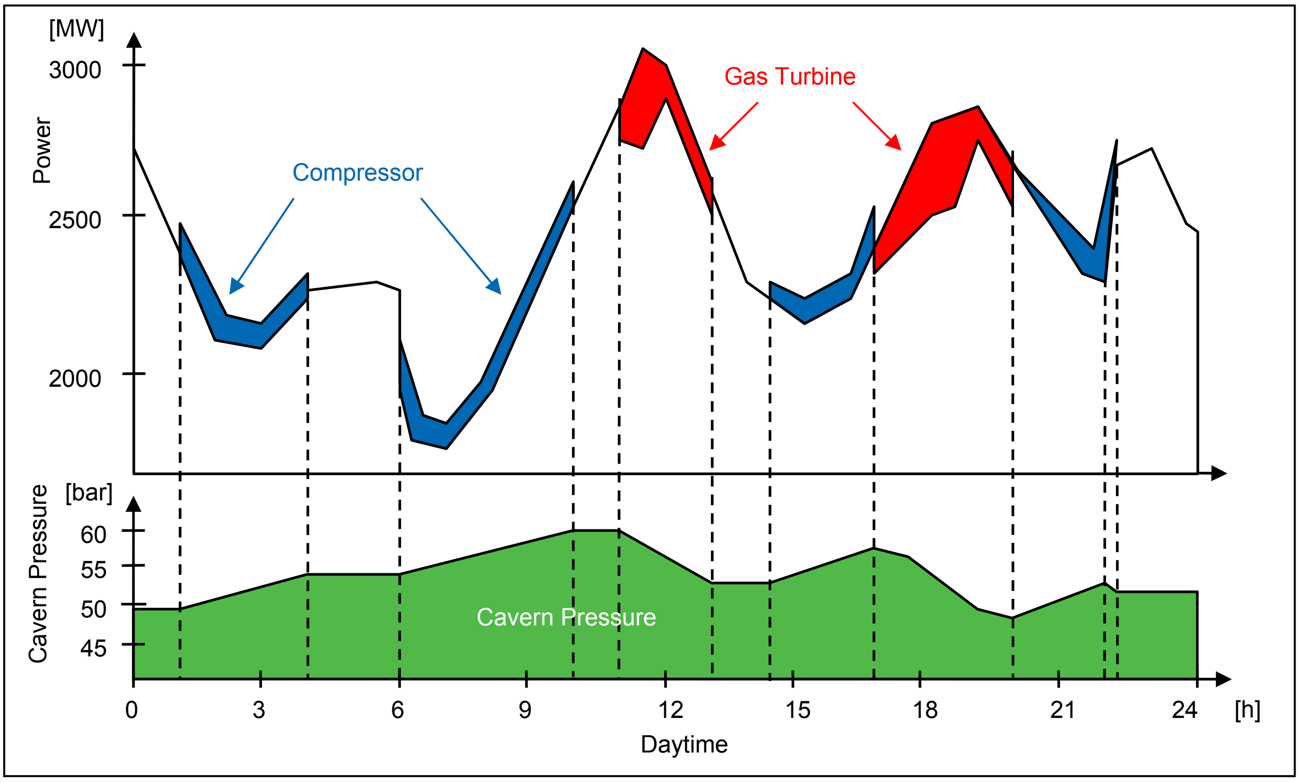

Figure 12: Example of diurnal power generation/consumption of a CAES system (Source: Crotogino et al, 2001)

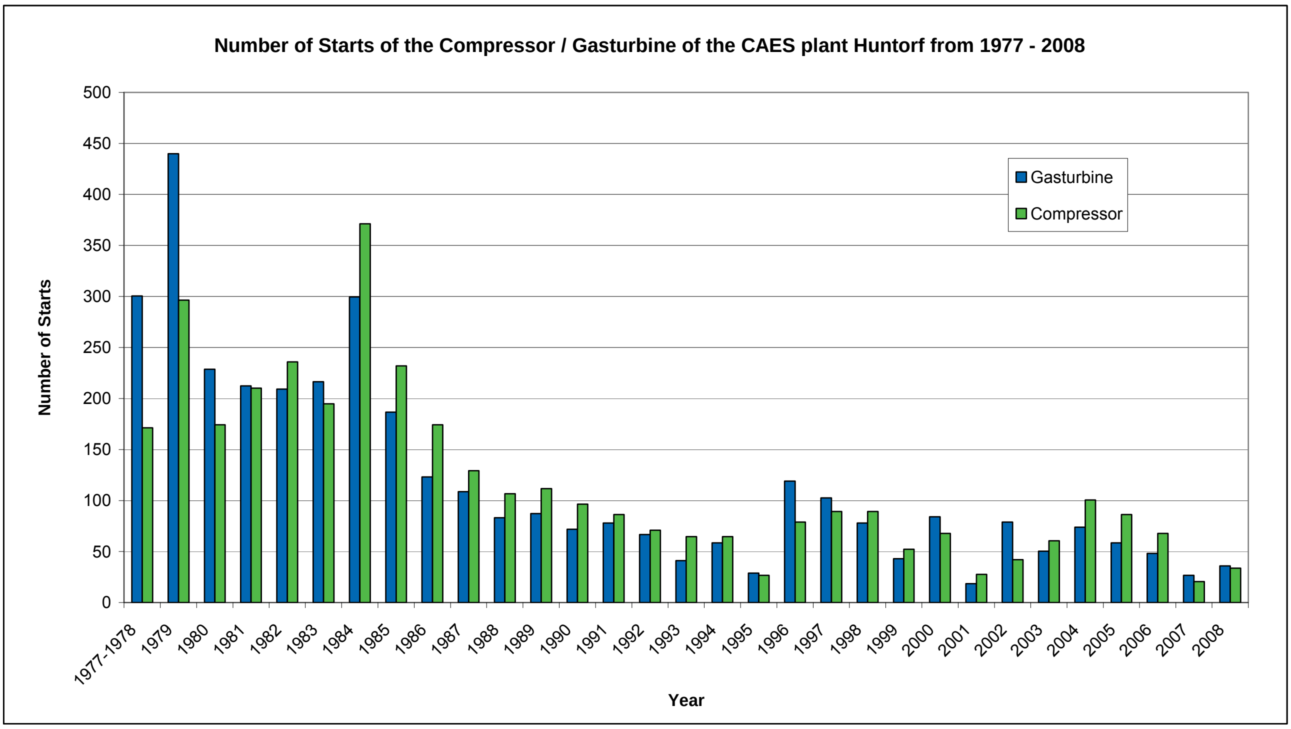

Figure 13: Number of starts of the compressor / gas turbine of the CAES plant Huntorf from 1977 to 2008 (Source: Folke, 2011)

energy storage per unit volume. With this method, CCS and CAES could use the same storage reservoir, since there is only minimal mixing between the gases (USDOE, 2012)

2.4 Other Energy Storage Technologies

Other energy storage technologies which are not subject to the core analysis of the stoRE project are briefly described in the following subchapters in order to provide a complete picture of storage technologies. (based on Mariyappan et al, 2004 and ESA, 2011)

2.4.1 Batteries and Electric Transport

Batteries are electrochemical devices that convert chemical energy into electrical energy during battery discharge. While primary batteries lose all of their electricity when the chemical reactions are spent, secondary or rechargeable batteries can reverse the chemical reaction by the introduction of electricity. The fundamental building block of a battery is a single electrochemical cell, which generally consists of two different electrodes and an electrolyte. The single battery cells can be connected together in variety of configurations to provide the necessary voltage, energy, and power for the application. Many different battery types exist today; in the following sections the most common ones are briefly described:

- ***Lead-Acid Batteries ($PbSO_4$)*** generally use lead and lead oxide as the electrodes and sulphuric acid as electrolyte, are the oldest and most mature battery technology currently in use. Lead-acid batteries are inexpensive and relatively efficient (~70%), however, the deployment is limited by their short cycle life. Lead-acid batteries have been commercial for many years and were also used in a few large-scale energy management applications, like the 10 MW / 40 MWh system in Chino, California, USA (in operation from 1988 to 1996).
- ***Nickel Batteries*** have been manufactured for many years and are the standard batteries for many applications in consumer goods. The two most widely used forms are nickel cadmium (NiCd) and nickel metal hybrid (NiMH). In general, nickel batteries have the main advantages of good power densities and very quick recharging times.
- ***Sodium-Sulphur Batteries (NaS)***, in contrary to most other secondary batteries, have no solid electrodes. Instead, they consist of electrodes made of molten compounds that require heating to remain in the liquid stage (usually 300 to 350°C) and a solid electrolyte. The main advantages of NaS batteries are high efficiencies and cycle lives. NaS battery technology has been demonstrated at over 190 sites in Japan with more than 270 MW of stored energy.
- In ***Lithium-Ion Batteries (Li-Ion)*** lithium ions are reversibly bound to the electrodes. They generally consist of a lithiated metal oxide cathode and an anode which is made of layers of graphitic carbon. The electrolyte of Li-Ion batteries is usually made up of lithium salts dissolved in organic carbonates. Compared to other advanced batteries, Li-Ion batteries have the main advantages of a high energy density and efficiency combined with high voltages. Like nickel batteries, Li-Ion batteries are widely used in consumer electronics, but a number of challenges still remain for large-scale Li-Ion batteries like relatively high cost due to special packaging, internal overcharge protection circuits and thermal management considerations.
- ***Metal-Air Batteries*** use anodes which are made of commonly available metals with high energy density like aluminium or zinc that release electrons when oxidized. Metal-air batteries are sometimes referred to as fuel-cells; the most common one is the zinc-air fuel cell. They have relatively low cost, high energy densities and are also environmentally benign when

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properly disposed. However, the main disadvantage of metal-air batteries is that electrical recharging of them is very difficult and inefficient at the moment.

- ***Flow or Redox Batteries*** essentially store chemical energy in two electrolytes, which are kept in separate tanks. During the truly reversible charge or discharge of the battery, ions are exchanged between the two electrolyte tanks through an ion permeable membrane. One of the main advantages of flow batteries is that they allow decoupling of storage capacity (volume of electrolyte tanks) and peak output (number of cells and surface area of electrodes).Three main types of flow or redox batteries exist, which are zinc-bromine flow (Zn-Br), vanadium redox flow (VRB) and polysulphide bromide batteries. Each of them has some unique features, but they are relatively comparable in terms of capability and price range.

Efficient batteries, in terms of energy storage and energy density, are also a precondition for the widespread deployment of electric transport / Electro-Mobility (E-Mobility). With increasing fleet sizes, E-Mobility will also become an interesting option for storing large amounts of electricity. However, schemes for storing and restoring electricity from E-Mobility are still under development and are strongly related to the deployment of Smart Grids.

2.4.2 Hydrogen and Fuel Cells

Hydrogen (H_2) is produced via electrolysis of water and can be used within a fuel cell to generate electricity. Similar to batteries, fuel cells consist of two electrodes separated by an electrolyte. Electricity is generated through an electrochemical reaction that only has the by-products of heat and water. As primary reactants, fuel cells can use hydrogen and oxygen, but they can also operate on a variety of other fuels (e.g. natural gas). An electricity storage system based on a fuel cell typically consists of an electrolyser to split water, a hydrogen storage (tank, cavern etc.) and a fuel cell to transform hydrogen to electricity. Since hydrogen has a relatively low density, special storage systems are necessary. The storage options include high pressure accumulators (e.g. high pressure storage tanks, underground salt and rock caverns etc.), storing hydrogen in liquid form (costly) and the binding of hydrogen to solids such as metal hybrids or carbon compounds etc.

The five most common types of fuel cells are Alkaline Fuel Cells (AFC), Proton Exchange Membrane Fuel Cell (PEMFC), Phosphoric Acid Fuel Cell (PAFC), Molten Carbonate Fuel Cell (MCFC) and Solid Oxide Fuel Cell (SOFC). They are characterised by different electrolytes, electrolysers operating temperatures etc. The main advantages of hydrogen fuel cell storage systems (HFCSS) are their modular design, potential for combined heat and power (CHP) supply and that they can use hydrogen from non-electricity sources. Contrary to this, fuel cell systems have high cost and are limited by current hydrogen storage options.

A rather new concept foresees the conversion of hydrogen (e.g. produced via electrolysis from RES-E) and CO_2 to methane (CH_4) (“Windgas”), which could be stored and distributed through the existing gas infrastructure. The “renewable” methane could then be used by conventional thermal power plants to generate electricity. The major drawback of Windgas is the low overall efficiency of about 25% but has the advantage that existing gas infrastructure could be used. (Sterner et al, 2011)

2.4.3 Flywheels

Similar to PHES and CAES, flywheels store electricity as mechanical energy, more precisely in kinetic or rotary motion. A flywheel usually consists of the following main components: a magnetic bearing, a steel tube container (vacuumed), a composite or steel rotor and a motor/generator. To store energy, the rotor is accelerated by the electrical motor until it reaches the maximum speed. When the maximum speed is reached, the flywheel is “fully charged”. To discharge or generate electricity, the machine is used in generator mode, which slows down the flywheel.

Flywheels can be either built as low-speed (e.g. steel rotor) or high-speed (e.g. composite rotor) systems. Since the amount of energy that can be stored in a flywheel is a function of the square of its revolutions per minute, the high-speed system contains nearly ten-times more energy because of higher rotational speeds. This clearly favours the development of high-speed models, with increasing rotational speeds to reduce the losses created by the friction of the rotating cylinder. Flywheels have the main advantages of having a long life, high power/energy densities and high efficiencies (~ 80%) and also of being compact at the same time. Furthermore, flywheels have a very low environmental impact. The main drawback of flywheels is their relatively high costs.

Today many small-scale high-speed flywheels are used in uninterruptable power supply and telecommunication applications. However, utility scale storage is also possible by combining multiple units into a “flywheel farm”, which can be used to store megawatts of electricity for applications needing minutes of discharge duration. An example of this is the “Smart Energy Matrix^{tm}”, a 20 MW frequency regulation plant from Beacon Power, USA, which comprises 200 high-speed high energy flywheels. (Beacon Power, 2011)

2.4.4 Electromagnetic Energy Storage

Electromagnetic energy storage systems store electricity “directly” without transformation in the electromagnetic fields. The main technologies are supercapacitors and superconducting magnetic energy storage (SMES) technologies.

- ***Supercapacitors:*** The capacitive energy storage is based on the parting of positive and negative electrical charge carriers. While normal capacitors have capacities in the range of up to some milli-Farad, supercapacitors have capacities in the range of some kilo-Farad. Supercapacitors are basically double-layered versions of normal capacitors but with considerably higher electrode surfaces and a fluid electrolyte. The layout of a supercapacitor is similar to a battery: two electrodes are immersed in an electrolyte with a separator, which is permeable for ions, between them. When a current is applied, dissociate ions in the electrolyte move to the electrodes and form an electrical double-layer together with the accumulated charge on the surface of each electrode. This way electricity is stored in the form of electric charge between the two electrode plates. Compared to lead-acid batteries, supercapacitors have lower energy density but they have longer cycle lives and faster charge and discharge capabilities than batteries. However, large-scale commercial supercapacitors are still under development, with cost being the greatest hindrance to date.
- ***Superconducting Magnetic Energy Storage (SMES):*** Superconducting magnetic energy storage (SMES) systems store electrical energy in the magnetic field of a coil. They typically consist of a superconducting coil, a power conditioning system, a refrigeration system for cooling of the coil and a cryostat/vacuum vessel. The superconducting material itself has very little resistive losses, but has to be cooled down by the cryogenic system to very low temperatures (~ 5 K). This cooling is mainly done with liquid helium, which leads to considerable high operational costs. The major advantages of SMES systems are their high efficiencies (~ 95%) and their ability to provide very high output and fully recharge in minutes. However, since SMES systems are relatively new technologies, there are only a number of demonstrations and prototypes taking place.

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2.5 Comparison of Key Technology Parameters of Energy Storage Technologies

Following the description of the individual electricity storage technology options, this section focuses on their key technological parameters. Therefore, Table 1 shows a comparison of the main properties of the previously discussed EST.

Table 1: Main properties of electricity storage technologies (based on Graabak et al, 2009, ESA, 2011 and Wietschel, 2011)

Technology	Typical Capacity	Response time	Discharge time	Efficiency	Life time	Development stage	Application[12]
Pumped hydro energy storage (PHES)	5 MW – 2 GW	1 min (if standing still) 10 sec (if spinning)	4 - 100 h	55-85%	50+ years	Mature	Primary[13] / secondary / tertiary control, energy arbitrage
Compressed air energy systems (CAES)	25 MW – 2.5 GW	15 min from cold start	2 - 24 h	40-70%	15-40 years	Mature / premature (AA-CAES)	Tertiary control, energy arbitrage
Batteries	1 kW – 50 MW		1 min – 3 h	65-75%	2-10 years	Premature / mature	Uninterruptible power supply, RES-E fluctuation reduction, primary / secondary control
Flywheels	5 kW – 20 MW		4 sec - 15 min	90-95%	~20 years	Mature	Primary control, power quality
Hydrogen Fuel Cell Storage System (HFCSS)	1 kW – 10 GW	Depends on fuel cell	0.01 sec-days	20-40%	5-10 years	Prototype	RES-E fluctuation reduction, tertiary reserve
Super magnetic energy storage (SMES)	10 kW – 1 MW		5 sec – 5 min	95%	~30 years	Premature	Uninterruptible power supply, power quality
Supercapacitors	< 150 kW		1 sec – 1 min	85-95%	~10 years	Premature	Uninterruptible power supply, power quality

From the assessment in Table 1 and especially from Figure 14, it can be clearly seen that PHES and CAES systems have major advantages concerning their capacities and discharge times in comparison to the other technologies. While batteries, flywheels, SMES and supercapacitors can only be deployed for short time periods up to a few hours, PHES and CAES have longer discharge times of up to a day. Therefore it is clear that PHES and CAES systems are the only mature large-scale energy storage systems available at present.

Hydrogen Fuel Cell Storage Systems (HFCSS) are an exception here; HFCSS also have the theoretical potential for longer discharge times and capacities, both depending on the amount of hydrogen stored. Since HFCSS are currently only available as prototypes or under research, the

[12] See chapter 4 for more details about applications of EST
[13] Primary control reserve can be provided if the turbine is already spinning

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properties of HFCSS will have to be verified in the future. Besides that, HFCSS suffer from low overall efficiencies of about 40 %, which is the result of a maximum efficiency of 70 % for electrolysis combined with an efficiency of ~60 % for power generation.

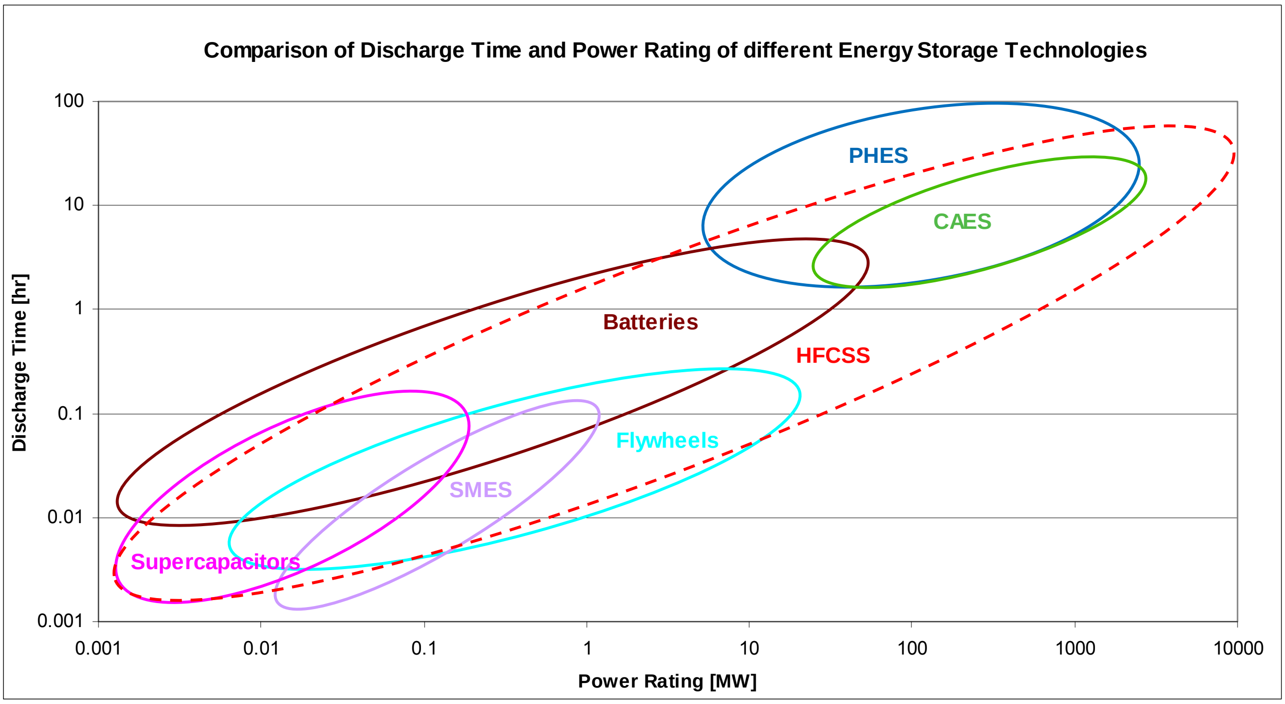

Figure 14: Comparison of discharge time and power rating of different electricity storage technologies (Source: EEG)

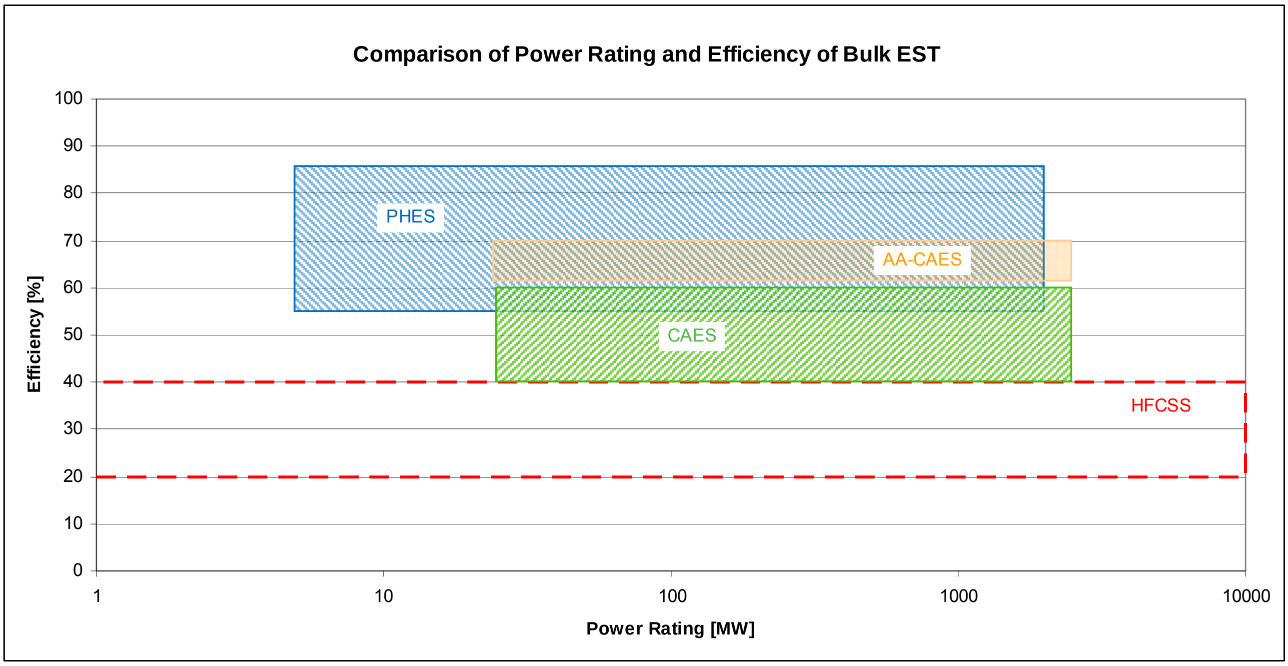

Figure 15: Comparison of efficiency and power rating of bulk electricity storage technologies (Source: EEG)

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Currently CAES systems have an efficiency of about 55 %, with a potential to reach up to 70 % in the future when new systems like AA-CAES are mature (compare Figure 15). In comparison with PHES systems, CAES systems offer lower efficiencies (compared with up to 85 % for PHES), shorter lifetimes and also slower response times. These disadvantages clearly favour the deployment of PHES systems at the moment for large-scale electricity storage. However, both systems can be used, amongst other applications (see chapter 4 for more details about applications), as tertiary reserve and also for price arbitrage for energy traders.

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3 Cost of Bulk Energy Storage Technologies

After describing the different storage technologies in the previous section from a technical point of view, this chapter focuses on the economics / costs of the two bulk energy storage technologies, PHES and CAES.

Generally, the cost of a power plant can by divided into capital cost for the construction and variable cost for the operation of the power plant. These two types of costs are described separately in the following sections.

3.1 Capital Cost

Figure 16 shows a comparison of the capital cost of bulk EST (PHES, CAES, AA-CAES) per power (€/kW) / per energy output (€/kWh)[14] and also indicates the costs of HFCSS. These values represent typical capital costs of each EST, whereas some storage plants may show different (even larger) costs due to plant specific characteristics.

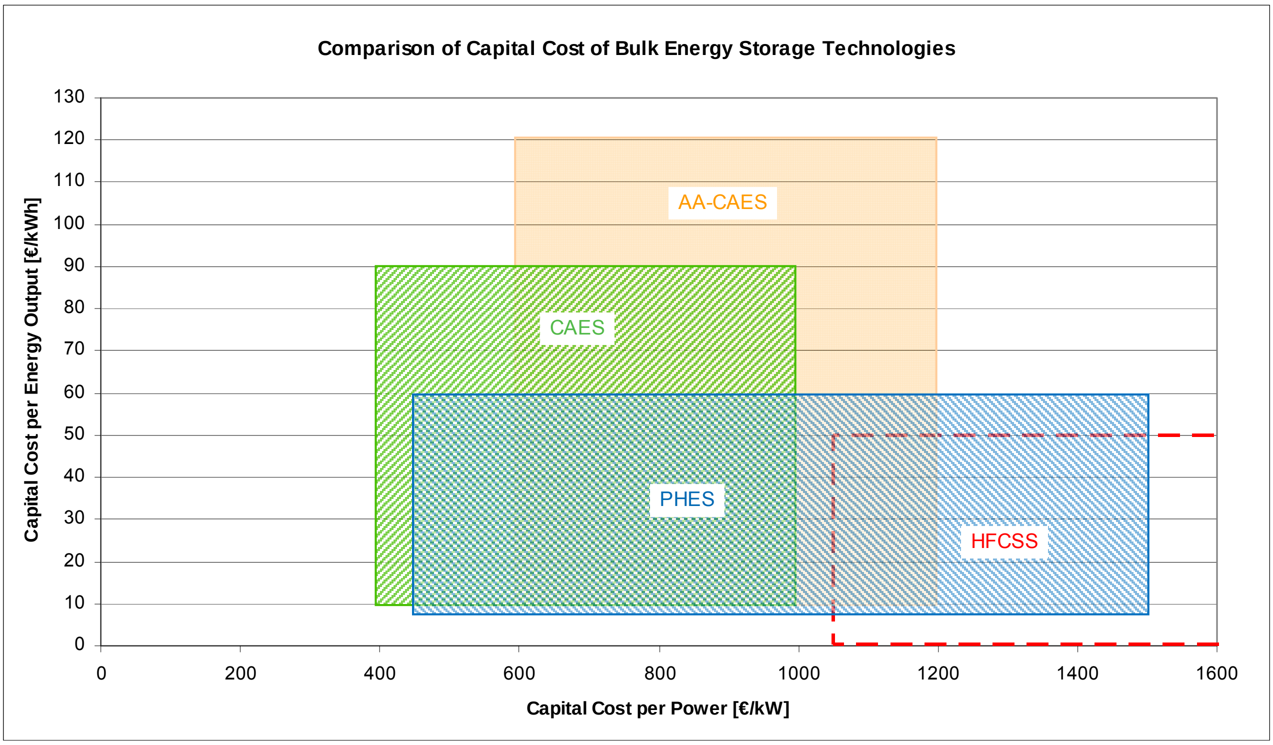

Figure 16: Comparison of the capital cost of bulk EST (Source: Wietschel, 2011)

Typically, PHES plants are characterised by long asset life (typically 50 – 100 years), high capital cost and low operation and maintenance (O&M) cost. Project costs for PHES systems are very site

[14] Under consideration of typical storage capacity, power rating and efficiency of the technology

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specific with some quoted costs varying from of 450 – 2500 €/kW. Additionally capital costs depend not only on the installed power but also on the energy storage (reservoirs) and power rating at any given site. Since PHES is a mature technology, its capital cost is not expected to change substantially in the future. Figure 17 details the specific investment cost (based on the published capital costs) and installed capacities (indicated by the diameter of the corresponding circle) for some existing and proposed PHES plants in Europe until 2020. The capital costs per kW for proposed PHES are between 470 €/kW and 2170 €/kW, whereas the majority are either extensions to existing projects, repowering of projects or pump-back PHES. However, it can be seen that most of the projects are between 500 €/kW and 1500 €/kW.

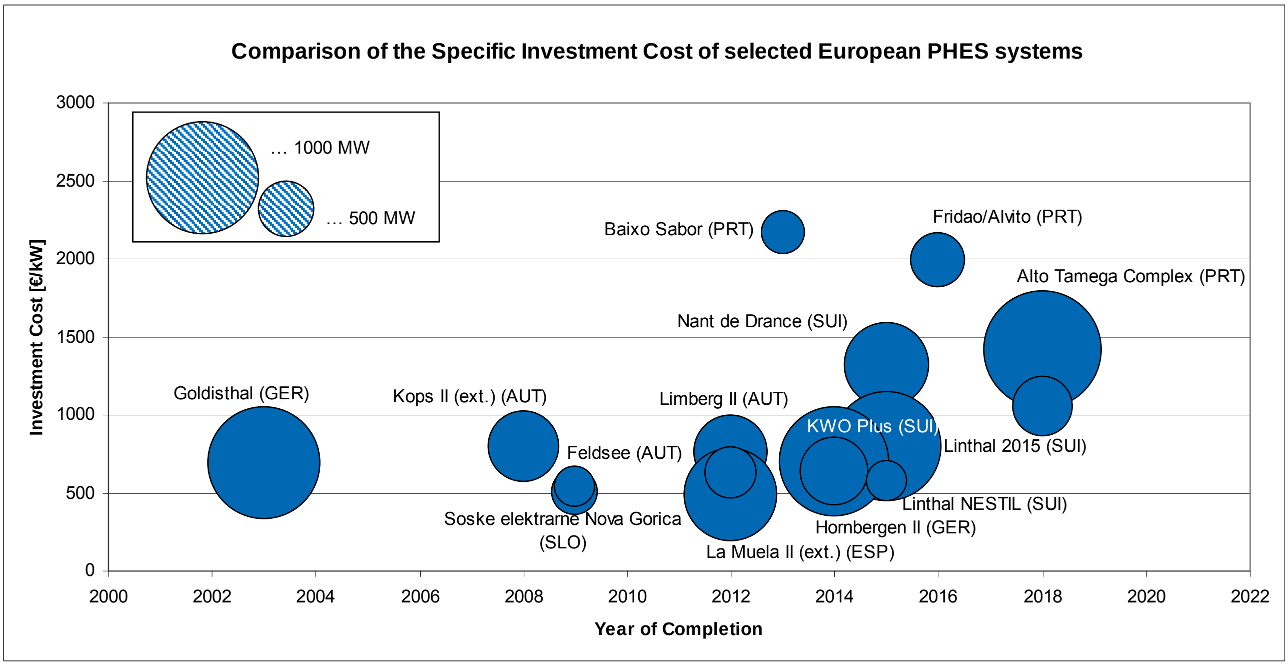

Figure 17: Comparison of the specific investment cost of some existing and proposed PHES plants in Europe until 2020 (Source: Deane et al, 2010)

A great number of existing PHES plants were built before liberalized markets by state owned utilities. Now, as the latest deployments of new PHES plants in Europe show, developers operating in liberalized markets tend to repower, enhance projects or build ‘pump-back’ PHES rather than conventional “pure” pumped storage. This trend is partly driven by a lack of economically attractive new sites. Furthermore, repowering or enhancing of existing plants is less capital intensive since existing infrastructure, usually reservoirs, is used and this also reduces environmental and planning issues. Repowered plants benefit from improvements in technology and design and usually use more efficient and larger turbines/pumps. “Pump-back” facilities have the advantage that the energy storage capacity is generally much greater[15]. PHES systems with significant hydro inflow may also operate as conventional hydroelectric generation units during times of excess inflow which also helps to increase the economic competitiveness of the plant. (Deane et al, 2010)

In contrast to the large deployment of PHES systems, currently only two operational CAES plants exist. Both, the Huntorf and McIntosh CAES plant, had about the same specific investment costs of ~ 400 €/kW. Current investment costs are estimated to be between 450 – 1000 €/kW, strongly

[15] Additionally, pump-back retrofits also have lower environmental impacts from construction than alternative PHES configurations.

dependent on the structural conditions of the site, e.g. cavern condition, form and volume. Since no AA-CAES plant has been realised to date, investment cost estimations are more uncertain. However, current assessments state a bandwidth of 600 – 1200 €/kW, where the lower boundary represents the estimated cost in the medium term due to technological learning / economies of scale. The major cost difference between a CAES and an AA-CAES system is the additional cost for thermal storage.

3.2 Variable Cost

The variable cost of bulk EST consists of operation and maintenance (O&M) cost, the cost of the charging current as well as optionally fossil fuel costs (in case of conventional CAES). O&M costs of PHES systems are about 1 – 2 % of its investment costs, whereas for CAES O&M costs are in the range of 0,6 to 2 % of its investment costs (without fossil fuel costs). In Table 2, the O&M costs of PHES and CAES are divided further into fixed (€/kW/yr) and variable O&M costs (€/kWh). However, O&M costs of CAES systems show a larger bandwidth, since they also depend on the compressed air storage technology used: cavern/reservoir systems are on the lower end, vessels on the upper end of the cost spectrum.

Table 2: O&M costs of PHES and CAES systems (Source: Connolly et al, 2010)

Technology	O&M Costs		
	% of Investment Cost	Fixed [€/kW/yr]	Variable [c€/kWh]
PHES	1 – 2	3,8 (6 – 11)[16]	0,38
CAES	0,6 – 2	1,42 – 3,77 (< 13)	0,01 – 0,27

In order to compare different EST, it is necessary to define reference cases. Otherwise, life time, efficiencies or investments for the storage alone are not adequately considered. Therefore, the overall costs of a daily storage and a long term storage are compared for the different bulk EST.

Figure 18 shows a comparison of the electricity generation cost of a daily storage realised with different bulk EST (also including hydrogen) at two different charging electricity levels[17]. It can be seen that the charging current has a big influence on the overall electricity generation cost. However, PHES systems are the most cost effective solution here (site specific), followed by AA-CAES plants as the next best (future) alternative. Because of the additional cost factor for fossil fuel, conventional CAES systems are only the third best solution, but get increasingly interesting with increasing charging electricity price. Additionally, CAES systems suffer from the risk of increasing gas and CO_2 prices.

[16] Values in brackets based on Danish Energy Agency, 2010

[17] Calculation based on a daily storage with one cycle per day, a generation capacity of 250 MW, a storage capacity of 2000 MWh / 8 h, a capacity factor of 33 % and an interest rate of 10 %.

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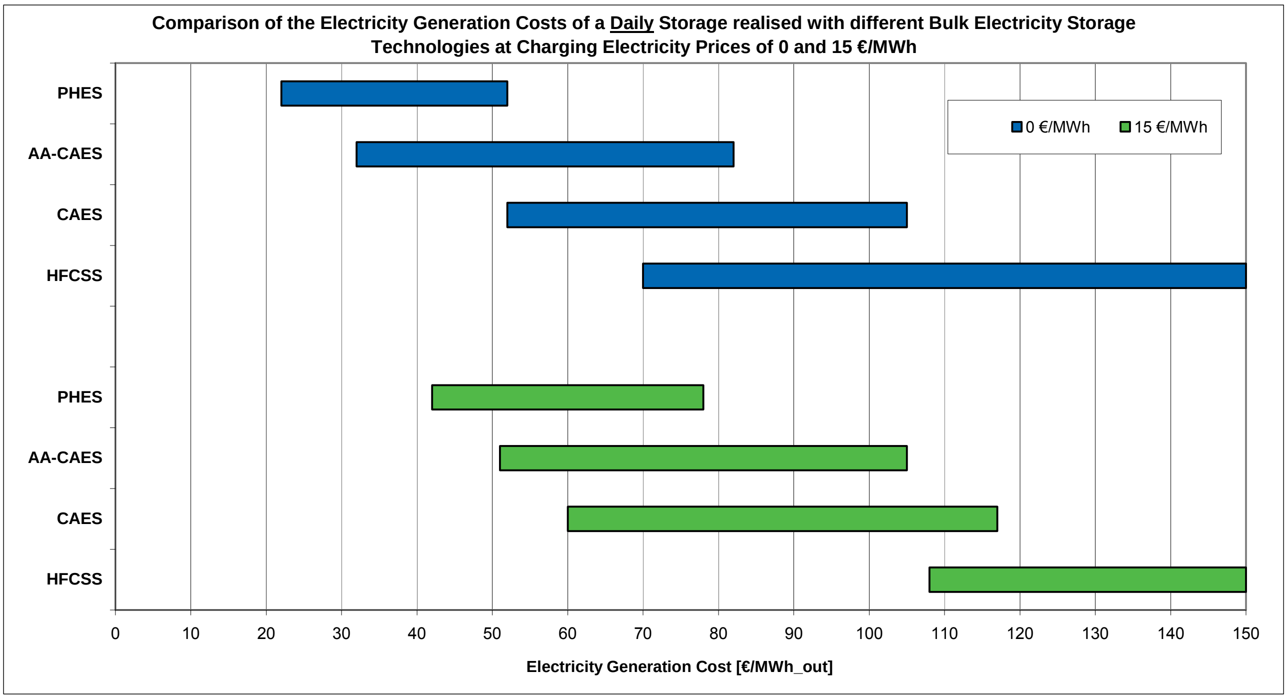

Figure 18: Comparison of the electricity generation cost of a daily storage realised with different bulk energy storage technologies at two different charging current prices (Source: Wietschel, 2011)

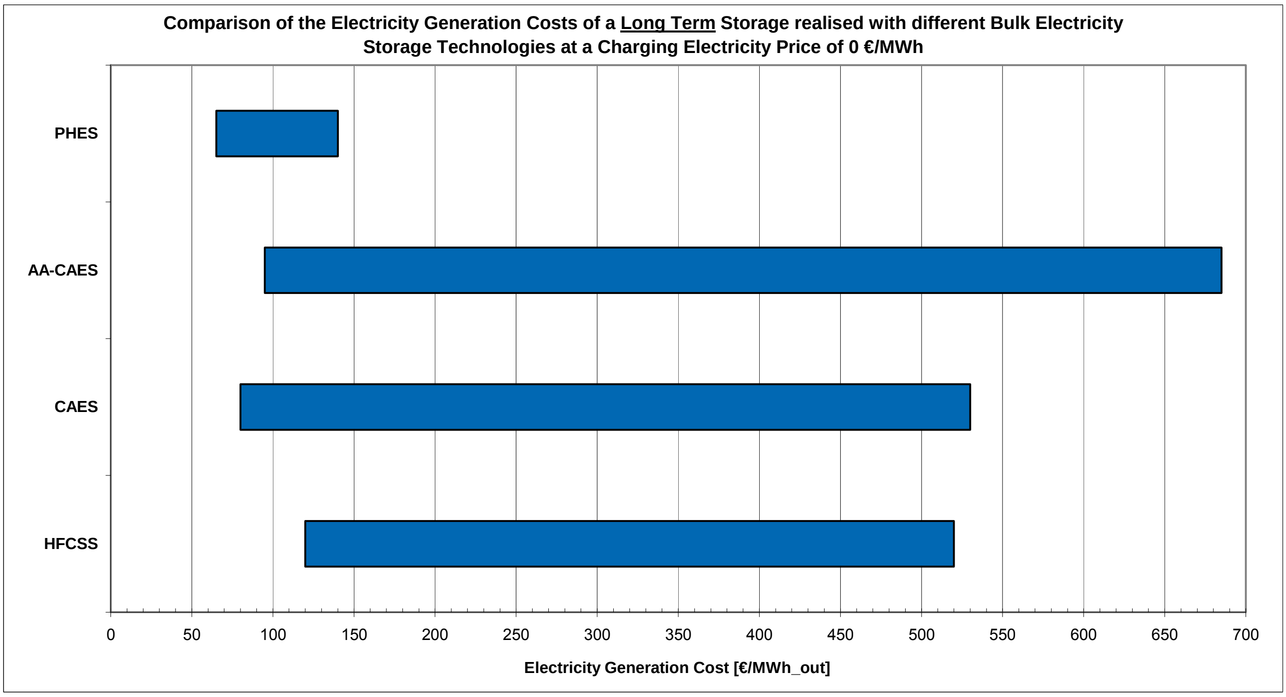

Figure 19: Comparison of the electricity generation cost of a long term storage realised with different bulk energy storage technologies at a charging current price of 0 €/MWh (Source: Wietschel, 2011)

In distinction to the daily storage, Figure 19 shows the electricity generation cost of a long term storage realised with different bulk EST[18]. The layout as long term storage results in high overall electricity generation costs for all technologies (compared to conventional power plants). Again PHES systems have the lowest resulting costs, followed by CAES systems (high costs related to storage capacity). AA-CAES systems additionally suffer from high costs related to the heat storage capacity. HFCSS with cavern storage may also become an alternative long term storage option in the future.

As said before, most PHES systems were built before electricity market liberalisation. Nowadays, in liberalized electricity markets, PHES and CAES projects may be remunerated through ancillary services payments, capacity payments and electricity trading. Usually electricity trading is the major source of revenue for PHES and CAES systems since operators may take advantage of energy arbitrage opportunities.

Neglecting O&M costs, energy arbitrage is profitable for EST when the overall efficiency of the plant is greater than the ratio of the electricity prices for storage and generation.

$$\eta > C_{store} / C_{generate}$$

η … overall efficiency of EST; C_{store} ; $C_{generate}$ … Electricity cost during storage; generation

Therefore, for arbitrage pumping, the price has to be at least 20 – 30 % lower than the selling price to compensate for energy losses. This also implies that significant volatility (not necessarily high energy prices) must be present in the wholesale price of electricity to make revenue. (Dena, 2010)

However, PHES systems are risky investments without an additional, more predictable profit other than energy arbitrage like e.g. revenues from ancillary services, capacity payments or a balancing market. (Connolly et al, 2011)

[18] Calculation based on a long term (weekly) storage with 0,06 cycle per day, a generation capacity of 500 MW, a storage capacity of 100 GWh / 20 h, a capacity factor of 50% and an interest rate of 10%.

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4 Overview of Applications for Energy Storage Technologies

4.1 Introduction

EST can be used for a number of applications on different time scales, which are not all directly related to the support of variable / intermittent RES-E generation. However, the different applications contribute to the development, cost reduction (technological learning) and deployment of different types of storage technologies. The applications, where EST can be used, are divided into the following main areas:

- RES-E management applications
- Generation and reserve capacity provision
- Transmission and distribution applications

In the following sections, the different areas of applications are discussed in detail.

4.2 RES-E Management Applications

The management of variable / intermittent RES-E generation is an important application of EST. Essentially, RES-E management applications of EST can be described as output smoothing of variable / intermittent RES-E generation on different time scales. Figure 20 shows the basic principles of output smoothing.

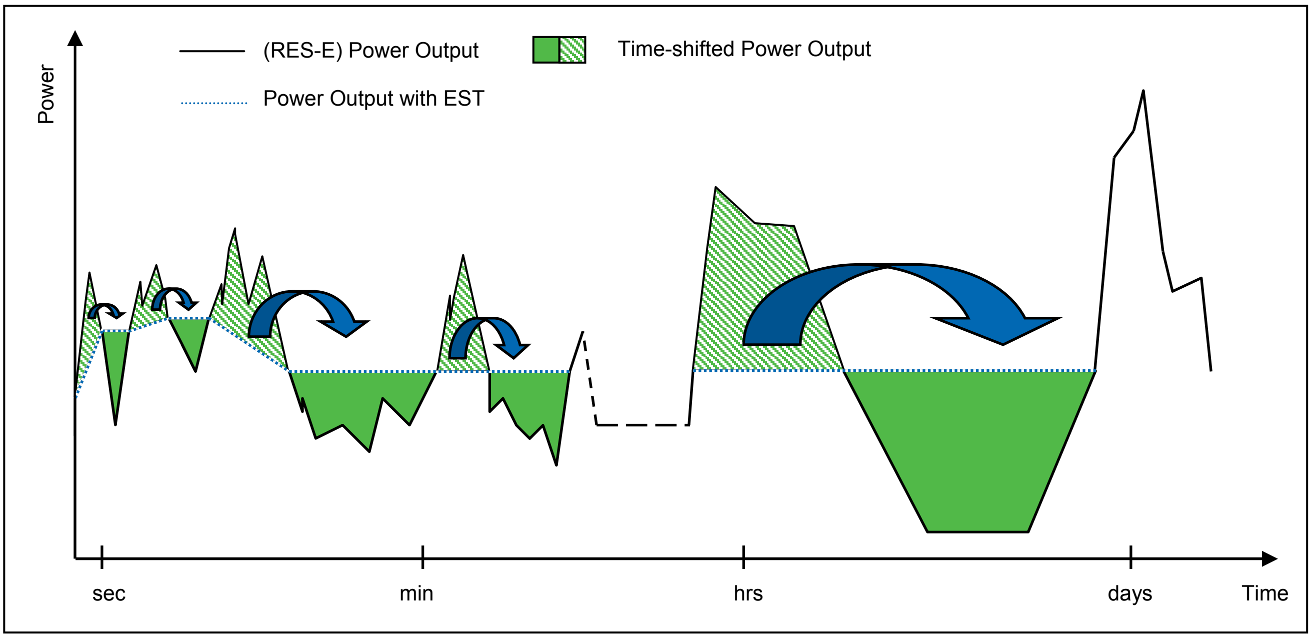

Figure 20: Basic principles of output smoothing of EST on different time scales (i.e. storage capacities and response times) (Source: EEG)

Variable and/or intermittent RES-E generation (e.g. wind, PV) impose very short–term challenges for the electricity system due to their unpredictability and inability to following load. EST can help to

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control and synchronize many individual RES-E generation units, so that they resemble conventional power plants in their ability to reduce or increase output on demand ("virtual power plant"). Furthermore, voltage flickers or surges[19] common to intermittent RES-E generation can be reduced by EST, which could also enable de-rating of power components and connection of new RES-E generation technologies to a lower voltage level. Generally, this short-time output smoothing requires EST with very low response times like flywheels, super-capacitors or SMES.

In the time interval of a few seconds to minutes, EST can deal with excessive power output which could not be absorbed by the network at that particular moment and discharge the power delayed when the network is ready again. This helps to gain advantage of all power generated by RES-E technologies without the need to shed excess generated electricity, i.e. the curtailment of RES-E will be reduced (c.f. Ummels et al, 2008; Tuohy et al, 2011). Besides flywheels, batteries and both bulk EST are also well-suited technology solutions for this area.

In longer time periods, EST enable firming up and backup of variable / intermittent RES-E generation to allow for extended periods of low electricity generation which typically characterises patterns of wind and / or PV generation. This also allows RES-E generation to take advantage of daily load patterns, enabling them to shift generation in time (intraday) and, furthermore, to capitalise higher peak load prices. Applicable technologies for firming up and backup of intermittent / variable RES-E generation include PHES, CAES, batteries and fuel cells.

However, it is generally not cost effective to provide dedicated balancing EST for variable RES-E generation in large power systems, since the variability of all loads and generators is effectively reduced by aggregation. (IPCC, 2011)

4.3 Generation and Reserve Capacity Provision

Generation and reserve capacity provision is the second important field of applications and potential market segment for EST, especially for bulk EST. The discussion of this field of applications is divided into three categories:

- Primary, secondary and tertiary control
- Blackstart capability
- Load levelling or commodity storage

4.3.1 Primary, Secondary and Tertiary Control

Any imbalance between electric power generation and consumption will result (in real-time) in a frequency change within the entire network of the synchronous area, i.e. a frequency deviation occurs. If the system frequency declines below 50 Hz, the total demand has been larger than the total generation. If the frequency rises above 50 Hz the total demand has been less than the total generation. To stabilise the system frequency to 50 Hz after a sudden imbalance, the primary control activates the primary control reserves (also called rapid or spinning reserve), which allow a balance to be re-established at a system frequency other than the frequency set-point (see Figure 21). Primary control reserves are provided by all transmission system operators (TSO) connected to the synchronous area and have to be fully activated within max. 30 seconds after a deviation occurs (ENTSO-E, 2011).

[19] EST can also help to provide necessary protection from voltage spikes and sags which may cause damage or malfunction of sensitive electronic devices, i.e. EST enhance the power quality.

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Since primary control reserve has to be capable of being activated within seconds, normally bulk EST (PHES & CAES) cannot be applied[20].

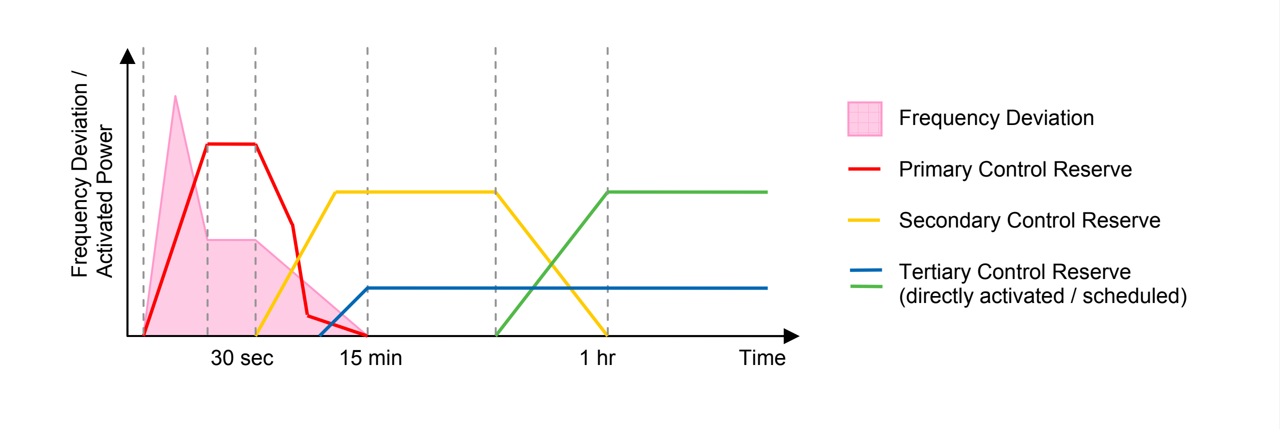

Figure 21: Principal of frequency deviation and subsequent activation of reserves (Source: ENTSO-E, 2011)

Secondary control reserve (or standing / energy imbalance reserve) is activated after 30 seconds to restore system frequency to 50 Hz within the synchronous area and to rebalance generation and consumption within each control area / block. Whereas all control areas have to provide mutual support to primary control reserve, only the control area / block affected by a power imbalance is required to undertake secondary control action for correction. Since, in practise, electricity demand varies continuously (even without forecast errors), secondary reserve is required on a continuous basis. Further on, its activation makes primary control reserve available again (ENTSO-E, 2011). EST suited for secondary control reserve includes among others also PHES systems.

Tertiary control reserve (also called minute reserve) is typically operated in succession or, in case of larger incidents, as a supplement to secondary control reserve. Its function is to free up secondary control reserve and any primary control reserve still in use (compare Figure 21). It is usually activated manually by the TSO in the case of observed or expected sustained activation of secondary control. Total tertiary control reserve of a control block / area has to be larger than the largest expected loss of power (generation unit, power feed-in etc.) of the control block / area (ENTSO-E, 2011). Besides bulk EST (PHES, CAES), batteries and fuel cells are also well-suited technology solutions for this area.

Table 3 provides an overview of the applicable control reserve for bulk EST (PHES & CAES).

Table 3: Applicable control reserves for bulk EST

Technology	Applicable Control Reserve		
	Primary	**Secondary**	**Tertiary**
PHES	(X)[16]	X	X
CAES			X

[20] However, some special PHES systems exist, like the Dinorwig PHES in UK, which can set the turbine units spinning in air when the generators are on standby. This way it is able to provide power in around 12 seconds and is therefore also applicable for primary control reserve (Edison Mission Energy, 1999)

4.3.2 Blackstart Capability

Blackstart is the ability of a power plant / electricity system to start-up and provide necessary power to re-energise the grid and start other power generating systems without the use of an external power resource after a complete outage or islanding situation. Only power plants with no or very low start-up energy needs (e.g. provided by diesel engine / generator etc.) have the ability of a blackstart. Another important feature of a blackstart-compatible power plant is its flexible controllability, which allows it to cope with demand variations when new loads are connected. In particular, PHES, hydro, gas and compressed air power plants are well-suited technologies for this kind of services. So the two main bulk EST highlighted in this document (PHES, CAES) can be awarded to perfectly incorporate the functionality of blackstart capability.

4.3.3 Load Levelling or Commodity Storage

Similar to firming up variable / intermittent RES-E generation, load levelling and commodity storage applications seek to take advantage of cheap off-peak electricity generation units, to store electricity and then sell it in the market again during high-price hours. The major difference between firming up RES-E generation and load levelling is that load levelling occurs much more frequently and on a larger-scale, i.e. capacities > 100 MW being discharged over periods of up to 10 hours on a daily basis. Additionally, generation, transmission and distribution systems benefit from a more uniform load factor. This application area is well-suited for bulk EST technologies like PHES and CAES.

An interesting coherence of load smoothening by bulk EST and the resulting wholesale electricity prices is shown in Figure 22 and Figure 23. During the minimum load period, the electricity demand is covered by base- and mid-load power plants (e.g. nuclear, run-of-river and lignite power plants) which are characterised by low running costs. In peak-load hours (e.g. midday) additional peak-load power plants are needed to cover the demand. In general, these peak-load power plants (e.g. gas power plants) are characterised by low capacity factors and high operation costs (i.e. high marginal costs). Therefore, only low specific costs incur for the meeting of the base-load, while covering the peak-load is connected to high specific cost. Bulk EST have the ability to decrease this price and electricity demand spread (Dena, 2010).

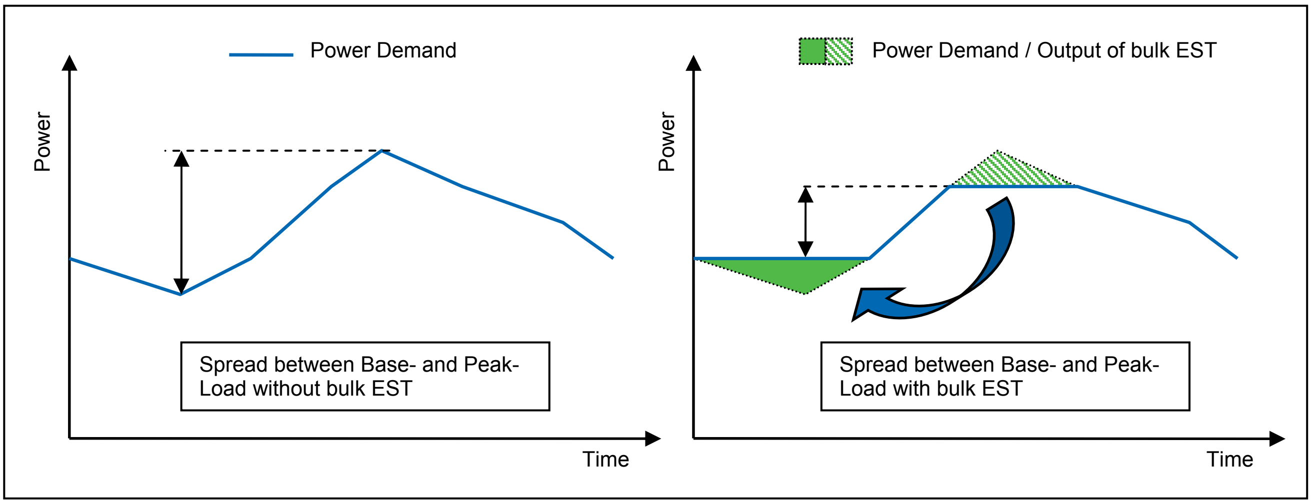

Figure 22: Bulk EST influencing spread between base- and peak-load (Source: EEG)

In general, bulk EST store electricity in periods of low demand, which leads to an increase in demand in these periods (green coloured area in Figure 22 (right)). In peak-load hours bulk EST “restore” electricity, i.e. the residual peak-demand is lower than without bulk EST (green hatched area in Figure 22 (right)). These two effects result in a smaller spread between base- and peak-load compared to a case without bulk EST.

Figure 23 shows the influence of bulk EST on the wholesale electricity price. Through “restoring” electricity in peak-load hours ($P_{on\text{-}peak}$) by bulk EST, the electricity price during this period can be significantly lowered ($C_{w/o\ PHES}$ => $C_{w/\ PHES}$), since the use of costly peak-load power plants is avoided. On the other hand, the electricity price during the minimum load period ($P_{off\text{-}peak}$), when electricity is stored in bulk EST, is characterised by a smaller increase due to a more moderate incline of the marginal cost curve. In this way, high price electricity generation during peak-load hours is substituted by cheap base-load generation (Dena, 2010).

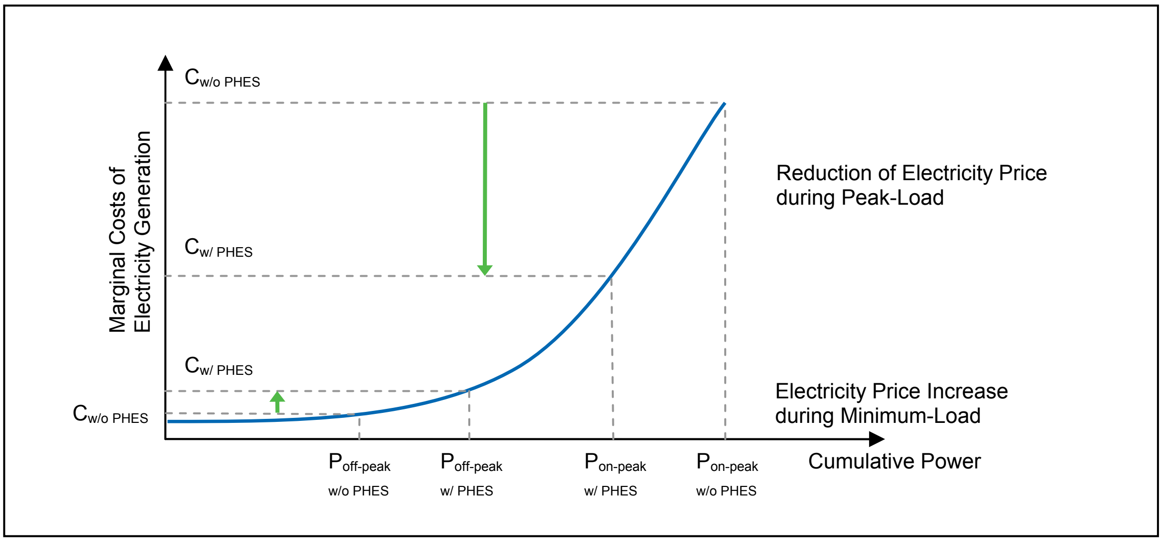

Figure 23: Bulk EST influencing wholesale electricity prices (Source: Dena, 2010)

Figure 24 shows the long-term effects of wholesale electricity market price convergence, ultimately effecting the future deployment of EST: as described above, the use of EST significantly lowers electricity prices in the peak-period and increases them in the off-peak period. In addition, this effect is amplified by the combined application of functional EST (e.g. load management; green line) and active EST (e.g. PHES, CAES, batteries etc., blue line). In overlay to this, stringent RES-E generation lowers the arbitrage between peak and off-peak prices in the long-term[21]. Therefore, EST have to face increasing economic inefficiency caused by small peak/off-peak electricity price differences in the medium to long-term.

[21] This issue is comprehensively discussed in Deliverable 2.2 (D2.2) of the stoRE project.

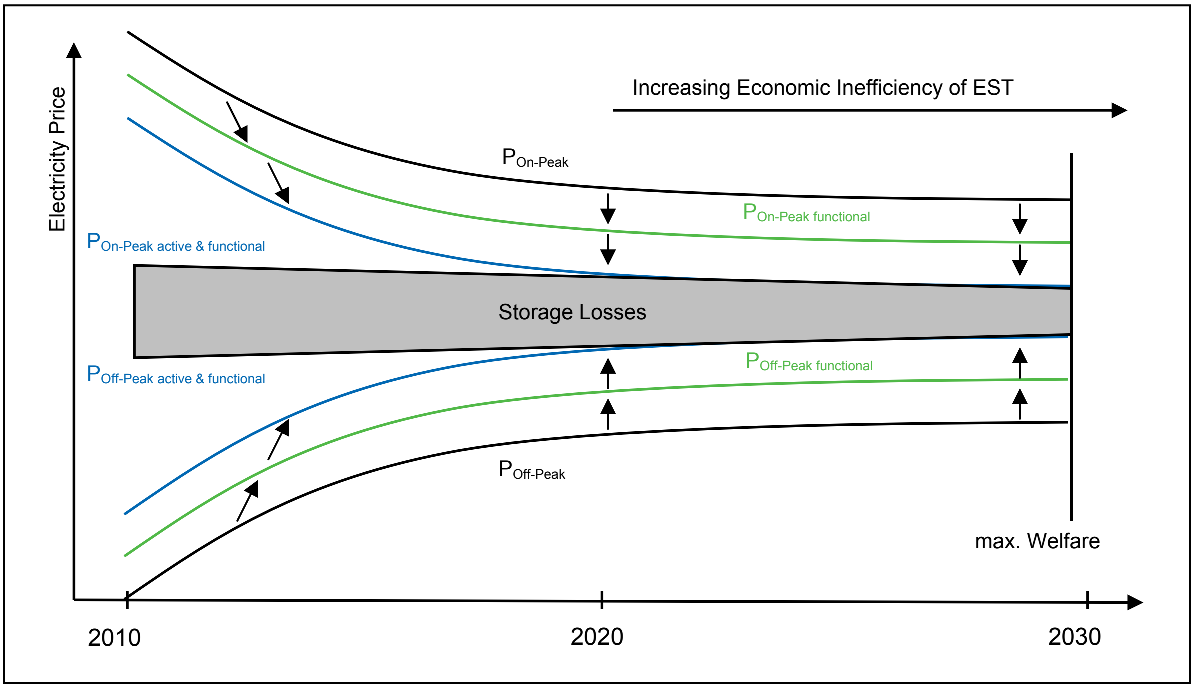

Figure 24: Basic principles of the influence of active & functional EST on future electricity prices (based on: Ehlers, 2011)

4.4 Transmission and Distribution Applications

Finally, an important application of EST is in the field of transmission and distribution grids. In particular, these are corresponding applications within the changing regulatory environment of network operators. They can be further divided into the following categories:

- Transmission stabilisation and voltage control
- Transmission and distribution investment deferral

4.4.1 Transmission Stabilisation and Voltage Control

EST improve the performance and stability of the transmission system to the extent that they are capable of providing high power and short duration impulses of both real and reactive power when placed at specific locations along the transmission line. Especially for long transmission distances between key generation sources and served loads, injection or absorption of reactive power at specific locations is important for frequency stabilisation. Typically, reactive power can be provided by EST during real power discharge or charging as well as during states of inactivity. Batteries, SMES and supercapacitors are applicable EST in this specific application area.

4.4.2 Transmission and Distribution Investment Deferral

The deferral of transmission investments, e.g. the delay of new constructions and upgrades of connection lines, transformers, stations, etc., is to a certain degree a supplemental benefit that arises from transmission stabilisation and voltage control described above. Additionally, also the avoidance of the use of transmission and generation resources during peak-load hours contributes to transmission investment deferral. This can be achieved by installing EST units near loads (bulk

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EST like PHES and CAES in particular), which reduce losses and increase efficiency, lower the need for bulk transfers and peak outtakes and finally reduces the use of transmission lines (c.f Denholm et al, 2009)[22].

What has been stated for transmission investment deferral above is also true for the distribution system. EST can help to delay investments into the distribution system, e.g. avoidance of new sub-stations, circuit breakers or transformers and distribution lines.

In summary, EST in general, and bulk EST like PHES and CAES in particular, allow the existing transmission and distribution systems to be used for a longer time, whereas the benefit is generally equal to the annual carrying charges for the capital investment that are avoided if the upgrade/replacement is deferred.

[22] Also distributed RES-E generation located close to loads can have similar beneficial impacts, especially when combined with EST.

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5 Conclusions / Outlook

This report provides an overview of the status quo of EST with special focus on the two main bulk EST, PHES and CAES.

PHES systems are currently the most mature and widely used EST. Power ratings of PHES systems reach from several MW up to 2 GW with discharge times up to 100 hours depending on the storage volume of the reservoirs. They show the lowest overall cost for large-scale electricity storage. However, their deployment potential is constraint across Europe, since PHES systems are strongly dependent on certain geographic requirements and topographical conditions. Therefore, most of the currently proposed new PHES plants are either extensions or upgrades / repowering of existing storage and / or PHES power plants. Nevertheless, new developments are still going on, as plans for reusing open cast and underground mining structures for PHES systems demonstrate.

At present, CAES systems - the second major bulk EST - need additional fossil fuels to recover stored electricity. Therefore, at the moment CAES systems are not characterised as “pure” electricity storage technologies, but hybrid systems. In terms of their key technology parameters, they are very similar to PHES systems. So far, only two commercial CAES systems have been built worldwide. Even though they are in use since many years, further technological developments are needed in order to reach higher overall efficiencies (currently ~40 %) and to eliminate the need for using additional fossil fuels (AA-CAES). Since high capacity / pressure air storage above ground (vessels) is uneconomical at the moment, CAES systems are dependent on underground caverns. Therefore, the deployment potential for CAES is also limited due to geographic requirements.

In this report, furthermore, other (non-bulk) EST such as batteries, supercapacitors and flywheels are also briefly described; however, no in-depth analyses is conducted since they are outside the scope of the stoRE project. Their major role in future electricity systems with high shares of variable/ intermittent RES-E generation will be in short-time applications, e.g. output smoothing within seconds etc. and applications on low voltage levels. These applications, where bulk EST like PHES and CAES cannot be used - because of their high response times or high voltage level - will form a niche market for other non-bulk EST. However, hydrogen fuel cell storage systems also have the potential to become bulk EST in the future, but suffer from low efficiency.

The major application for bulk EST like PHES and CAES is expected to be output smoothening of variable / intermittent RES-E generation on multiple time scales and energy arbitrage, i.e. storing RES-E generation in off-peak hours and restoring it again in on-peak hours. Also the provision of secondary and tertiary control reserve is a possible and profitable application for bulk EST. Several other possible applications for EST in general and bulk EST in particular - like blackstart capability and transmission and distribution investment deferral - are also briefly outlined in this document.

The important role of bulk EST in optimising the physical and financial functioning of electricity markets and the corresponding commercial energy trading activities in the future electricity system is discussed in detail in Deliverable 2.2 (D2.2) of the stoRE project. There, several of the new, market-driven requirements/needs of bulk energy storage technologies on different time scales (intra-daily, daily, weekly, monthly and seasonal energy trading and balancing) are structured and critically discussed in D2.2.

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Appendix: Definitions and Terminology for Pumped Hydro Energy Storage

The following is a description of the basic types of PHES. Within these basic types there are many possible variations. The actual details of a given scheme are influenced mainly by the site characteristics. We have identified three main types of PHES.

Note on Power House Configurations

The power house for a PHES can be constructed in an underground cavern or in an open shaft near the lower reservoir. For the cavern configuration the power house is located deep inside the mountain with vehicular and personnel access through a tunnel. The penstock and tailrace pipes are both tunnelled. In a shaft configuration the power house is constructed in an open excavation close to the lower reservoir. This is normally only possible where the active range of the water in the lower reservoir is only a few meters. The tailrace forms an integral part of the power house. For the shaft configuration the penstock pipe can be an overground pipe, a buried pipe or a tunnel.

A-1 Closed-Loop PHES

The closed-loop PHES consists of two reservoirs neither of which is connected to a river system. Both reservoirs can be either artificial or modified existing lakes. The most common layout is that one reservoir is artificial and the other is a modified existing lake. A typical example of a closed loop system is Turlough Hill, Ireland, where the lower reservoir is a modified lake and the upper reservoir is artificial.

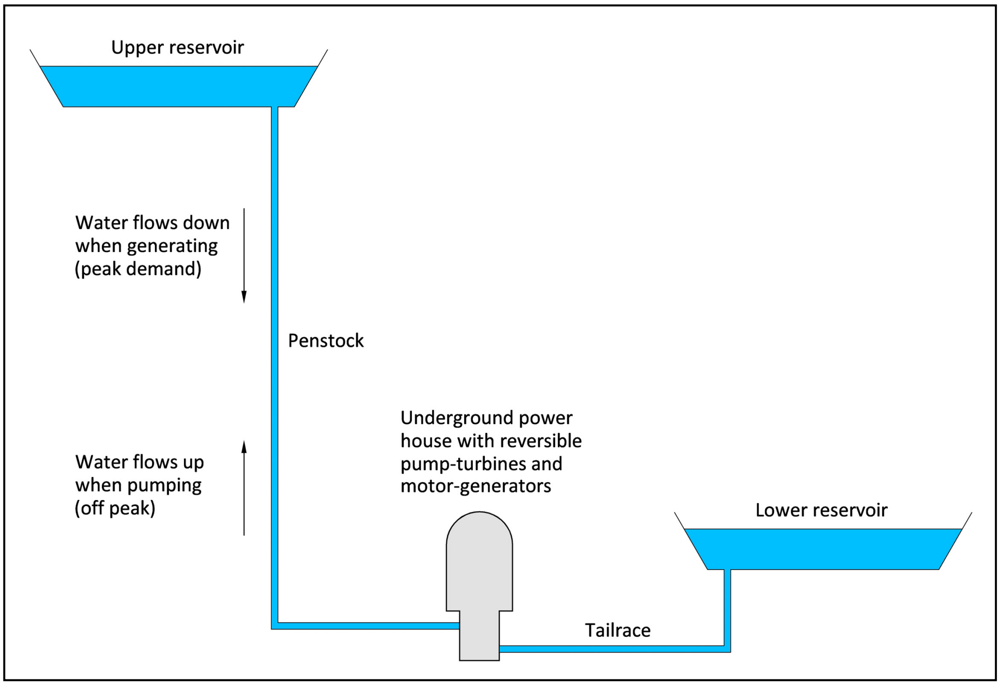

Figure A-1: Schematic diagram of a closed-loop PHES

Figure A-2: Turlough Hill closed-loop PHES system, Ireland (Source: ESB.ie)

A-2 Semi-open PHES

The semi-open PHES has one artificial reservoir, the other reservoir forms a part of a river system. An example of this type is Goldisthal, Germany, where the upper reservoir is artificial and the lower reservoir is part of a river system. Marine PHES, which uses salt water (like Okinawa, Japan) is a form of semi-open PHES as the upper reservoir is artificial and the lower reservoir is the ocean.

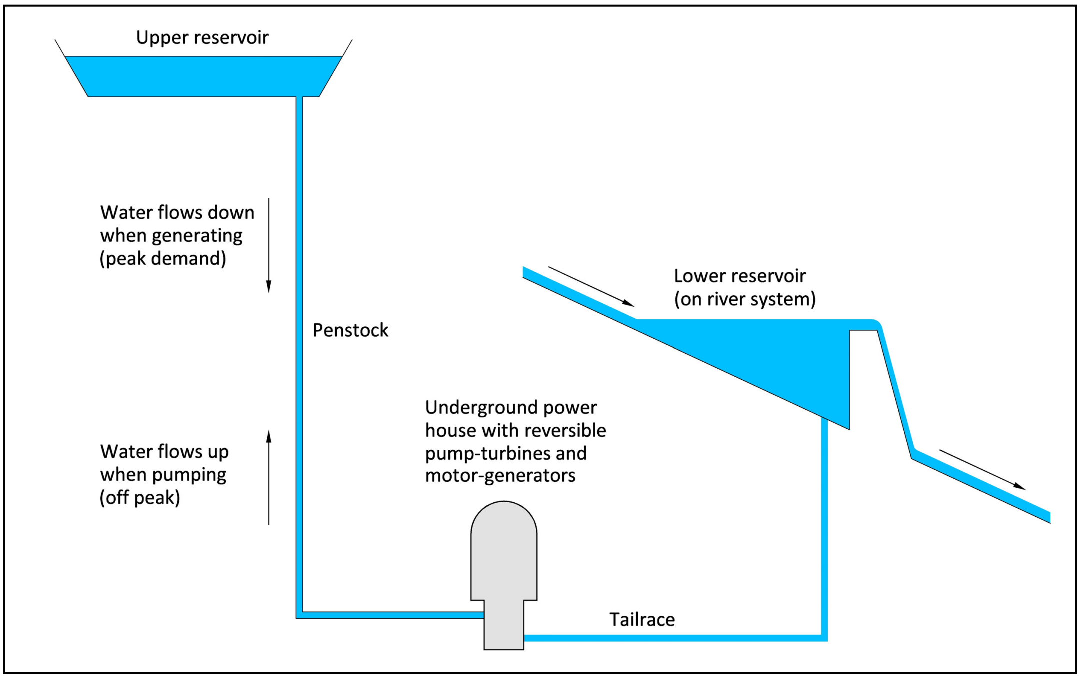

Figure A-3: Schematic diagram of a semi-open PHES

Figure A-4: Goldisthal semi-open PHES system, Germany (Source: Goldisthal.de)

A-3 Open System PHES

The most common open system PHES is the so called "pump-back" PHES. Constructed on a single river system, it can operate as a conventional hydro scheme when there is sufficient flow in the river. Pump-back PHES schemes are often created by retrofitting existing hydropower schemes with pumping capabilities. An example of a pump-back PHES would be Thissavros, Greece.

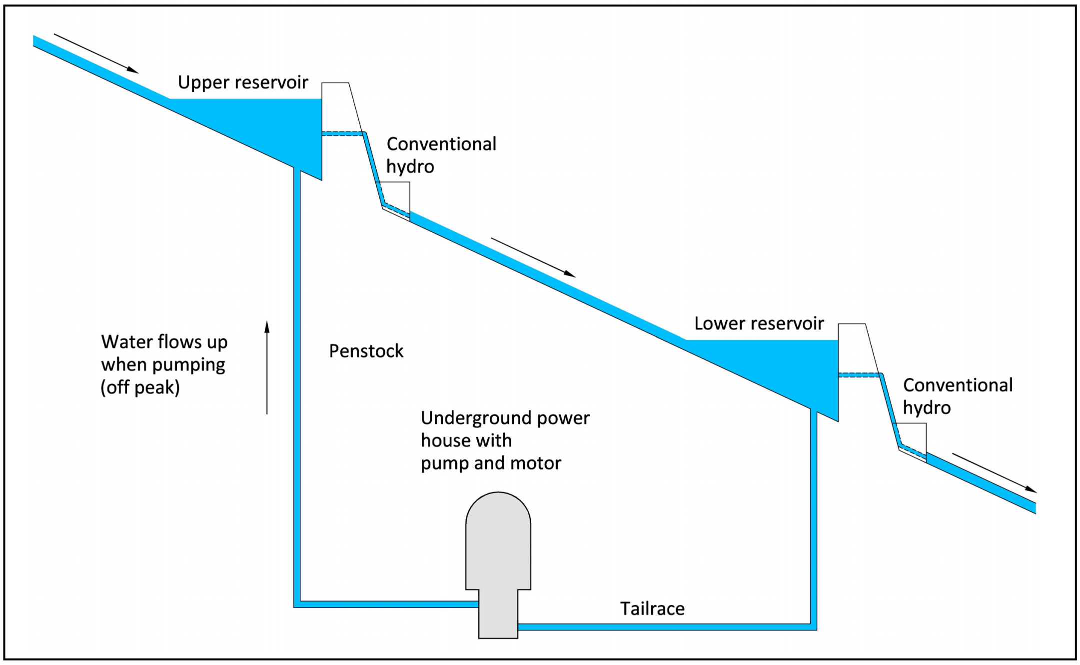

Figure A-5: Schematic diagram of a pump-back PHES

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Figure A-6: Thissavros pump-back PHES system (upper dam), Greece (Source: METKA.gr)