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# COMMISSION STAFF WORKING DOCUMENT

*Accompanying the document*

## REPORT FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS

## JRC technical report on "Assessment of the potential for energy efficiency in electricity generation, transmission and storage"

{COM(2023) 1 final}

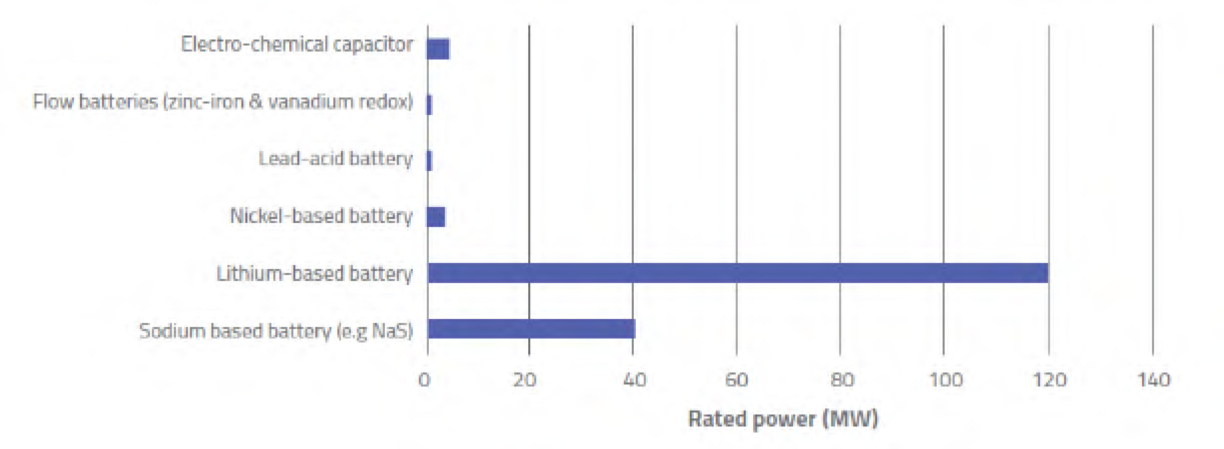
## Contents

## 3 Storage technologies

### 3.1 Introduction

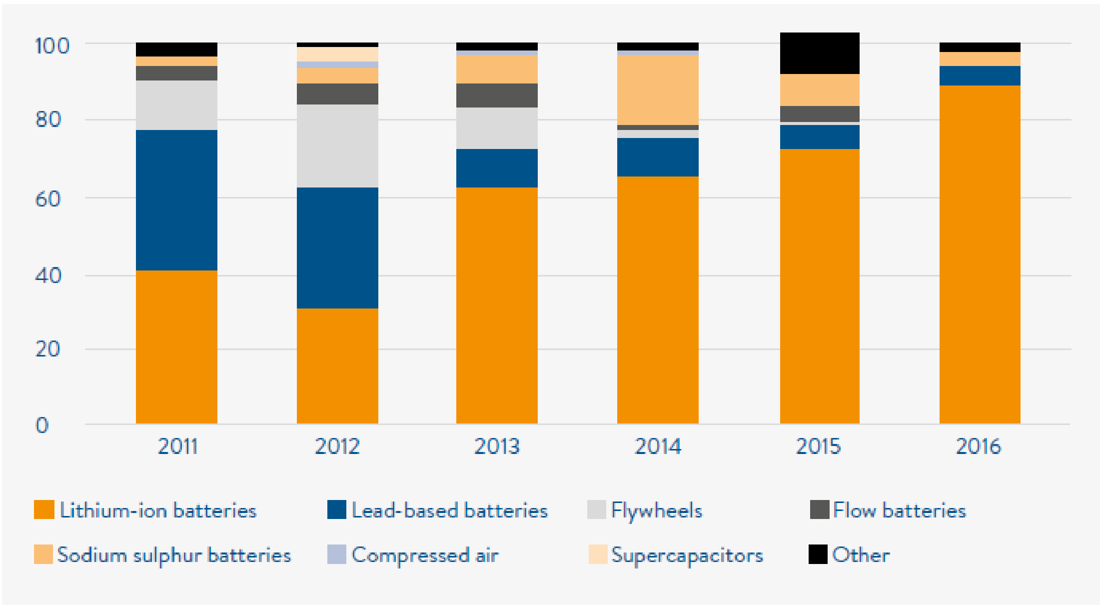
In a power network increasingly penetrated by renewable energy production, characterized by large variability, storage plays a pivotal role in improving the efficiency of the system while pursuing the objective of a transition towards a carbon-neutral power system. To date, pumped hydro is by far the most widespread type of storage, accounting for more than 90 % of the total capacity installed worldwide [22]. In the European Union, more than 45 GW of pumped hydro are installed [23], while less than 200 MW of electro-chemical storage are available (Figure 15).

**Figure 15**: Electro-chemical storage deployment in Europe [24]




Given the strict relation of pumped hydro with the availability of suitable geographical locations, largely already in use, the other storage opportunities are increasingly gaining attention. In particular, lithium-ion batteries are earning a prominent role in the storage market, as shown in Figure 16.

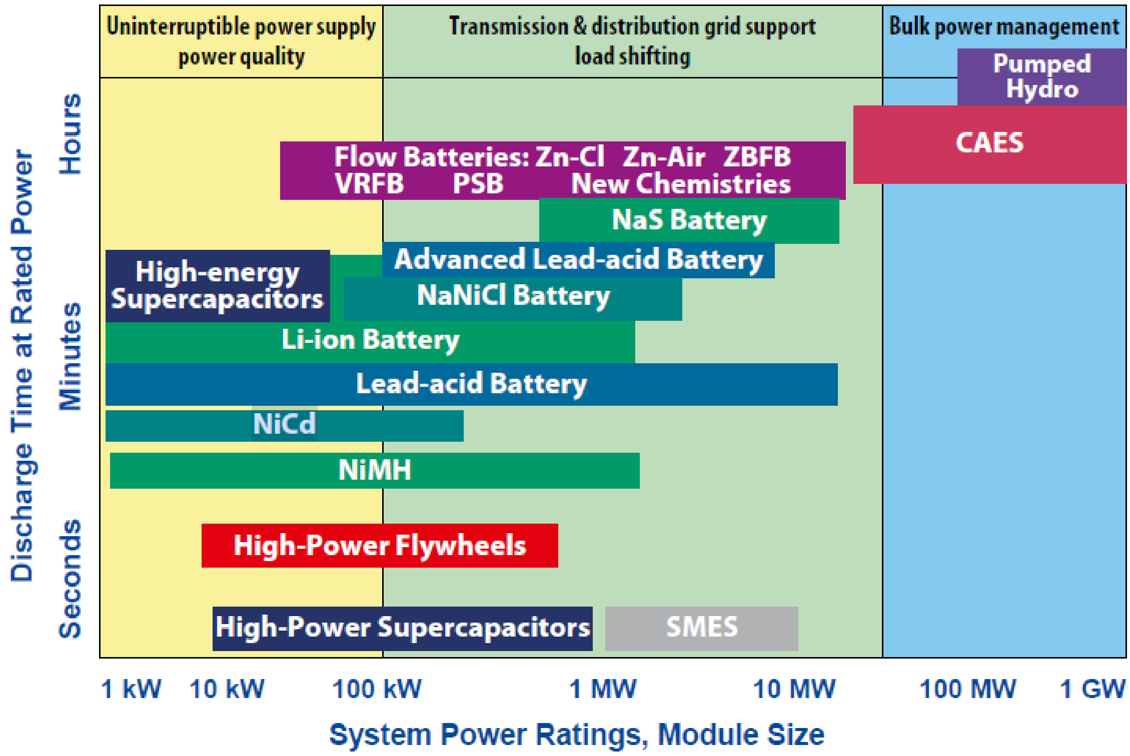
**Figure 16**: Technology mix in storage installations excluding pumped hydro [25]




In the scope of the "Clean planet for all" EU strategy, total storage installed for stationary applications in the European power system is expected to reach between 250 TWh and 450 TWh by 2050 [26].

There is a wide variety of available technologies, each characterized by its response time, efficiency, cycle lifetime, power and energy features, etc. According to these features and to the typical power ratings, a classification of possible services to be provided to the power network is shown in Figure 17.

**Figure 17**: System services that storage technologies can provide depending on the service timescale and typical power ratings [27]




The technologies analysed in this report can be divided into the following categories:

— Mechanical energy storage: pumped hydro storage, Compressed Air Energy Storage (CAES), Liquid Air Energy Storage (LAES), flywheels;

— Electrochemical energy storage: lead-acid batteries, lithium-ion batteries, flow batteries, high-temperature batteries;

— Electrical energy storage: supercapacitors, superconducting magnetic energy storage (SMES);

— Chemical energy storage: power-to-hydrogen.

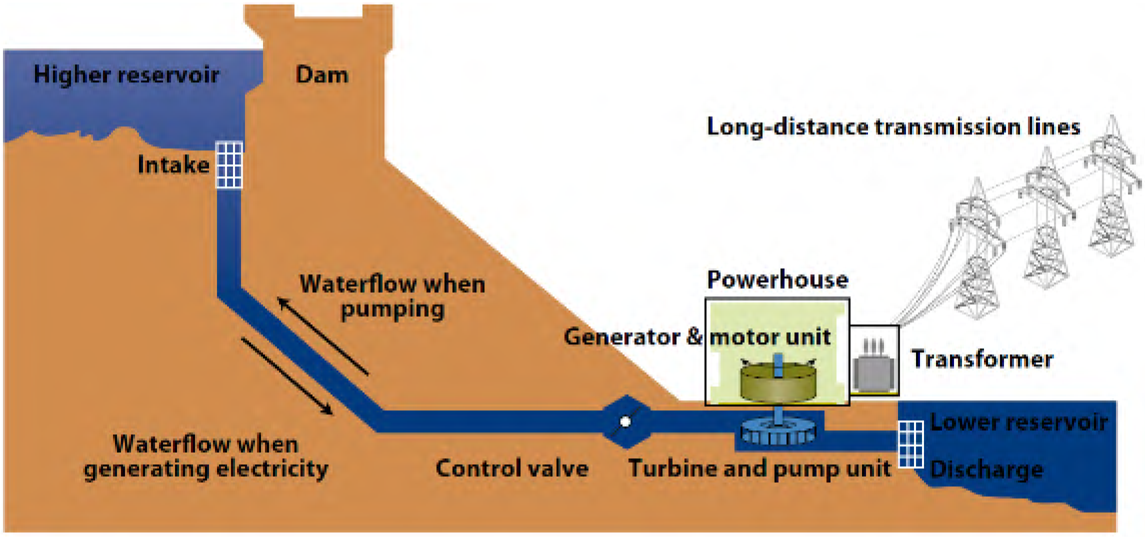
An efficiency overview of the electric energy storage systems is presented in Appendix III.

## 3.2 Mechanical energy storage

### 3.2.1 Pumped hydro storage

Pumped hydro storage (PHS) constitutes more than 90 % of the total storage capacity installed worldwide [22]. It is a very mature and flexible technology, whose most common sizes currently range from few MW up to thousands of MW. A 3600 MW PHS project is currently under construction in China and will become the largest of the world [28]. PHS allows to store electric energy in the form of gravitational potential energy: water is pumped from a lower to an upper reservoir during off-peak hours or in case of excess of energy; water is then sent to the turbine during peak hours or in case of supply of system service to the network. The layout of a typical PHS plant is shown in Figure 18.

**Figure 18**: PHS plant layout [29].




Three configurations are possible [30]:

- Quaternary set: this was the first configuration been adopted, in which the pump is driven by a motor and the turbine powers a generator. Hence, the two groups are completely decoupled and individually optimized. This is the most expensive option, which also allows the best overall efficiency, because each functionality is optimized;
- Ternary set: pump and turbine on a single shaft, together with the electrical machine. The latter works as either motor or generator, depending on the operating mode of the plant. Also in this case, pump and turbine can be designed individually and high efficiencies are reached.
- Binary set: a reversible hydraulic machine is used both in pumping and generation mode (depending on the rotation of the shaft) and it is coupled with an electrical machine working either as generator or as a motor. To date, this is the most widespread configuration due to its reduced cost, but this comes at the expense of efficiency, as the hydraulic machine is designed as a compromise of its double use.

The basic layout of a pumped-storage hydropower plant involves two reservoirs, one above the other, and a turbine/pumping hall capable of both generating power from the stored water in the upper reservoir and pumping water from the lower reservoir back to the upper. For hydropower plants in general, the energy available from a given volume of water is greater, the greater the head of water. In the case of the pumped-storage plant, this head is the vertical distance between the upper reservoir and the turbines.

Roundtrip efficiencies (RTE) range from 70 to 84 %, where the highest values are achieved thanks to the development of variable speed PHS [27], [31]. The per-unit cost of the energy produced may vary approximately in the range from 5 up to 100 €/kWh [32], [33].

PHS can provide large-scale storage and a plant can last many decades; on the other side, suitable geographical sites need to be found and the environmental impacts to be carefully considered: indeed, the expansion of this technology in Europe is held back by environmental restrictions and by the fact that most suitable sites have already been exploited [27]. For this reason, some new approaches are under consideration, in particular the use of the sea/ocean or underground caverns as lower reservoirs [34].

Moreover, small scale plants are today considered to store renewable energy produced locally, but their economic sustainability is questionable today, in comparison to other types of storage. For such smaller plants, efficiencies are lower and may fall below 50 %, as machines are not singularly designed and optimized, like in the case of larger power stations.

Given the high maturity of the technology, no significant improvements in terms of technical and cost performance are expected in the coming years.

### 3.2.2 Compressed Air Energy Storage (CAES)

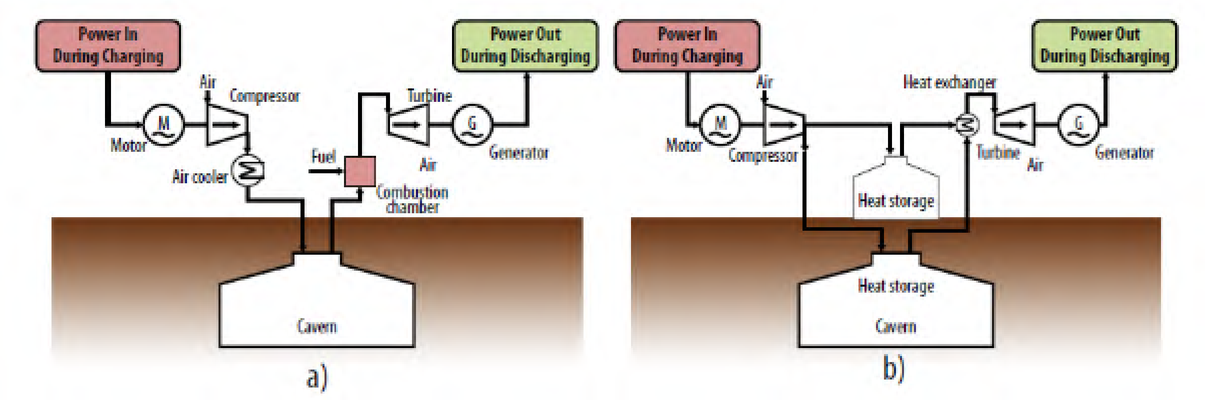
In Compressed Air Energy Storage (CAES), energy is stored in the form of pressurized air, in a cavern in case of large size plants: electric energy is used to drive compressors to store air in a reservoir. The cavern can be either a former salt or gas reserve or a purpose-built cavern. This last option is rarely adopted, as it leads to a dramatic cost increase. This kind of storage is able to provide very large amount of power (above 100 MW); hence, it results in an interesting option for network operators.

CAES stores the energy by compressing air as an elastic potential energy. It has separate compression and expansion processes. During low demand, the extra electrical energy is stored in the form of compressed air in air storage vessels. When the demand is high, the compressed air is converted to electrical energy through an energy conversion process using a high-pressure turbine where the compressed air is mixed with the gas.

Two main CAES technologies are available [25], [27], [35], as discussed below and shown in Figure 19:

- Diabatic CAES: the compressed air, which needs to be heated when exiting the reservoir, is mixed with natural gas in a combustion chamber and expanded in a gas turbine. This is the only commercially available option, which comes with a cost of about 50 €/kWh and RTE of 55 %. The low efficiency is one of the main drawbacks, together with emissions related to the combustion process.
- Adiabatic CAES: the technology stores the heat generated during the compression cycle and uses it to heat the air up before expansion. This removes the need of a combustion and efficiency can reach 70 %. Adiabatic CAES has been under study for years and is now close to reach commercialization phase.

**Figure 19**: Diabatic (a) and adiabatic (b) CAES layout [27]




Furthermore, isothermal CAES is currently under development: nearly isothermal compression and expansion would improve the efficiency up to 80 %. No combustion is needed [33].

Several projects have been commissioned in Europe for the years 2020-2024 [25]; this is expected to push towards a cost reduction and an improved efficiency.

Some innovative projects have been proposed. In Germany, the world's first large-scale AA-CAES project—ADELE—with 70% cycle efficiency has been designed by RWE Power, General Electric and other partners [36] [37]. The aim of this project is to optimize the co-existence and smooth interaction of the individual energy sources, especially for wind power. It is planned to have 1 GWh storage capacity and be capable of generating up to 200 MW, said the RWE power. The ADELE project could provide backup capacity within a very short time and replace forty state-of-the -art wind turbines for a period of 5 h. The project is currently in its final phase of development.

In the Netherlands, the CAES Zuidwending project, scheduled for commissioning in 2024-25, will have a generation capacity of approximately 300 MW and a daily storage/delivery capacity of approximately 3-4 GWh (gigawatt-hours).

In UK, the Gaelectric Energy Storage Ltd promoted the Cheshire CAES project, with a maximum active power of 268 MW and a storage capacity of 1,6 GWh.

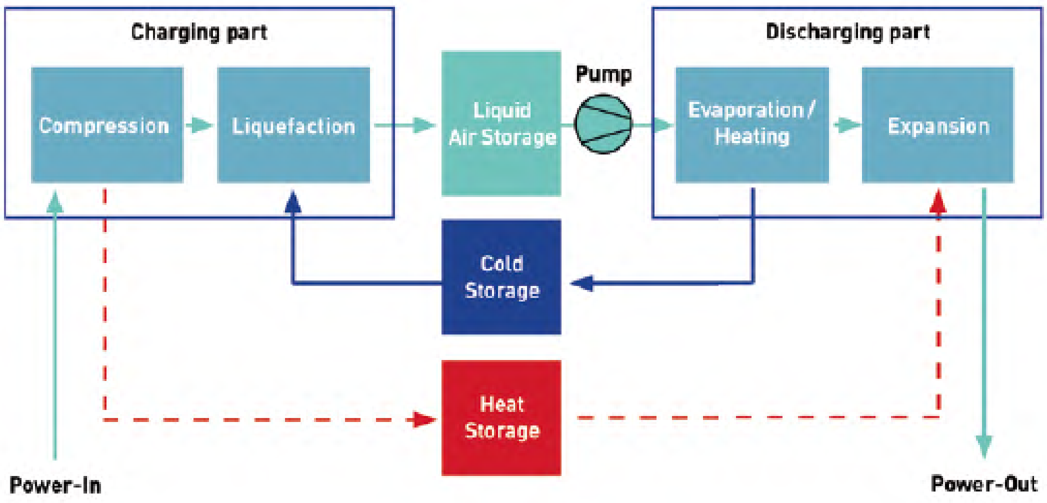
In China, on July 16, 2020, the Chinese Academy of Sciences Institute of Engineering Thermophysics achieved a new breakthrough successfully performed the integration test of the world's first 100 MW CAES expander.

There is another 50 MW AA-CAES project underway in Jiangsu, China, in 2017, which is certified by the consulting panel. In this 50 MW AA-CAES system, underground salt caverns are adopted as the air reservoirs. The final objective is to build 100 MW AA-CAES informed by the learnings from the 50 MW system. In 2015, Hydrostor has started a pilot project for the World's First Offshore Compressed-Air Energy Storage Project in Toronto (Canada). It was the first test of an underwater compressed-air energy storage system. The project used drilling techniques that reduces the demand for boats and cranes at the surface to deploy the pipes and storage balloons.

### 3.2.3 Liquid air energy storage

Liquid air energy storage (LAES) is based on cryogenic energy conversion: electric energy is used to remove heat from ambient air taken from the environment to produce liquid air. The fluid is then stored in an insulated tank at low pressure. When electricity is needed, the liquid air is pumped to high pressure, heated and expanded in a turbine [38], [39]. LAES layout is shown in Figure 20.

**Figure 20**: LAES mode of operation [40]



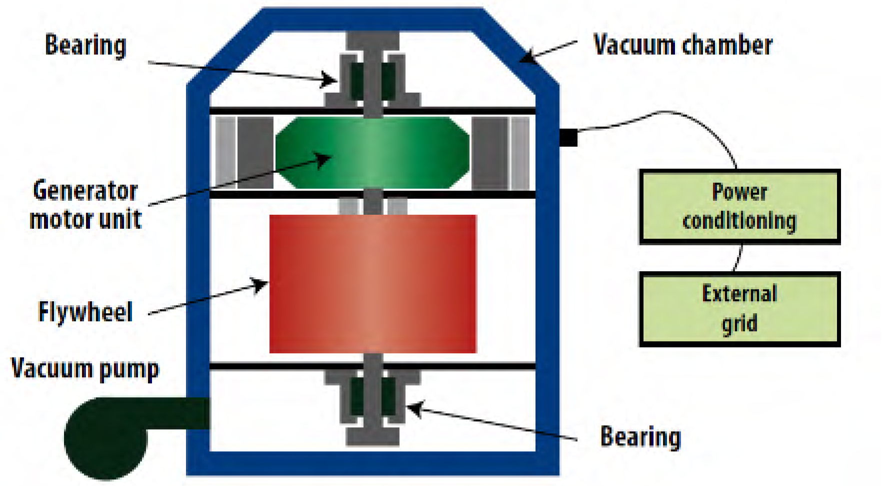

The advantage of LAES over CAES is that it does not come with any geographical restriction, as the high energy density allows the use of tanks to store the liquified air [39]. The cost of the technology is 250÷600 €/kWh and is expected to decrease to 150÷400 €/kWh by 2030 [40].

This storage option takes advantage of the use of mature supply chains and components, but it is currently at demonstration phase. Few small-scale pilots have been fully built and have shown a roundtrip efficiency below 20 % [38], [40]. Researchers claim this result is strictly related to the size of the system, and efficiencies of around 50% could be reached for wider scales. An important boost in the efficiency could be obtained by coupling LAES with industrial processes providing waste heat to be used upon expansion. This option could lead to an efficiency >65 % [40].

### 3.2.4 Flywheels

Flywheels store energy in the form of kinetic energy. A rotating mass is connected to a reversible electrical machine which acts as a motor in charging phase, increasing the speed of the rotating mass and the relative stored energy, and as a generator in discharging phase, extracting energy and decreasing the speed of the rotating mass [41]. The system is enclosed in a vacuum chamber to reduce aerodynamic drag and rotation is smoothed by magnetic bearings. These elements allow flywheels to keep their maximum speed for days by only being provided the energy to compensate idle losses [25], [40]. The state of charge is easily determinable from the rotational speed [27].

**Figure 21**: Flywheels layout [29]




There are two types of flywheel: low-speed (<10000 rpm) and high-speed (up to 100000 rpm). The former is made of metallic materials, is easier to build and is characterized by higher weights; hence, it is more suitable for stationary applications. The latter is made of composite materials, such as carbon fibres, which provide better performances at higher costs; this option is adopted for low-energy applications [25], [40].

This system is mainly applied to the high power/short duration EES applications (e.g., 100 kW/10 s), which provide support power during interruptions, for short time periods or when shifting from one power source to another.

Flywheels can usually respond extremely quickly. In grid backup systems[42][43] they should be capable of reaching full power within half a cycle (25 ms at 50 Hz), and some are quoted with response times of 5 ms. Such units will probably be able to supply their full output for between 5 and 15 seconds. Commercial flywheels are available with power ratings of between 2 kW and 2 MW and with storage capacities of between 1 and 100 kWh.

One of the largest commercial systems is a unit with ten 100 kW flywheels used by the New York Transit System to support its electric traction power network. This system can supply 1 MW of power for 6 seconds. However, the largest flywheel is the one used in Japan for nuclear fusion research. This system can supply 340 MW for 30 seconds.

In North Western Australia, a flywheel system has been integrated into a town’s power supply to support the increased power demand during the tourist season [43]. Coral Bay, a wind energy operated power station, consisted of seven 320 kW low-load diesel generators with three 200 kW wind turbines. In 2007, the integration of a 500 kW flywheel virtual generator into the system allowed the wind turbines to provide up to 95% of Coral Bay’s supply at peak times. The reported data shows that for nearly 900 h per year, 90% of the power station’s total supply comes from wind generation. In addition, while maintaining the grid standards and improving the power quality, 80% of this total power is wind-generated for one-third of the year [43]. Another flywheel-based stabilisation system has been planned for the Marsabit wind farm, a remote community served by an isolated microgrid in northern Kenya. A 500 kW flywheel-based system will be integrated into the existing two 275 kW wind turbines and diesel generators. The PowerStore flywheel to be installed by ABB will stabilise the grid connection to maximise renewable energy penetration [43]. Power Store is a flywheel-based stabilising generator which is mainly used for improving the power quality. It enables the integration and control of renewable wind and solar energy in the electrical grid. Acting like a static synchronous compensator (STATCOM), it combines an 18 MWs (Megawatt second) low-speed flywheel with solid state converters that absorb or inject full energy in 1 millisecond. The range of models from 500 kW to 1,5 MW allows the configuration of either a grid support mode for MW scale grids, or as a virtual generator for use in smaller isolated grids.

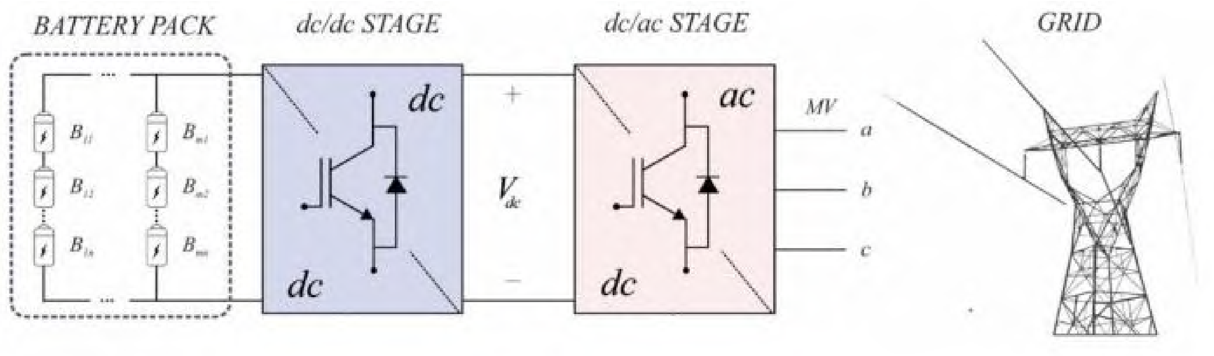
In general, flywheels provide fast-response services thanks to their high power density, their rapidity of charging/discharging and to minimize the impact of idle losses. They are characterized by a long cycle-life and ask for limited maintenance. RTE can reach 90 % in optimal operating conditions [44] and is not expected to go through a significant improvement in the future, while research on material will most likely enable a relevant reduction of costs, currently in the range 500÷3000 €/kWh [40].

## 3.3 Electrochemical energy storage

All the technologies belonging to this category can be identifies as Battery Energy Storage Systems (BESS). The basic concept behind BESS is that both electrical and chemical energy use electrons as carriers. This makes the storage particularly efficient, because it avoids losses due to conversion to any other type of energy. A cell of an electrochemical storage is basically composed by the following components: two electrodes, an electrolyte, a separator to avoid contact of the electrodes and a container. Reversible oxidation and reduction reactions cause the flow of electrons which allow to withdraw or inject energy in the system [25], [40].

Figure 22 shows the connection of BESS to the AC grid: an electronic converter is needed to get AC current and this affects the roundtrip efficiency. In case of connection to a DC bus, the DC/AC stage is not present. Efficiencies in the following subsections will refer to DC/DC RTE. The AC/AC RTE can be obtained by multiplying the DC/DC RTE by the roundtrip efficiency of the DC/AC converter (94÷95 %) [45].

**Figure 22**: BESS connection to AC grid [46]



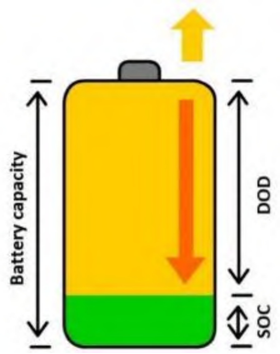

This kind of storage has the advantage of being highly modular, cells can be connected in different configurations in order to reach the desired voltage, energy capacity and power, but care must be taken to prevent non-optimal usage from rapidly reducing battery life or even damaging it. The technology is currently increasing its market penetration, exploiting the significant progress made in terms of cost and lifecycle.

### 3.3.1 Lead-acid batteries

Lead-acid batteries have been the first to reach technological maturity and are currently the most widespread battery type. There are two types of lead-acid batteries: vented lead-acid (VLA), in which oxygen and hydrogen are dispersed into the environment, and valve-regulated lead-acid (VRLA), in which oxygen and hydrogen are recombined to form water. VLA batteries have lower cost and longer lifetime, but requires more maintenance than VRLA batteries [27], [32].

Lead-acid batteries are normally subject to a 2-3 % monthly self-discharge and do not respond well to deep discharging: the maximum Depth of Discharge (DOD), i.e., the complement of the State of Charge (SOC) (see Figure 23), should be at most 50 %. The maximum number of full charge/discharge cycles can reach 2500 if operated in optimal conditions [32]. Lead toxicity may be an issue for some applications; on the other hand, materials are highly recyclable [27].

**Figure 23**: Depth of Discharge and State of Charge of BESS




Their roundtrip efficiency is in the range 70÷90 % and their cost is around 120÷200€/kWh. These two characteristics make lead-acid batteries one of the most convenient batteries in terms of performance/cost trade-off. Limited improvements in the manufacturing process are expected, which may lead to reduce the cost below 100€/kWh while maintaining similar RTE [27], [40].

Several very large-energy storage facilities based on lead-acid batteries have been built. These include an 8,5 MW unit constructed in West Berlin in 1986, while the city was still divided into East and West and a 20 MW unit built in Puerto Rico in 1994. Although the former operated successfully for several years, cell degradation led to the latter closing after only 5 years. Lead-acid cells have been very popular for renewable applications such as small wind or solar installations where they are used to store intermittently generated power to make it continuously available [47]. Duke Energy added 36 MW of lead-acid battery storage to its Notrees wind power facility in West Texas. When the lead-acid batteries were first installed, the battery system participated in the region’s frequency regulation market, which required rapid charging and discharging that significantly degraded the batteries. In 2016, Duke Energy replaced the original lead-acid batteries with better performing lithium-ion batteries [48].

### 3.3.2 Lithium-ion batteries

These batteries base their electrochemistry on the flow of lithium ions between the electrodes. The peculiarity of lithium ions stands in their very limited size, which allows this technology to have very high power and energy density [25].

Lithium batteries have very high DOD, up to 100 %, very limited self-discharge, impressive efficiencies in the range 92÷96 % and lifetime of 4000÷5000 cycles. The main disadvantage is the need of a battery management system, to improve safety and performance characteristics: in case of overheating, the battery degrades rapidly and gas leaks may even cause fires. Moreover, a robust metallic case is needed [27], [32]. These features lead to a high specific cost of around 250 €/kWh [40].

Besides the massive use of lithium batteries for electronic devices, medium and large size batteries are claiming attention for network services. Many efforts are currently put into improving the performances of such storage technology. By 2030, efficiencies are expected to reach 94÷98 % while costs are expected to decrease to less than 100 €/kWh [27], [40].

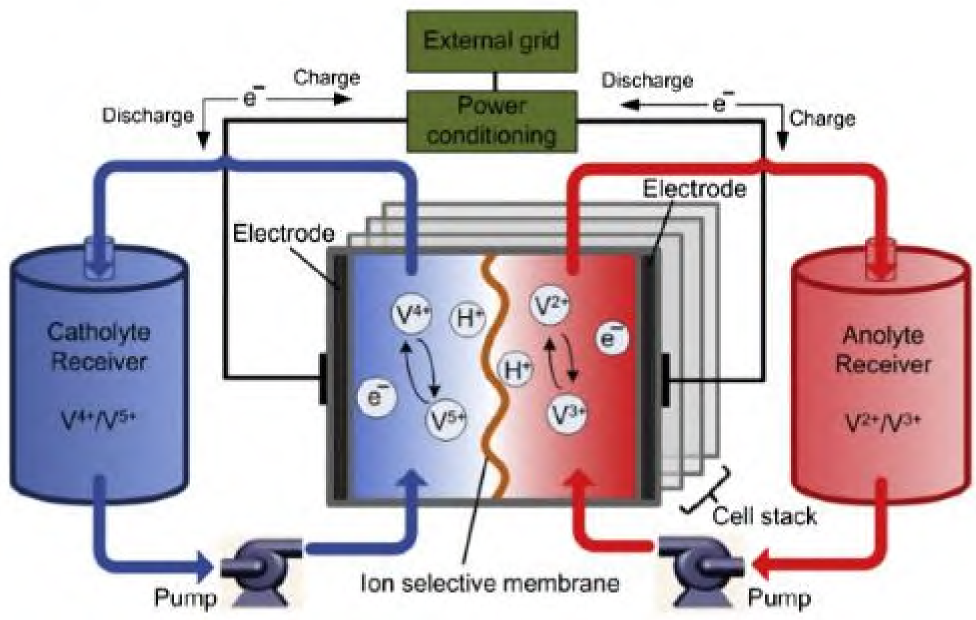
The very rapid growth in the use of this technology has brought to pay attention to problems on the supply of raw materials and on the recycling of degraded batteries, on which options are being developed but which at the moment are not yet widely applied given the scarce economic convenience [27].

An early large pilot battery storage installation rated at 2 MW was commissioned on the Orkney Islands, which are located off the coast of north-western Scotland, in 2013. This was topped in 2017 when the US utility San Diego Gas and Electric opened a 30 MW battery storage facility based on lithium-ion batteries with 120 MWh of storage capacity. A 20 MW facility is also being planned by the utility Southern California Edison. The world’s largest lithium-ion power reserve (100 MW/129 MWh storage capacity, now expanded to 150 MW) is the Hornsdale battery energy storage system, in Australia. The future development of lithium batteries may benefit from interest by automotive manufacturers in their use in hybrid and electric vehicles [47].

### 3.3.3 Flow batteries

The electric energy circulates through flow batteries thanks to the presence of two electrolyte materials pumped into two separate loops. The movement of ions to the electrodes is enabled by a membrane putting in contact the two fluids [25]. The most common technologies are vanadium and zinc bromine flow batteries, but to date only the former has been widely employed around the world [27].

**Figure 24**: Schematic of vanadium redox flow battery [29]




This configuration requires the presence of pumps and sensors to regulate the flow (see Figure 24); moreover, the risk of leaking of acid fluids needs to be taken into account. Hence, the system is more complex compared to other types of batteries and it calls for more demanding maintenance. On the other hand, flow batteries respond well to deep discharges and their cycle lifetime can exceed 10000 [27]. A very important characteristic of flow batteries is that power and capacity are completely decoupled: the former depends on the pumps and on the membrane surface; the latter depends on the size of the tanks containing the electrolyte materials [25], [32]. The RTE of the battery is strictly related to the pumps and can vary in the range 60÷85 %; however, by 2030 efficiency is expected to reach and exceed 90 % in the best configuration [27], [33].

Given these interesting characteristics, many researchers have investigated possible advancements in the performances of flow batteries and new options in terms of fluids and materials are currently under study. The cost of this technology is around 400 €/kWh, but given the great research efforts, it is expected to fall below 100 €/kWh before 2050 [35].

### 3.3.4 High temperature batteries

The peculiarity of this kind of batteries is that the electrodes are separated by a solid ceramic electrolyte. They operate at 250÷350 °C in order to keep the electrodes in liquid state and to improve the conductivity of the electrolyte.

The two most common technologies are sodium sulphur (NaS) and sodium nickel chloride ($NaNiCl_2$) batteries: the former is characterized very high recyclability, safety issues related to the production of a corrosive compound and idle losses of around 3 % of the rated power to maintain the needed temperature; the latter has usually a shorter cycle life but requires lower operating temperatures and is made of less corrosive materials [27].

High temperature batteries are characterized by low self-discharge rates and their DOD can reach 100 %. Roundtrip efficiency is around 85 % and the number of cycles ranges from 1000 to 10000 [27], [33].

Current research is focusing on decreasing the working temperature, to operate in an all-solid state. The cost of the technology is in the range 250÷700 €/kWh, with the potential of decreasing by 75 % if progress is made in terms of operating temperatures. However, the presence of a very limited number of technology providers may slow down these developments [27], [40].

$NaNiCl_2$ batteries have been successfully installed in the Duke Energy Rankin Substation (North Carolina) with the purpose of PV power smoothing in combination with a 1 MWp PV plant. This installation won the 2013 "Grid Integration of Renewable Project of the year award". Another meaningful installation is the "Toucan Project", in French Guiana, where 2 MW of Sodium-Nickel batteries have been connected to the photovoltaic panels in the plant prepared in the area near to Montsinéry near a MV substation, in the back land of the French Guiana, whose energy will be stored by them during the day for releasing it during the night hours. Also, the Italian Transmission System Operator, Terna, is testing the Sodium-Nickel batteries with the installation of 3,4 MW in the high voltage network with the aim of providing grid services, above all the grid frequency regulation [[49][50][51][52].

The overall installed NaS power in the world is 365 MW. These batteries have been installed for both stationary applications and for power supply (UPS): they have found great applications for peak shaving with a twenty-year experience. The biggest installation in the world is at Rokkasho (Japan) with 34 MW rated power. The system is linked with a 51 MW wind farm [53]. In Italy, three NaS battery installations are in South Italy and have a total power of 34,8 MW. Their function in the grid is charging and discharging in long intervals in order to avoid congestions on the power transmission lines due to the great amount of renewable energy fed into the grid[53]. Other meaningful stationary applications are the 9,6 MW installation in the Hitachi car industry and the 6 MW/48 MWh installation in the Ohito substation owned by TEPCO[53].

## 3.4 Electrical energy storage

### 3.4.1 Supercapacitors

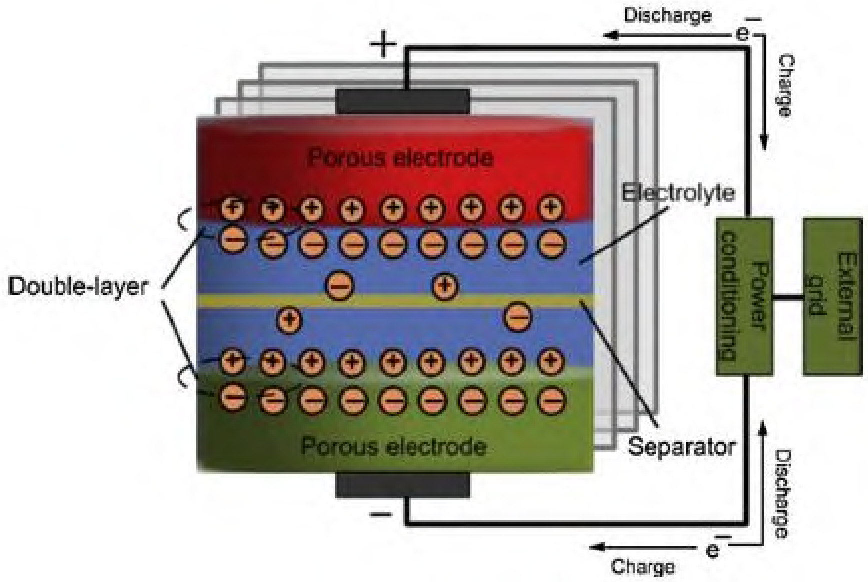
Supercapacitors are characterized by the presence of two electrodes immersed in an electrolytic solution and separated by a permeable membrane. Energy is stored in the form of static charge on the surfaces of the electrodes [25]. The most widespread configuration has carbon-based electrodes and organic electrolytic solution (Figure 25).

A simple electrostatic capacitor comprises two plates with a dielectric material between them. When a voltage is applied to the plates, charge builds up on them to neutralise the voltage by creating an equal and opposite static charge voltage across the plates. An electrochemical capacitor is similar to this in that it has a dielectric material between the capacitor plates but in this case the dielectric is a liquid electrolyte such as sulphuric acid or potassium hydroxide which can support a much higher build-up of charge. The capacitor plates themselves are inert materials which will not react with these reagents.

Electrochemical capacitors can be cycled for tens of thousands of times without degradation, provided the voltage across them is kept below the maximum so that no internal reaction takes place. However, once they are charged, they do lose charge slowly through leakage in the same way as a battery. The leakage levels in water-based electrochemical cells are similar to that of a lead-acid battery. Leakage levels are lower with organic-based electrolytes. Leakage will reduce long-term storage.

This technology is characterized by high power density (2000÷5000 W/kg) and low energy density (3÷5 Wh/kg), with a discharge time that spans from few seconds to one minute. The installation cost is in the range 250÷2000 €/kWh and the DC/DC RTE is above 95 % [31], [32].

**Figure 25**: Supercapacitor layout [29]

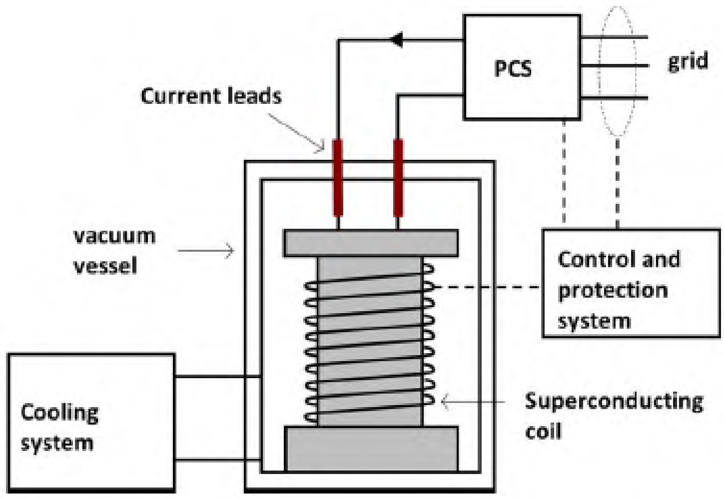



Despite the very high efficiency, this storage option is not considered for energy services in power systems, while it is already widely used for mitigation of power quality issues (short interruptions and high-power applications). Many aspects are still under development; in particular, much research is ongoing on materials. The high cost and the low energy density do not allow at the moment a wide employment of the technology for grid energy storage, which is mostly limited to pilot projects [32], [40]. Efforts in research are expected to produce a significant cost reduction in the coming years.

### 3.4.2 Superconducting Magnetic Energy Storage

In Superconducting Magnetic Energy Storage (SMES), electric energy is stored by making a current flow through a coil made of superconducting material, generating a magnetic field. A schematic representation of SMES is shown in Figure 26. A refrigeration system is needed to allow superconductivity; despite this, DC/DC RTE is extremely high (>95 %) as the resistance of the superconductor is practically null [25], [54].

**Figure 26**: SMES layout [54]




This technology is characterized by high power density. Hence, it would be prone to provide power systems with fast services. SMES are considered to be still under development; many researchers are investigating the potential of this kind of storage. Costs are currently high and extremely volatile, ranging from 300 to 2000 €/kWh [54], but are expected to fall to around 200 €/kWh by 2050 [40].

## 3.5 Chemical energy storage

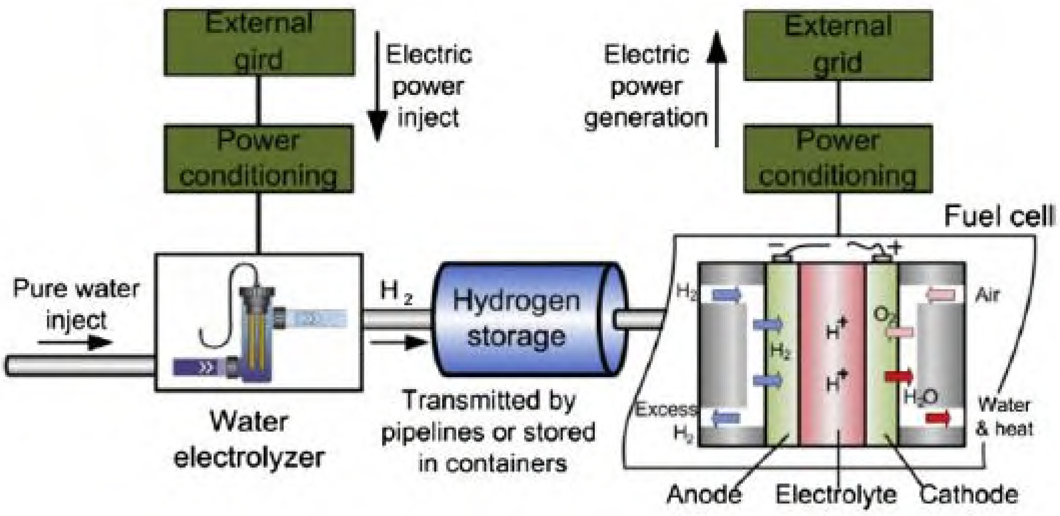
### 3.5.1 Power-to-hydrogen

In power-to-hydrogen (P2H) storage, electrolysers use electricity to split water into oxygen and hydrogen; the former is released, while the latter is stored. This can be done in various forms: at low pressure in caverns, at high pressure in tanks, as a liquid in cryogenic tanks (temperature below -253 °C), as a solid or liquid hydride (e.g., ammonia) [25], [35].

The most common electrolysers are ALKaline (ALK) and Proton Exchange Membrane (PEM) electrolysers. ALK are widely commercialized and cost around 750 €/kW; while PEM are still under demonstration phase, especially for large-size storage, and they provide higher efficiency and faster response at a cost of around 1200 €/kW. The technology of solid oxide electrolyser is currently under development; it provides the advantage of limited need of rare materials, but it is still quite expensive and requires to be close to a high-temperature heat source [55].

When the stored energy is needed, the electrolysis process may be reversed in a fuel cell to recombine oxygen and hydrogen to produce electricity and water (as shown in Figure 27), or the gas can be expanded in a gas turbine [25].

**Figure 27**: Hydrogen storage and electricity production with fuel cell [29]




Despite the low efficiency, which hardly exceeds 45 %, this technology has gained great attention because of the high density of energy, of the capacity to store for long periods and the suitability for large scale storage [32]; in a scenario of high penetration of renewables, P2H is expected to have a prominent role providing a cost-effective storage solution [56].. Costs are likely to decrease by more than 30 % by 2025 [55].

## 3.6 Summary of storage efficiencies

A summary of the efficiencies and costs of each technology described in this report is presented in Table 3.

**Table 3**: Efficiency and cost of each storage technology

| | Mechanical | | | | Electrochemical | | | | Electrical | | Chemical |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | **PHS** | **CAES** | **LAES** | **Flywheels** | **Lead-acid** | **Li-ion** | **Flow** | **High-temperature** | **Super-capacitors** | **SMES** | **P2H** |
| **RTE** | 70÷84 % | >55 % | <50 % | <90 % | 70÷90 % | 92÷96 % | 60÷85 % | 85 % | >95 % | >95 % | <45 % |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Cost** | 5÷100 €/kWh | >50 €/kWh | 250÷ 600 €/kWh | 500÷ 3000 €/kWh | 120÷ 200 €/kWh | 250 €/kWh | 400 €/kWh | 250÷700 €/kWh | 250÷ 2000 €/kWh | 300÷ 2000 €/kWh | 750÷ 1200 €/kW |

Given that each technology is suited for a specific range of system services, the hybridization of the network in terms of storage technologies is considered beneficial. Still, support schemes are needed in order to make extensive storage employment profitable [33].

The European target of 32 % renewable generation at 2030 [57] must be enabled by actions in several areas of intervention, namely increased interconnections, demand flexibility and storage. In order to meet this target, ENTSO-E has recently released the Ten-Year Network Development Plan (TYNDP) 2020, which includes 23 storage projects for EU27: 2 BESS projects, 1 P2H project, 3 CAES projects, 17 PHS projects. This expansion of the storage availability is supposed to decrease the annual RES curtailment in 2030 by 10.6 TWh [59]. Moreover, storage may be used to flatten the generation curve of thermal plants, allowing a more efficient operation of these technologies.