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An investigation of the role of Pumped Hydro Energy Storage in changing electricity networks with a focus on systems in Asia, and a comparison with the situation in the EU.

MASTER THESIS

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DEDICATION

I would like to dedicate this Master Thesis to my parents, the most wonderful people I have ever met, the ones who have supported me the most in my life and who have instilled in me the fundamental values that I currently have.

Thank you for your unconditional love.

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I would like to thank my supervisor Dr. Arthur Williams, Director of Post-graduate taught courses in EEE in the Faculty of Engineering, for giving me the opportunity to live this experience that has enriched me in both linguistic and personal ways.

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1 INTRODUCTION

For decades there has been a growing awareness of the environmental impact due to fossil fuels like petrol, coal or natural gas, mostly used for industrial activities and transport. Such activities emit the so-called greenhouse gases, causing what we know and endure today as global warming.

In consequence of this serious problem of the fossil fuels' use, along with its cost and energy dependency, a growing research and implementation of "*clean energies*" with no emission of polluting gases has emerged, such as photovoltaic, wind, tidal, geothermal, wave, among others. These are the so-called Renewable Energies which importance is growing everywhere.

At this point is when an obvious question arises: Why do not we replace these fuels and polluting energy forms by renewable energies that have a lower emission of harmful gases? The answer is simple, focusing on the most developed ones, due to the good knowledge of their technology and its wide acceptance in the global electricity market, solar and wind power have an important drawback: they are intermittent energy sources, i.e., they only produce energy when the sun is shining or when the wind is blowing. As a consequence of this problem, which makes the energy's field to be dependent from the use of fossil fuels, new studies and technologies are being developed.

Figure 1.1.- Pump Hydro Energy Storage Plant (Limberg II and Kopswerk II, Austria)

One possible good solution and that today is having a huge boom, is the one which concerns this project: the energy storage systems, and particularly the Pumped Hydro Energy Storage (PHES), which allows to integrate the wind power into the power system and to store the energy when there is a excess in production, therefore reducing the peak-to-valley difference.

2 OBJECTIVES OF THE THESIS

The objectives of this Thesis are the following: to do an investigation about what is a pumped hydro energy storage (PHES) plant, explain its functioning and analyse its role in changing electricity networks, by focusing on a comparison between systems in Asia and in the EU.

Within the framework of this study different aspects have been investigated, such as the pros and cons of these plants, costs, the differences between fixed and variable speed generators, the behaviour of PHES by comparing them with other energy storage technologies. Furthermore, a brief description has been done about the cooperative operation between PHES plants and wind farms.

3 HOW A PHES WORKS

The description of a pumped storage plant is simple: it only consists in two reservoirs with a significant height difference between both, which are connected by water tunnels or big penstocks. Inside the mountain, and connected with both reservoirs, is located the power house which contains the reversible turbine, an electrical substation and transmission connection.

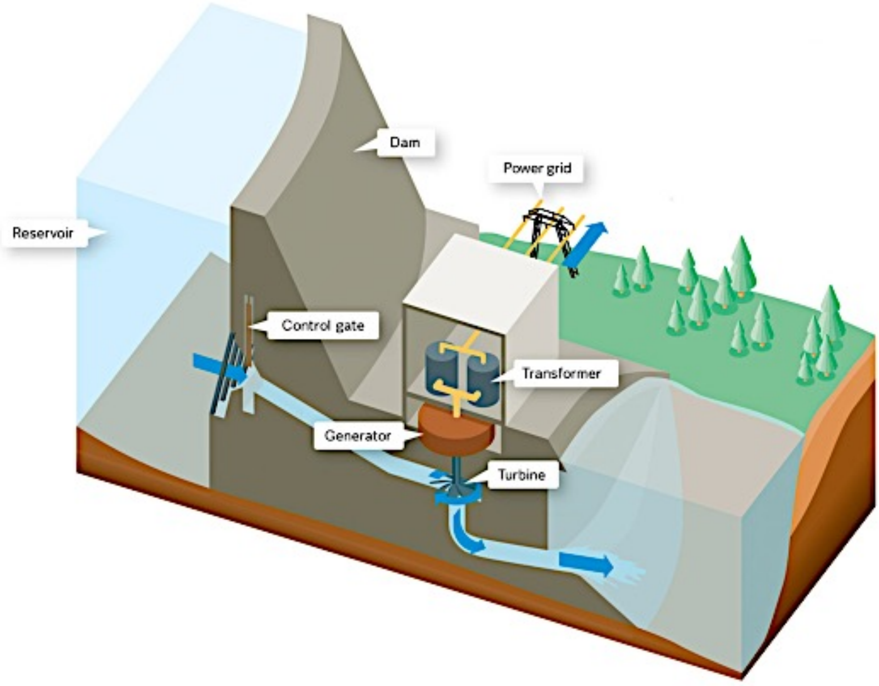


Figure 3.1.- Different parts from a PHES plant

PHES has two working modes [1] as it is shown in Figure 3.2. The first one is when the turbine is driving the generator: this happens when there is a peak of electricity demand. Hence, the water is released from the upper reservoir to the lower one so when it passes through the turbine, the kinetic energy is converted by the generator into electricity which then will feed the grid. This electricity will have the appropriate voltage thanks to the action from the transformers placed between the generator and the grid.

The second one appears when the generator is working as a motor to drive the turbine and pump the water. The particularity of this method is that it acts like a storage of energy when the price of electricity decreases or when there is lower energy demand for instance in the weekend or at night, or when there is an energy excess in the grid by other generating sources; in this last case, the turbines work in a reverse way using this generation excess capacity (for instance, from the wind farms or photovoltaic systems) to pump the water back to the upper reservoir where it can be released again when demand requires it.

Pumped hydro energy storage, as well as the rest of energy store systems, does not have a 100 % efficiency as it depends on some factors, even though it can reach the 80% which is considered as high efficiency. Some of the losses are due to the reversible turbine that are almost impossible to minimise.

Besides this, it should be mentioned that the power capacity that these plants can deliver depends on the size of the reversible turbine and the amount of energy stored depends on the volume of the reservoir and the height difference between the lower and the upper reservoir.

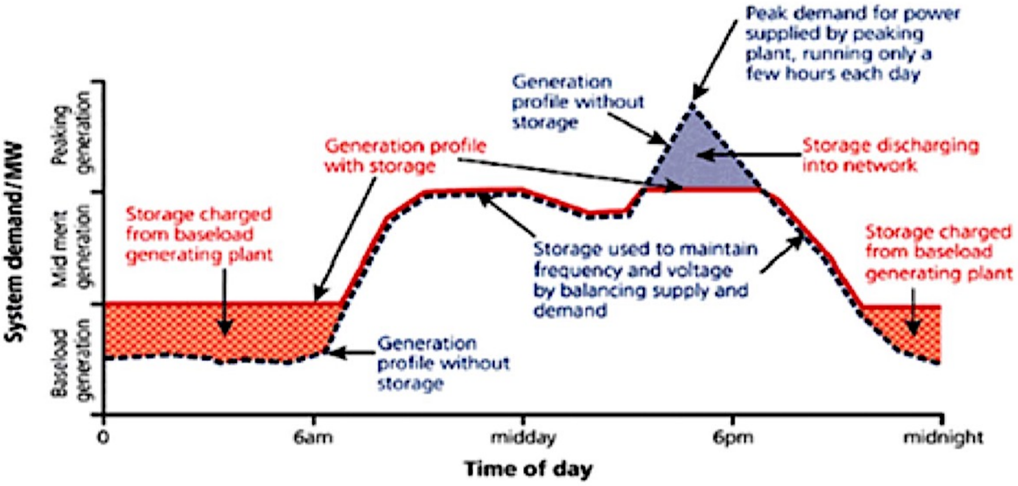


Figure 3.2.- PHES plant Generating (usually at midday or in the afternoon) and pumping mode (early in the morning or during the night) chart.

The most common way to classify these storage systems is based on their power capacity. According to The United States Department of Energy (DOE), it could be found the following PHES sizes:

- Large scale pumped hydro: More than 30 MW
- Small scale pumped hydro: Up to 10 MW
- Micro scale pumped hydro: Up to 100 kW
- Pico scale pumped hydro: Up to 5 kW

3.1 Advantages and disadvantages of PHES

3.1.1 Pros of PHES plants

One of the most beneficial features of PHES is its ability to react when fluctuations occur in the grid, i.e. they are capable of starting the turbine or the pump in about 30 seconds and start feeding the network without an external power supply for example in the case of a power failure.

Furthermore, one of the reasons why PHES has earned its reputation is that it has an unlimited capacity. Its function is not dependent from natural conditions, thanks to its reversible action, although there is no rain, or if there are variations in river flow or even in case of a lack of water during some periods of the year.

Apart from helping to integrate the renewable sources into the grid, the reliability of the Pump storage usage has several benefits which improve the power quality and grid stability. Some examples of them are the real-time load levelling, frequency regulation, voltage control and sometimes spinning reserve, among others.

The term of ***Load levelling*** refers to the possibility of balancing the power network at times of peak demand or excess energy. As it is known, the electricity demand by the industrial activities and consumers is in continuous fluctuation, so that the momentary demand is not always the same. The energy storage is a way to reduce these peaks of demand by storing the energy excess at a given time, as well as feeding the grid when there is an energy lack. In addition to this, it also reduces the need of shutting down and starting up other energy sources (for example wind farms) when production exceeds the grid demand. These stops and starts represent an extra cost, and lead to the need of maintenance more often.

The ***frequency control*** in energy systems has a great importance because it is essential to balance both the supply and demand of electricity.

Speed governors are used to control the frequency, as to maintain the balance required between supply and demand of electricity. These regulators operate differently depending on whether it is a single speed PHES or a variable speed one. In conventional PHES in which the speed does not vary, the frequency control is performed by varying opening wicket gates that can thus vary the fluid speed while passing through and therefore precisely control the frequency. This operation could last about 10 sec.

Nonetheless, a PHES plant with possibility of variable speed operation can balance the network's peaks in a very short period of time (150 ms), taking advantage of the inertia created by the rotation of the turbine acting as a generator or motor. Such plants also contains a frequency regulator to operate in case of larger fluctuations. Thanks to this technology, the machine manages to change its speed while the balance of the output power is achieved, as it is able to control both, the speed of rotation and the rotor current, independently throughout the frequency excitation. In addition, the wicket gates are also controlled by a speed governor.

It is important for the plant to keep the voltage within certain limits (as in the previous case of the frequency), to operate in optimum conditions and to avoid lowering its performance, so as to achieve a balance of reactive power, which will be the most important to reach the desired energy supply and demand balance. Both, conventional PHES and variable speed PS, working in both pumping and generating mode, through a voltage regulator, vary the current excitation field system, managing to ***control the voltage***.

However, although the conventional PHES have some responsiveness in voltage regulation, the issue of voltage fluctuations is mainly important when it occurs in short periods of time. The only systems capable to react quickly to this problem are only capable the ones based on variable speed. Whereas, the load levelling and the frequency issue are problems which could be fixed in a longer periods of time (relatively longer as we speak about less than a minute).

3.1.2 Cons of PHES plants

One of the most important challenges or problems that the construction of a PHES must face, is finding the appropriate the emplacement with optimal geological conditions with the necessary extension, which often hinders the engineering process. What is usually done is either take advantage of hydraulic old facilities, and so to build just the upper reservoir or build the upper reservoir and use as a lower reservoir a river, a lake or a dam constructed in the past.

Last but not least, one prevention measure which must been done when building the installation, is to place a filter system in both inputs and outputs of the penstock from the upper and lower reservoir in order to prevent the entry of organisms which could adhere to the duct's walls hindering the passage of water at both the inlet and outlet of the plant. In addition, bases and walls of both reservoirs must be perfectly sealed so as to prevent the penetration of salt water into the ground.

Among its cons it should be considered the potential danger of these plants in case of a reservoir failure. Apart from that, social issues remain as people's displacement issue in case of the government allowing the construction of a PHES plant in or in the surroundings of a village/town.

The most important problem is the environmental impact that PHES represents, very controversial topic which lead to cancel construction of many plants. Normally PHES construction involves destroying the surrounding nature, damaging rivers or water flows, mountains and therefore the landscape, animals and the ecosystems.

Finally, the PHES investment and civil engineering costs are very high and its response time very slow. These two concepts will be explained later on.

3.2 Efficiency

The efficiency itself, in a particular point of operation, is calculated from the following expression:

$$\eta = \frac{W_{ut}}{W_{st}}$$

Where,

η: the efficiency

W_{ut}: the released energy [kW]

W_{st}: the energy stored [kW]

However, it should be better specified and more precise because efficiency not only depends mainly on the relation existing between the released and stored energy, but also on the possible leaks that the components of the installation could have. This is why the calculation should be made considering these losses, to obtain an overall performance from the plant because the higher this result is, the more reliable and efficient the storage system will be. Furthermore, for an optimum operation process, losses from the energy transfer and self-discharge should be controled between little limits as it is shown in the next graph.[2]

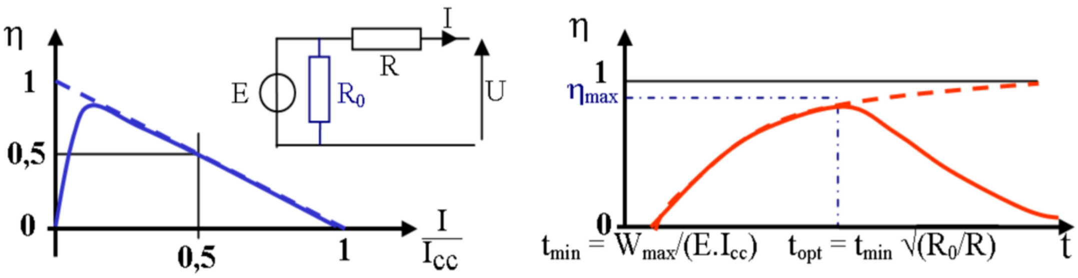


Figure 3.3.- Efficiency explanation graph

The resistance in parallel on *E* simulates the auto-discharge.

The first graph represents the effect that the current and time discharge has on the efficiency while in the second one, is shown what happens to the efficiency when there is a self-discharge. Both are compared with a model without self-discharge resistance represented by a dotted line.

Besides, *I* means source of current and *Icc* means short-circuit current.

However, there is another way to calculate the efficiency of the plant. Since the energy supplied in generation mode depends on the generation efficiency (η_g) and energy consumed in pumping mode depends on the pumping efficiency (η_p), it comes up the other way to explain the total efficiency of the PHES which relates both concepts:

$$\eta = \eta_g \cdot \eta_p$$

These plants usually reach high efficiencies, finding values between 70% and 80%. [3]

3.3 Problems which decrease PHES efficiency

The main problems that may constitute a risk of the plant's efficiency reduction, are mostly composed by the natural process of evaporation of water, losses in transmission over power lines, leaking in some of the installation's parts and poor design of some of the parts of the plant, mainly of the turbines. [4]

3.3.1 Evaporation Losses

Losses due to the evaporation of water are the most obvious and, depending on the situation, they could be one of the most important to consider. These losses are mainly depending on the climate zone, size and depth of the basin, so that a large and shallow reservoir will be more likely to suffer losses due to evaporation than a smaller and deeper reservoir. Similarly, if it is located in an area in which the incidence of the sun is high, the evaporation will be more favourable than in a cooler zone. Likewise, they could reduce such losses if the deposit is located between mountains which will provide shade.

3.3.2 Transmission Losses over Power Lines

These losses exist in some parts of the transmission line with unstable voltage and therefore can affect the performance of the plant. If the PHES is located near this area, using a reactive power control could be helpful to reduce the high levels of reactive power and so to improve the voltage stability.

3.3.3 Leakage Losses

The main place where leakage could be found are cracks from the pipes through which the water escapes. It could also appear at the bottom of the reservoir. Therefore, the engineering work in the construction of these plant parts, as well as a periodic monitoring of these leaks, are essential. [4]

3.4 Generated Power & Power Required

There are two different powers to be calculated. The first is the power that is obtained at the outlet of the pump-turbine assembly, when the plant operates in power generation mode facing an energy demand from the grid, and taking advantage of the waterfall from the upper to the lower reservoir. The second one corresponds to the power needed to pump the water from the lower reservoir to the upper one, when there is an energy excess in the network, i.e., when the power plant works in pumping mode.

- *<u>Rated power output from generator:</u>*

$$P_g = \rho \cdot g \cdot H_g \cdot Q_g \cdot \eta_g$$

where:

P_g: Rated power output [kW]

ρ: water density [≈ 1000 kg/m^3]

g: gravity [≈ 9,81 m/s^2]

H_g: head in generating mode [m]

Q_g: the flow through the turbine [m^3/s]

η_g: generator efficiency

- *Power required to pump:*

$$P_p = \frac{\rho \cdot g \cdot H_p \cdot Q_p}{\eta_p}$$

where:

P_p: power consumed by the pump [kW]

ρ: water density [≈ 1000 kg/m^3]

g: gravity [≈ 9,81 m/s^2]

H_p: head of the pump [m]

Q_p: the flow through the pump [m^3/s]

η_p: pump efficiency

3.5 Variable speed vs Fixed speed

The generators of a conventional pump storage plant are usually synchronous machines, which operates at a constant speed because, as being connected directly to the grid, they must work at the system frequency (50 Hz or 60 Hz depending on the country). This system has only one variable which is the position of the gate. Consequently, operating at a constant speed, the power input in the pumping operation is not able to vary. Because of this, fixed speed turbines have a lower efficiency than the turbines that are coupled to generators, which can change its rotation speed thus adapted to suit to existing power oscillations and the variations of the flow of water from the head. [5],[6],[7]

Basically, a variable speed system is composed by a reversible pump-turbine unit connected to a generator, which can work both as motor and generator, as shown in Figure 3.4. Compared with synchronous machines, they have higher efficiencies and provide stability to the power system. Nowadays, the highest efficiency that variable speed systems can reach is about 85%.

Within variable speed systems, there are two topologies: double fed and fully fed. The fully fed configuration consists on a converter between the generator and the network. Based on numerous articles such as [7],[8],[9],[5],[10], this research project concludes that the most recommended topology for these facilities is the double fed due to its several advantages:

- by the possibility of adjusting the speed, the turbine can operate in optimum conditions of speed which makes its lifetime greater and increases its efficiency.
- better dynamic control of the active and reactive power, in a decoupled way, which contributes to a better stabilization of the network
- the converter requires less power to operate than in fully fed configuration, thus it has lower losses and lower initial cost.

The most common configuration of this “new” way of the pumped storage operation is a variable speed architecture based in double fed induction generators (DFIG) [11]. The next figure shows how a converter is connected to the rotor, and how it is connected to the grid. The aim of this converter is to control the rotor's currents so as to control the active and reactive power of the rotor and therefore to be able to control the slip of the induction machine. By controlling this slip, the rotor can be rotating at varying speeds, but the frequency of the electricity from the stator is always maintained at the same level. The stator is directly connected to a transformer which is connected to the grid. The control action of the converter reduces the need of the mechanical control of wicket gates for adapting the current's speed to the network frequency, regardless of the speed of the water flow into the generator input.

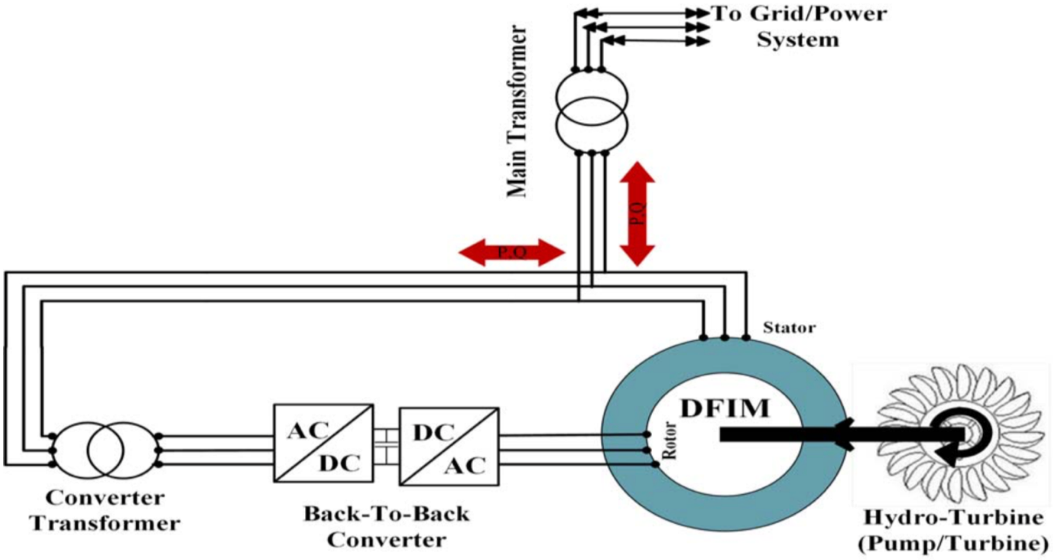


Figure 3.4.- Variable speed pumped storage doubly fed configuration. [5]

In other words, the converter's operation makes that even though, by the action of the water, the rotor rotates faster, the frequency obtained in the generator's output will be the same that the one required by the network. [5]

A recent study showed the advantages and disadvantages of variable speed operation and fixed speed operation by comparing both dynamical behaviours in a pumped storage plant. It concludes that the variable speed has better control strategy thanks to the advantage to control active and reactive power in a separate manner. It has a better behaviour facing grid faults such as voltage drops or short circuit. When a voltage drop appears, variable speed machine's active and reactive power can be balanced in a shorter period of time than the synchronous machine. The same can be said of short circuits, the DFIG can stabilize before the synchronous machine (normally after 1 second). Nevertheless, the synchronous machine voltage's performance is better. [7]

After a torque perturbation test, the variable speed machine's response is better as it absorbs these fluctuations. It has such small oscillations of active power, reactive power and voltage that it is almost immune in this situation. What happens is that it experiences huge speed variations but as we are talking about a variable speed configuration, this does not represent a problem.

To sum up, after this study, it could be concluded that by replacing conventional fixed speed systems with the new variable speed operation systems, it is possible to reach a better behaviour in the grid's stabilization, facing power perturbations ensuring that the power production will be better. Moreover, those systems have the capability to give a fast response facing sudden events in the grid, allowing the renewable energy sources, as wind or photovoltaic systems, to join the power system network, and thus reducing the non-renewable fuels consumption.

Table 3.1.- PHES plants with variable speed in Europe and Asia

Country	Name of the PHES plant
Japan	Okawachi Power Plant of The Kansai Electric Power
Japan	Kansai Electric Power's Narude Power Plant
Japan	Omarugawa Power Plant of the Kyushu Electric Power Co.
Japan	Okutataragi Power Plant of Kansai Electric Power
India	Tehri
Germany	Goldishtal Pumped Storage Plant
France	Le Cheylas

4 ENERGY STORAGE ALTERNATIVES

Due to the increasing development of renewable energies and the strong percentage of solar and wind energy generation, a wide interest emerged in different types of energy storage technologies, in order to cope with fluctuations in the grid.

This is so because these energy sources are intermittent in nature, so they only produce energy when the sun is shining and with the wind existence. By storing the produced energy, these technologies are able to continue powering the grid even when it gets dark or the wind stops blowing.

The most common way to store energy is by the pumped storage hydropower. As mentioned before, the water is dropped from the upper reservoir to the power generators, which convert the kinetic energy into electricity when demand peaks during the day, and is pumped back uphill at night using the grid’s excess electricity.

Summarising, storage technologies give the possibility of transferring the energy excess of the grid to some places where it can be stored to handle it back when needed; here lies the growing interest in researching this new type of technology.

Taking all into account, besides allowing greater use of renewable electricity generation which leads to a reduction in carbon dioxide emissions, these storage technologies also provide a greater flexibility and ability to adapt to the power grid's changes and to improve the power quality by frequency regulation. Moreover, it allows companies to produce power when it is cheaper and the most efficient, which could mean a more reliable power grid providing a constant source of power during the whole day, more diverse and a more competitive supply regarding overall costs.

As a result of the slow response from pumped hydro to grid changes, different types of energy storage technologies have been developed so far including compressed air, SMES, batteries, flywheels, thermal storage, and ultracapacitors. Apart from them, there is another new technology which is known by the acronym of FLES (Flat-land Large-scale Electricity Storage): it works similarly to pumped hydro but it also has significant differences.

4.1 Compressed Air

The philosophy of Compressed Air Energy Storage (CAES) plants is based on using the excess power in electricity production (at a very low cost in those hours) for compressing ambient air and then store it in an underground cavern, especially built in this purpose. After that, when the underground storage reaches its maximum capacity or during periods of high energy demand, the pressurized air will be heated and expanded in an expansion turbine which drives a generator to feed the electric grid.[12]

Figure 4.1.- Illustration of a small scale compressed air storage system

After years of research and development, the first power plant using this technology was built in 1978 in Germany.

Instead of constructing highly specialized surface pipes, which can be expensive economically speaking, the ideal form of storage of compressed air is by injecting it in an existing geological formation, such as a hard-rock or disused salt mine.

Leaks are the most important negative factor of this technology. Usually, around 20-50 % of compressed air disappears as leakage, so here lies the importance of making periodic maintenance checks of the compressed air system in order to detect these leaks and fix it as soon as possible.

It could be possible to save a lot of money through this periodical review, by fixing leaks, adapting the machines and air consumers to the appropriate operating conditions and replacing tools and equipment for another options with less energy consumption.

Another issue to consider is that the air heats up when it suffers the phenomenon of compression. Likewise, when there is electricity demand, this compressed air needs to be expanded and this process needs a supply of heat. Due to this, there is a growing demand from companies whom investigate these process to try to find different ways to best store the heat generated during compression for its later use in the expansion process, which would allow to obtain a much more efficient process.

Nowadays there are lots of investigations about different processes which could be possible solutions of this matter; for instance, the natural gas in the expansion process, the use of liquid metals in heat exchangers, some types of salts and other solids which could extract the heat of the compressed air and give it back during the expansion. SustainX, a company from the USA, is another example of investigation in this field. They are working on a process which consists in the injection of water vapour into compressed air. Through this methodology, the water absorbs the heat and is stored to give it back when needed in the expansion process.

However, some of these methodologies of energy storage are not sustainable nor renewable such as natural gas. Therefore, research about the option of thermal storage mechanism is driven, as it avoids the use of fossil fuels in the expansion process.

There are three investigations on how to reuse this heat, focused on the compression process which are the Adiabatic storage, Diabatic storage and finally, the Isothermal storage:

Diabatic storage: This technology is based primarily on the use of a multistage compression process with intercooling followed by the multistage expansion process with reheating. As the heat from the compression process is not stored, when there is an electricity demand, the compressed gas must be reheated by burning fuel to experience the expansion that will drive the turbine to produce the needed amount of electricity. The highest efficiency reached with this process is around 54 %. [12]

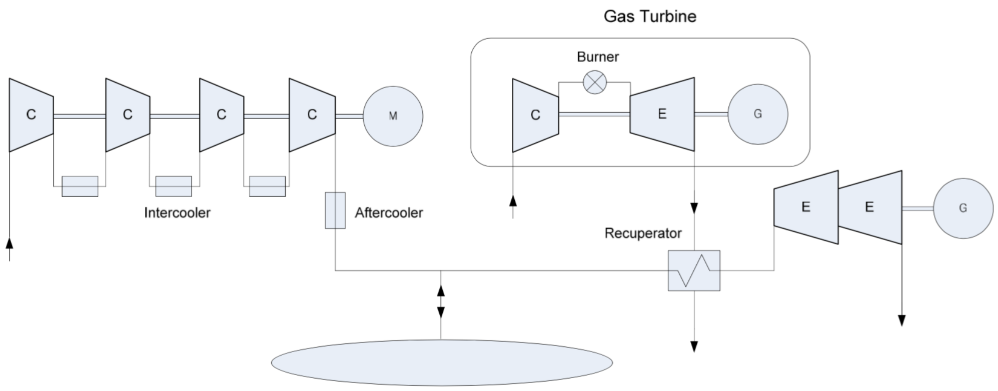


Figure 4.2.- Configuration of Diabatic CAES system [13]

Adiabatic storage: Researchers are working on another possible configuration to improve efficiency of Diabatic CAES; one of this proposals is Adiabatic storage. This technology does not use fuel to heat the compressed air in the expansion process. As mentioned before, when the air suffers the compression there is heat built up which is stored in a Thermal Energy Store (the air is compressed up to 50 bar adiabatically, the outlet air temperature of compressor is about 685 ºC. [13]. Afterwards, when there is a demand peak, the compressed air is heated by this stored heat up to 622 ºC and it is expanded driving the turbine which produces the electricity required. If another heat, instead of the stored one, was used this would lead to a very low efficient process (less than the expected one which is around 70%).

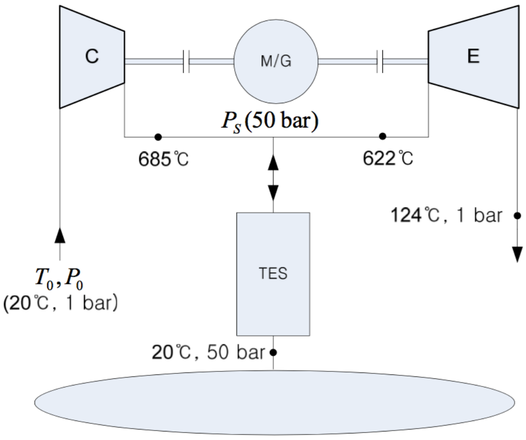


Figure 4.3.- Diagram of an Adiabatic CAES system [13]

Isothermal storage: This technique focuses on maximizing the work needed for the isothermal compression/expansion of the air, and minimizing the work in the compression process, thanks to the process heat transfer between air and its surroundings which means that there is a very small change in gas pressure by the liquid piston. [13]

SustainX is the most famous example of a company which is investigating this process[14]. Its technology is based on the adiabatic process but it also developed another point of view: instead of using turbines to generate electricity and high temperature thermal energy storage, the company uses pistons driven by electricity to compress air, and above ground storage tanks in which the compressed air is stored. When energy is required, the air is expanded to drive the pistons in reverse, by this way feeding the generator. There is another process working in a parallel way which is based on storing the extra heat of the compression thanks to a water spray placed inside the cylinders. It absorbs the heat and the hot water is stored in the aim to be sprayed again into the cylinders during expansion (as in this process the gas is able to be more efficient by absorbing heat from its surroundings [13] and then drive an hydraulic motor that turns on the electric generator). This technology constitutes a huge advantage as it does not require additional fuel to heat the air during expansion and moreover achieves a zero emission of greenhouse gas, which is an important concern in the world nowadays.

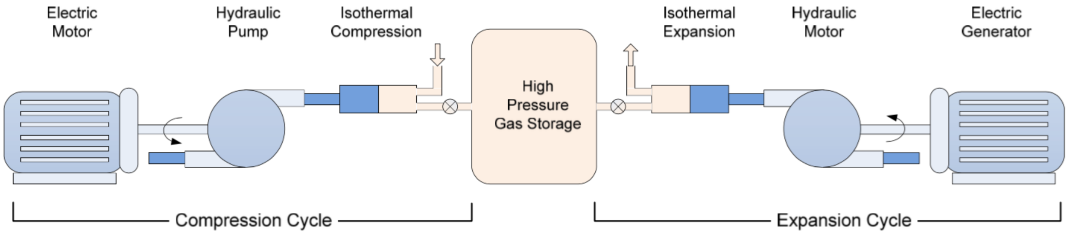
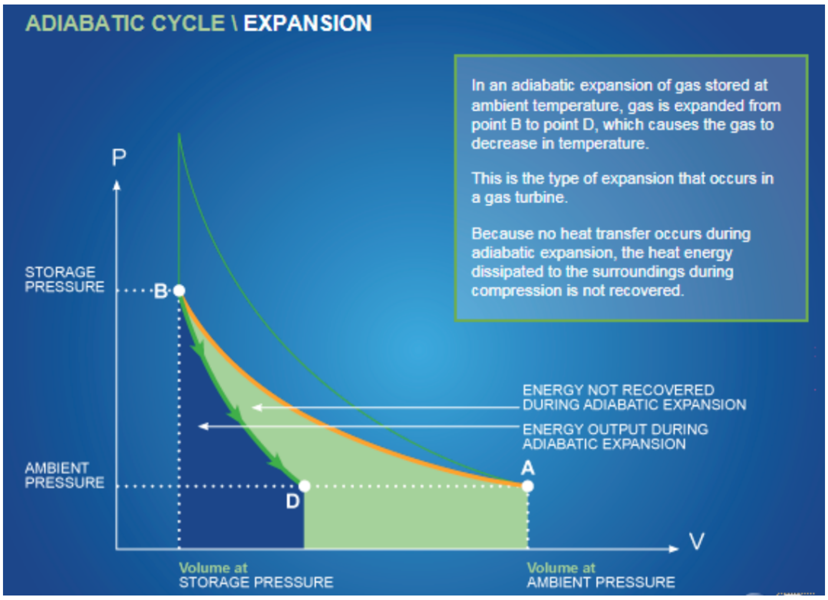


Figure 4.4.- Diagram of an isothermal CAES system



In an adiabatic expansion of gas stored at ambient temperature, gas is expanded from point B to point D, which causes the gas to decrease in temperature.

This is the type of expansion that occurs in a gas turbine.

Because no heat transfer occurs during adiabatic expansion, the heat energy dissipated to the surroundings during compression is not recovered.

Figure 4.5.- Adiabatic expansion process of the gas in an CAES plant

4.2 Superconducting Magnetic Energy Storage (SMES)

When a superconductor is charged by a voltage source, the electric current which flows through it creates a magnetic field and it keeps on circulating even when the conductor is disconnected from the voltage [15]. The principle of operation of a SMES is based on this phenomenon, therefore as it is a superconductor magnetic device at the cryogenic temperature avoiding resistive losses, it acts as electric energy storage in a coil to use it when needed. The temperature can be maintained thanks to the action of the helium or nitrogen liquid vessels which are in a cryostat and the energy losses, when the coil is on stand-by, are reduced using a bypass switch. [16]

The most important advantages of this system is that it has a high degree of efficiency (>90%), very fast response (the charge/discharge process could be made in milliseconds), the capability of controlling real and reactive power and its high durability (around 30 years) [17]. Nevertheless, it has some disadvantages too which are the high investment cost and its complex cooling process.

Normally, the SMES devices are designed to work into the primary control of the frequency of the grid.

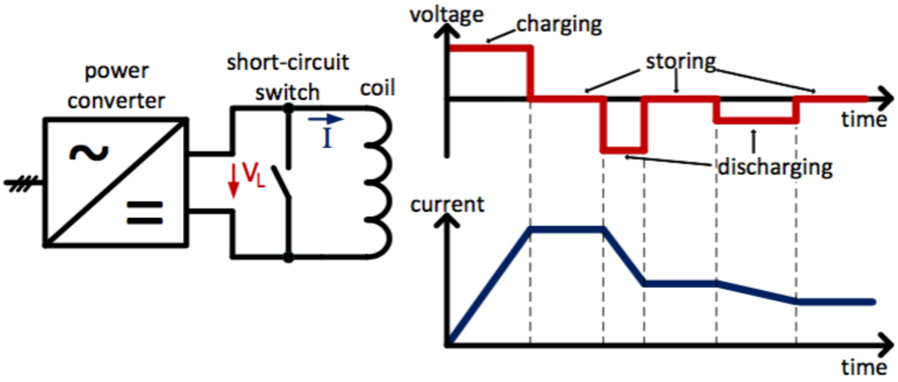


Figure 4.6.- Charge and discharge process of a SMES [17]

Compared with the pumped hydro energy storage, the SMES capacity is too low nowadays to replace the PHES.

4.3 Flat-land Large-scale Electricity Storage (FLES)

As mentioned before, a pumped hydro plant operation not only is on the drop down of water through a penstock from an upper reservoir to a lower end where it launches a turbine (operating as a generator) which produces electricity, but it also operates as an energy storehouse with help of the turbine, operating as a motor which is fed by the grid power. This time, the water is pumped backwards by the turbine from the lower reservoir to the upper one through the penstock. It is known that this storage system is very reliable, thanks to the good knowledge of its technology, with a high efficiency of 70%-85%. [18]

Most of the turbines used nowadays are the Francis single stage pump turbines which range can reach 800 m high, so, for instance, if we choose a large head of h=750 m as point of reference, we would get 7.3 MJ/m^3 of nominal energy density. The 90% of this nominal energy should be converted in kWh$_e$, summing up, more or less 2 GW·days. To get this result, each reservoir should hold 24·10^6 m^3, taking into account the following equation if energy:

$$E = \rho \cdot g \cdot H \cdot v$$

E: energy [kW]

ρ: density of the water [≈ 1000 kg/m^3]

g: acceleration of free fall [≈ 9,81 m/s^2]

H: head [m]

v: volume [m^3]

After this example we can see that its low density per unit volume of gravitational potential energy is a disadvantage as it means that finally the plant should hold a huge volume (24·10^6 m^3) just for reach the 2 GW·days.

This shortcoming has caused a great amount of investigations after which they discovered another option that could solve the problem of finding two reservoir sites that big, separated by several hundreds of meters, by the idea of building the lower reservoir in deep underground of strong homogeneous rock formations cavern and directly below the upper reservoir so that this system would only need one of them visible at the surface.

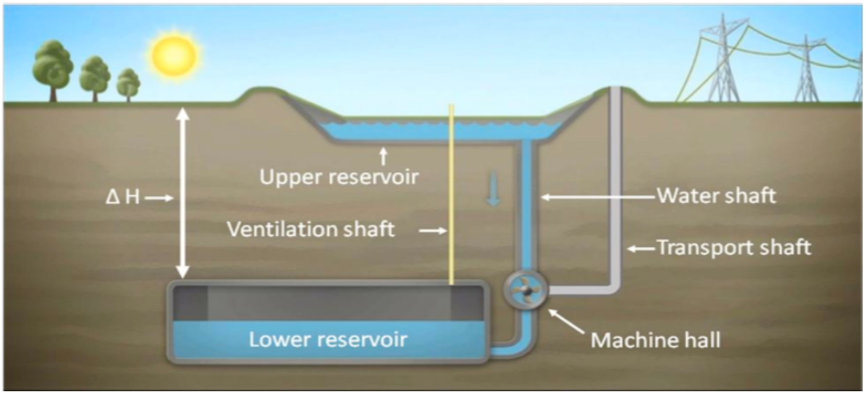


Figure 4.7.- FLES main components

The system is called Flat-land Large-scale Electricity Storage (FLES). This solution leads to various advantages which fix the shortcoming problems of the conventional pumped storage system: first of all, the visible landscape's impact is significantly reduced, it is not necessary to build the plant in a mountain, it just needs a thorough research to find the proper conditions of the ground which could contain the subterranean reservoir. Whereas the conventional pumped storage system needs a high length of headrace and tailrace, the FLES shortens them. Assuming there is a great space underground, the facility could be placed anywhere.

Taking into account the previous equation, the upper reservoir could be much smaller by maximizing the height difference between both since by having more height, the water volume needed is smaller to produce the same energy.

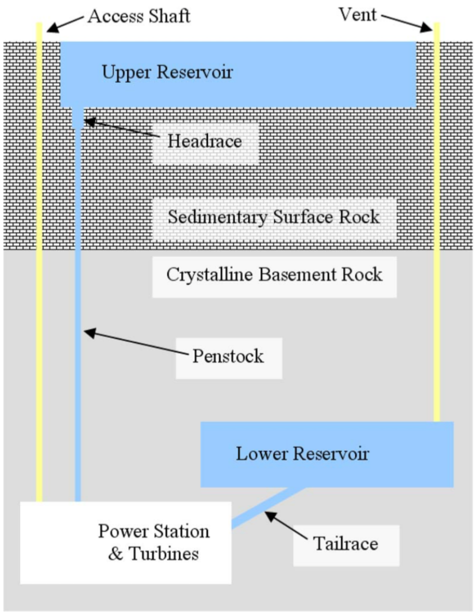


Figure 4.8.- FLES scheme

4.4 Batteries

4.4.1 Lead- acid batteries

The lead-acid batteries are the oldest type of rechargeable battery and its technology is one of the most commonly used to improve power quality and uninterruptible power supply (UPS), being itself a simple and low manufacturing cost technology that has been known for a long time. The main drawback of these batteries and therefore, the reason why they are not used for energy management, apart from its low durability and the toxicity from the sulphuric acid used, is that the energy level that they can store is not fixed as it depends on the discharging speed.

4.4.2 Metal-air batteries

The metal-air batteries are used to face energy demands. They are composed of porous carbon cathode or a metal mesh covered by a catalyst; and anodes made by metals like Al or Zn which release electrons after oxidation. Typically, the electrolytes are in liquid form.

These batteries have pluses as owning a high energy density, being cheaper and compact and environmental friendly. However, they are not commonly used to meet power demands due to the difficult and inefficient recharge (50%). Batteries Zn-air are the most common.

4.4.3 Sodium sulphide batteries

Sodium sulphide batteries are the high temperature batteries most commonly used. They are known for their high efficiency (75-86 %) [19], high energy density, low cost materials and recharge ability in which process the sodium is returning to its configuration as an element, keeping the temperature up to 300 ° C. The positive electrode is formed of liquid sulphur, and the negative electrode is composed of molten sodium. Both electrodes are separated by a ceramic alumina electrolyte.

When there is a power or energy demand, positive sodium ions of the electrolyte are combined with the sulphur to generate power drop in the external circuit of about 2V.

4.4.4 Flow batteries

Flow batteries are systems which convert chemical energy to electricity in a direct way. An external tank holds the most important part of these batteries: an electrolyte composed of one or more electro-active species which flow in dissolution along an electrochemical cell and the recharge process is simply done by replacing the liquid of the electrolyte.

Inside the group of flow batteries, the most used is the redox-vanadium. The term "redox" refers to the electrochemical potential due to oxidation-reduction processes between two different electrolytes. There are several advantages that should be mentioned into the redox flow batteries group, these are for instance, its great number of cycles due to the inexistence of solid-solid phase changes, its fast time response, and its zero emissions. Although its good qualities, they also have weak points, as they need a high initial self-discharge rate and are quite complex comparing with conventional batteries because of sensors, pumps, control and the secondary vessels requirements.

Aqueous Vanadium-redox chemistry is one example commonly used of Flow batteries which act when there is an energy demand and they store energy created by the reaction of vanadium redox pairs ($V^{2+/}V^{3+}$ in the negative place and $V^{4+/}V^{5+}$ in the positive) that are found in a sulphuric acid electrolyte. As it is possible to see in the following figure, besides both warehouses of electrolyte, there exists a membrane of permeable polymer that allows the exchange of ions H+ between both tanks in the processes of charge and discharge.

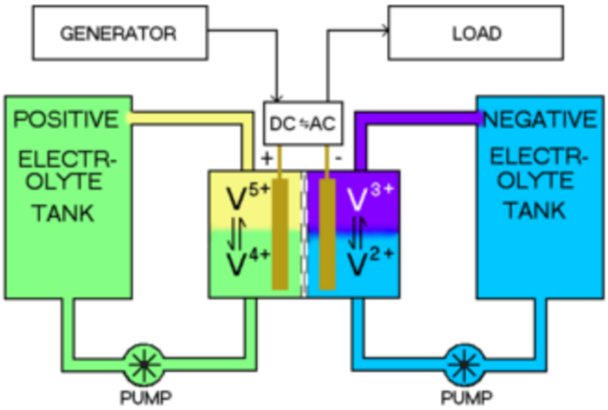


Figure 4.9.- Vanadium Redox Flow battery [20]

Despite its low energy density, the net efficiency of vanadium redox batteries reaches the 85% and guarantee almost an infinite number of charges and discharges without waste generation. Moreover, as mentioned before, the vanadium batteries capacity is huge as it just depends on changing the tank to another with a bigger size.

Vanadium redox batteries are used in some important applications such as helping generators for balancing the discontinuous generation sources (i.e. wind or solar) as well as helping generators to face demand peaks, all of this thanks to its huge capacity.

4.4.5 Lithium-ion batteries

The most common and proposed type of batteries used nowadays for electric storage in grids is lithium ion. They consist on an electrolyte composed by lithium salt (such as $LiPF_6$) dissolved in organic carbonates. The cathode is formed by lithium atoms which migrate in the charging process to the graphite anode where they are combined with electrons outside and then they are deposed in the carbon layers. In the discharge, the reverse process occurs.

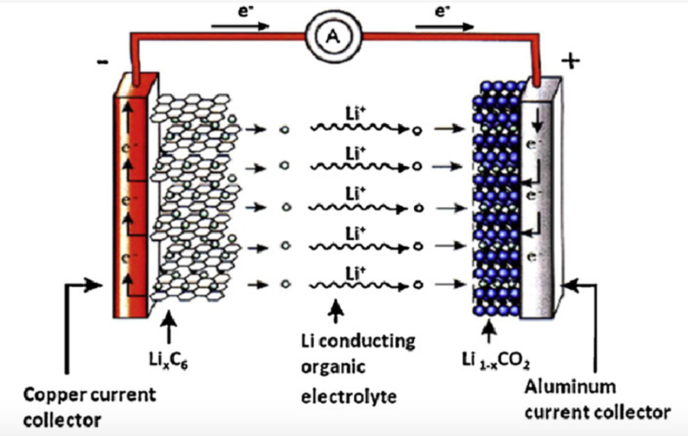


Figure 4.10.- Lithium Ion battery scheme [21]

These batteries are used whether there is an energy demand as when there is a power demand. It has many pluses and for that reason, are the most commonly used today. Among its main advantages it could be highlighted its high energy density (300-400 kWh/m^3, 130 kWh/Tm), high efficiency (almost 100 %), and high number of cycles within its average life (3000 cycles, 80 % of discharge depth).

According to a recent published research, the static battery such as Lithium-ion batteries, represents a cost effective advantage comparing with the flow batteries since, for increasing its efficiency, flow batteries need to improve its materials quality, having thus a profit decrease [22]. Besides this, flow batteries have the drawback of bigger size which leads to a more difficult study to find a proper place for them, and its technology system requires a lot more maintenance.

4.5 Flywheels

This way of energy storage is based on an electromechanical system. This system consists of a cylinder of high mass which is inside a stator subjected to magnetic levitation. The rotor contains a generator/motor which converts kinetic energy into electricity when the flywheel rotates so the energy is stored in this momentum of rotating rotor.

This system is commonly used to cover the power demand for short periods of time. Among the positive aspects, can be highlighted its long lifetime and low maintenance because the rotor operates in vacuum, rotating on bearings which reduces friction and increases efficiency. Moreover, it has a good resistance to environmental conditions.

Another aspect is the almost non-existent losses in stand-by (less than 1%) and its fast response time as it is able to go from 0% to 100% of power delivered in less than 5 ms. [23],[24].

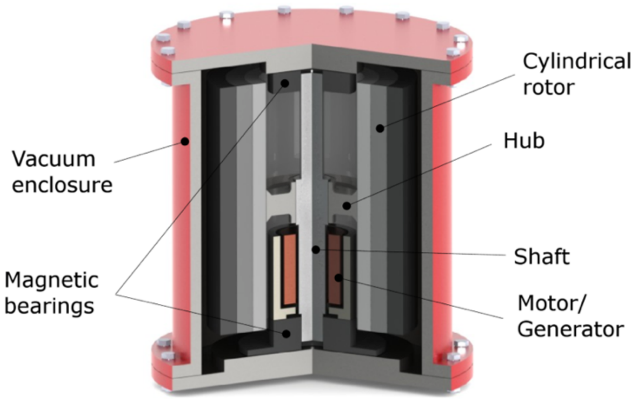


Figure 4.11.- Flywheel scheme

4.6 Ultracapacitors

The ultracapacitors use is focused on attending the demand for power. Its operation is based on storing electrical energy by two capacitors which are connected in serie. The electrical double layer is formed by the electrolyte ions. Electrolytes may be organic or aqueous, the last one being cheaper, but having the shortcoming of a low energy density. Besides, the electrodes are usually made with porous carbon. [23]

In addition to maintain the circuit voltage, more or less constant, the ultracapacitors do not need as much maintenance as flywheels and batteries. In addiction, its efficiency and high cycle life are also positive aspects compared to other storage methods.[25]

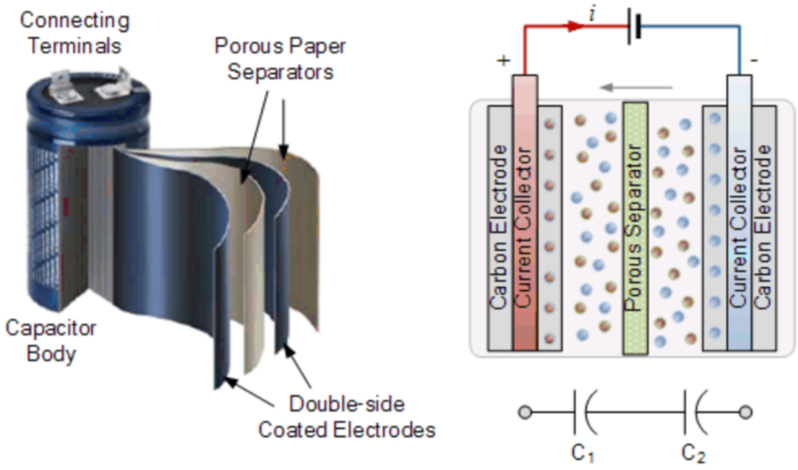
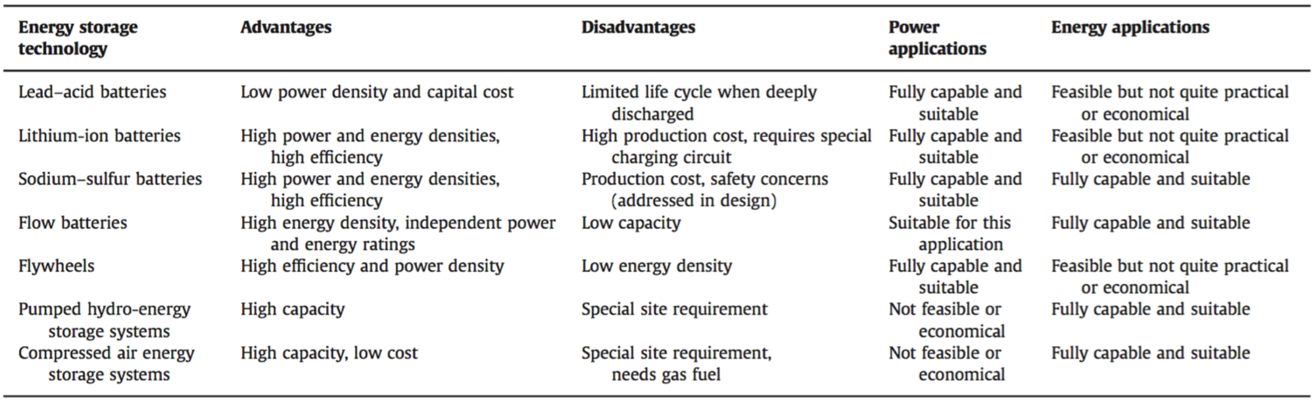


Figure 4.12.- Ultracapacitor scheme [26]

4.7 Comparison of energy storage alternatives

Table 4.1.- Comparison between the different energy storage technologies [19]



Energy storage technology	Advantages	Disadvantages	Power applications	Energy applications
Lead–acid batteries	Low power density and capital cost	Limited life cycle when deeply discharged	Fully capable and suitable	Feasible but not quite practical or economical
Lithium-ion batteries	High power and energy densities, high efficiency	High production cost, requires special charging circuit	Fully capable and suitable	Feasible but not quite practical or economical
Sodium–sulfur batteries	High power and energy densities, high efficiency	Production cost, safety concerns (addressed in design)	Fully capable and suitable	Fully capable and suitable
Flow batteries	High energy density, independent power and energy ratings	Low capacity	Suitable for this application	Fully capable and suitable
Flywheels	High efficiency and power density	Low energy density	Fully capable and suitable	Feasible but not quite practical or economical
Pumped hydro-energy storage systems	High capacity	Special site requirement	Not feasible or economical	Fully capable and suitable
Compressed air energy storage systems	High capacity, low cost	Special site requirement, needs gas fuel	Not feasible or economical	Fully capable and suitable

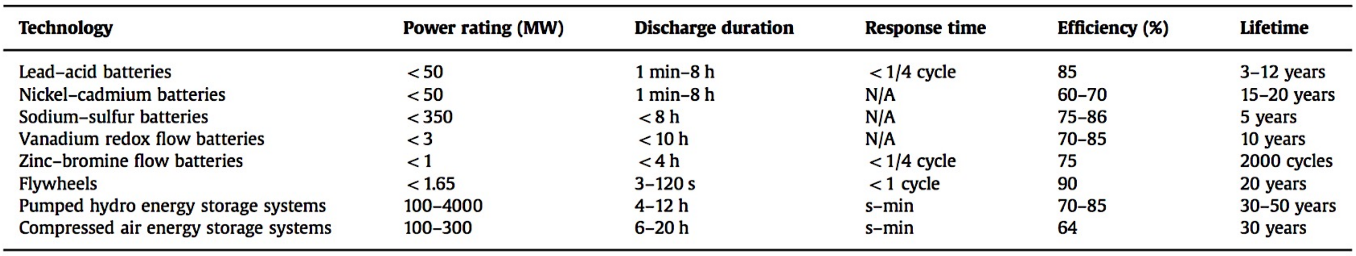
Table 4.1 shows the pros and cons of all different technologies of energy storage and their behaviour according to energy and power applications.

On one hand, in terms of capacity and costs it is clear that the pumped hydro-energy storage and CAES have the best qualities but if the site available is not big enough, they should be replaced by another storage technology.

On the other hand, the different types of batteries and flywheels, although their low capacity, they present quite positive aspects such as high efficiency as well as high power and energy densities.

Comparing the technologies with the power and energy applications, it should be taken into account that Pumped storage and CAES could not be aimed for power applications, whereas the rest of them could have both functions suiting best in one or the other depending on which of them we are talking about.

Table 4.2.- Technical characteristics of the different types of energy storage [19]

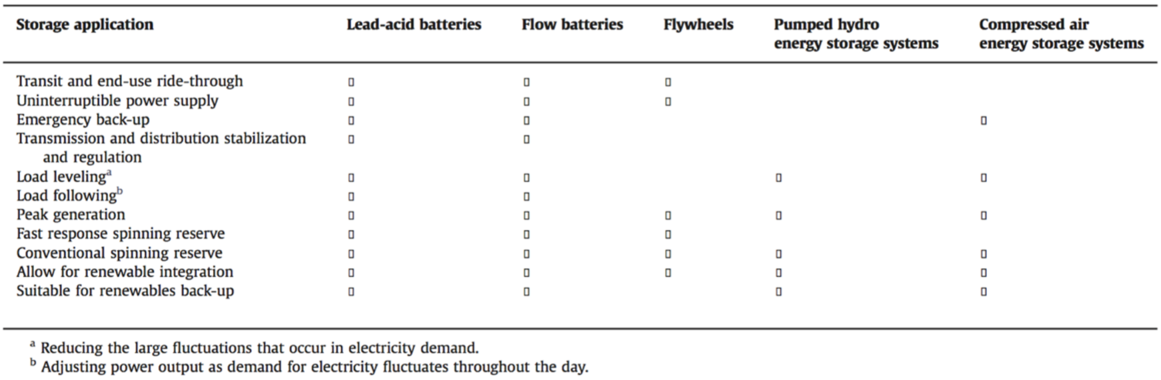


Technology	Power rating (MW)	Discharge duration	Response time	Efficiency (%)	Lifetime
Lead–acid batteries	< 50	1 min–8 h	< 1/4 cycle	85	3–12 years
Nickel–cadmium batteries	< 50	1 min–8 h	N/A	60–70	15–20 years
Sodium–sulfur batteries	< 350	< 8 h	N/A	75–86	5 years
Vanadium redox flow batteries	< 3	< 10 h	N/A	70–85	10 years
Zinc–bromine flow batteries	< 1	< 4 h	< 1/4 cycle	75	2000 cycles
Flywheels	< 1.65	3–120 s	< 1 cycle	90	20 years
Pumped hydro energy storage systems	100–4000	4–12 h	s–min	70–85	30–50 years
Compressed air energy storage systems	100–300	6–20 h	s–min	64	30 years

In Table 4.2 it is observed that despite its slow time response, the pumped hydro has the highest power rating and life time, moreover its efficiency is one of the best too.

On the contrary, batteries and flywheels have the huge advantage of being the ones which response time is the fastest, which gives a wide range of opportunities for working with them, but they also have their bad points which are its low discharge duration and power rating.

Table 4.3.- Technical suitability of the different types of energy storage [19]



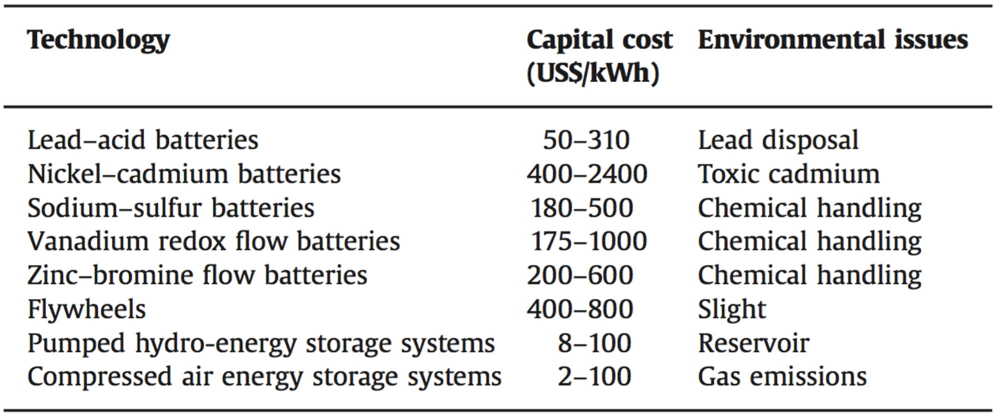
Storage application	Lead-acid batteries	Flow batteries	Flywheels	Pumped hydro energy storage systems	Compressed air energy storage systems
Transit and end-use ride-through	☐	☐	☐		
Uninterruptible power supply	☐	☐	☐		
Emergency back-up	☐	☐			☐
Transmission and distribution stabilization and regulation	☐	☐			
Load leveling[a]	☐	☐		☐	☐
Load following[b]	☐	☐			
Peak generation	☐	☐	☐	☐	☐
Fast response spinning reserve	☐	☐	☐		
Conventional spinning reserve	☐	☐	☐	☐	☐
Allow for renewable integration	☐	☐	☐	☐	☐
Suitable for renewables back-up	☐	☐		☐	☐

[a] Reducing the large fluctuations that occur in electricity demand.
[b] Adjusting power output as demand for electricity fluctuates throughout the day.

Talking about the suitability of the different storage technologies, pumped hydro energy storage systems work well in operations of load levelling, peak generation, conventional spinning reserve, renewable integration and renewables back-up applications. CAES shares not only the same aspects for such operations, but also it is suitable for emergency back-up aspects.

While Lead-acid batteries and Flow batteries are suitable for all the storage applications shown in the table, Flywheels only operates well in transit and end-use ride-through, uninterruptible power supply, peak generation, fast response spinning reserve and renewable integration.

Table 4.4.- Economical and environmental characteristics of the different types of energy storage technologies [19]



Technology	Capital cost (US$/kWh)	Environmental issues
Lead–acid batteries	50–310	Lead disposal
Nickel–cadmium batteries	400–2400	Toxic cadmium
Sodium–sulfur batteries	180–500	Chemical handling
Vanadium redox flow batteries	175–1000	Chemical handling
Zinc–bromine flow batteries	200–600	Chemical handling
Flywheels	400–800	Slight
Pumped hydro-energy storage systems	8–100	Reservoir
Compressed air energy storage systems	2–100	Gas emissions

Finally, Table 4.4 compares the different aspects that each technology has with reference to capital costs and environmental issues.

According to environmental possible problems, pumped hydro is the cleanest storage system without gas emissions, but at the same time should be considered the pollution emission while building the reservoir, and which also damage mountains which can affect the wildlife.

CAES has the obvious problem of its possible gas emissions, and batteries its chemical pollution. Nevertheless, flywheels have just a slight consequence in the environment.

In relation to energy cost, the cheapest storage systems are the pumped hydro and compressed air. Furthermore, lead-acid and sodium-sulphur batteries, flywheels and CAES are also the most economic energy storage technologies considering power costs.

Costs could be studied from an other point of view: the investment costs for the different types of storage systems. As showed in the next graphic, it could be appreciated that although the pumped storage has the most expensive investment cost, this technology is the only one which lasts higher number of hours followed by CAES, however, the SMES, Flywheels and Batteries, their investment cost is cheaper comparing with the two others but they can not be as reliable as pumped or CAES, in terms of working hours, power and capacity.

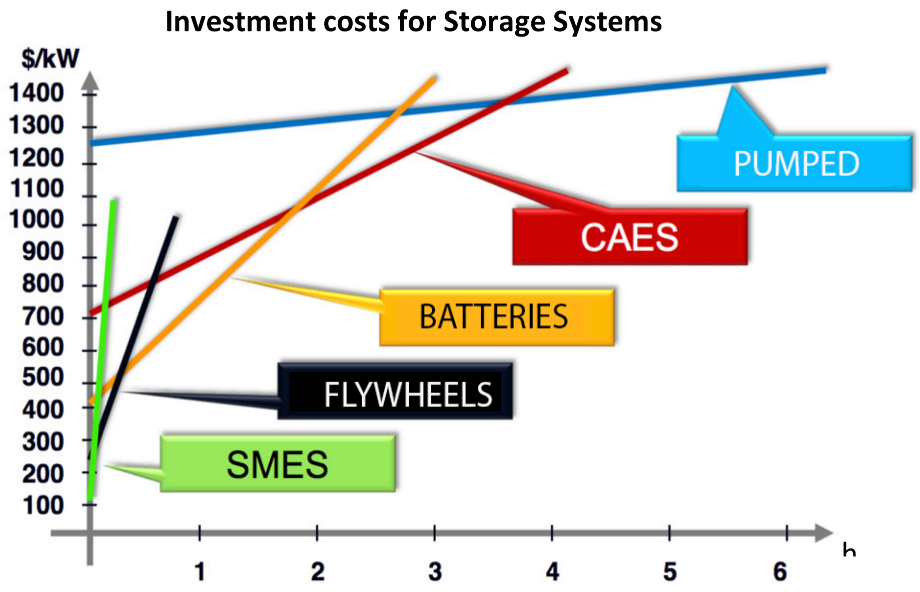


Figure 4.13.- Investment costs for Storage Systems chart

In conclusion, pumped hydro energy storage, despite its slow time response and therefore, its limited flexibility to adapt to sudden changes in the grid, is the ideal technology in terms of capacity and possibility of energy supply when peaks of demand for providing grid stabilization and frequency regulation. Nowadays, it is the most developed way to store the energy due to the good knowledge of its technology, its safety, long life, high efficiency and low maintenance cost all of which make up for its high investment cost. Moreover, it is a clean technology considering polluting gas emissions.

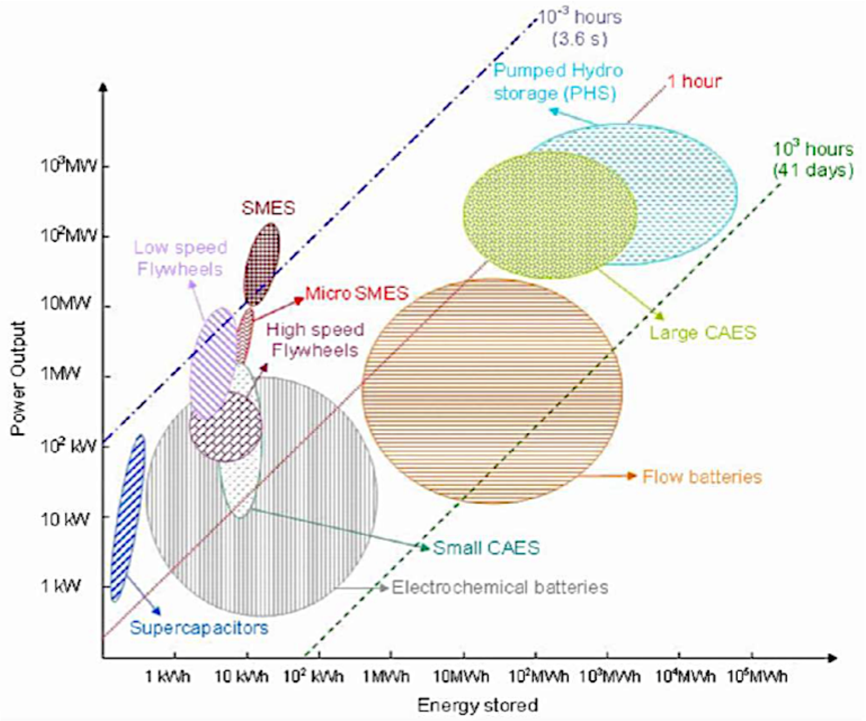


Figure 4.14.- Energy stored and power output comparison chart [27]

This graph compares the Energy stored and Power output of the different storage technologies as well as the time period displayed by the three diagonal lines.

Supercapacitors (or ultracapacitors) and Flywheels mainly are only used for voltage support in short terms.

This is another way to explain the same comparison made before. As it is shown in the graph, the best technologies for balancing the grid are firstly the pumped storage, and in the second position, the CAES, as they are the ones which have more capacity to store moreover they can provide more quantity of energy when required. Whereas, the SMES, Flow batteries, Electrochemical batteries and supercapacitors can be used as a support of the pumped storage when it is not able to respond in a quick way in case of short circuit or sudden event which requires energy immediately, or they can work in another industry processes to store lower amount of energy.

5 HOW WIND FARMS AND PHES WORK TOGETHER

The principle of operation of how PHES and wind farms work together is very simple and it could be explained with the help of Figure 5.1. This operation mode is called *wind-hydro hybrid system*[28]. When there is a peak of demand, the off shore and on shore generators can feed the grid by their selves. In case there is an excess of wind, the pump hydro can operate by storing this generation excess. In case there is a huge peak of demand, both wind generators and pump hydro plant could work together feeding the grid, this time the pump hydro plant will generate electricity by dropping the water down from the upper to the lower reservoir. The last case is when there is no wind, this time the grid will be fed only by the pump hydro energy storage plant.

As it was mentioned before, the importance of renewable sources is growing all over the world. The wind-hydro hybrid system is a solution to integrate wind power into the grid, reducing the short term fluctuations and improving the quality of the power network.

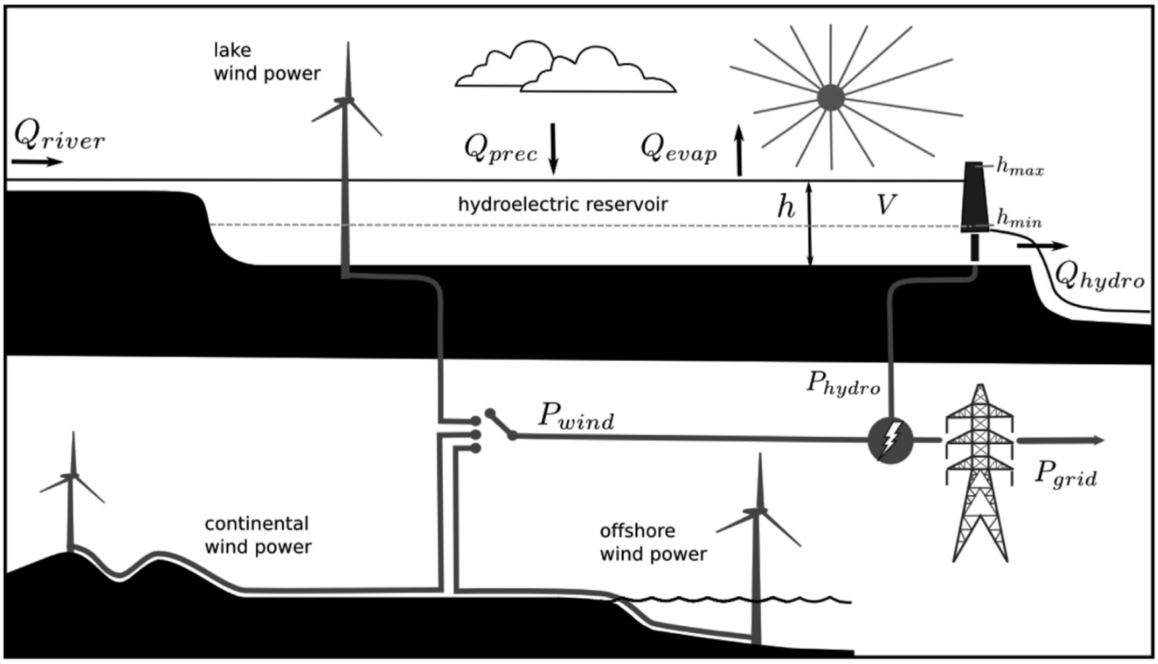


Figure 5.1.- Wind-hydro hybrid system. h: water level; Q_{river}: river discharge; Q_{prec}: precipitation; Q_{evap}: evaporation; P_{hydro}:hydro power; Q_{hydro}: reservoir outflow; P_{wind}: wind power generation; P_{grid}: delivered power to the grid; V: reservoir volume; A_r: reservoir area. [28]

6 COMPARISON OF PHES BETWEEN EUROPE AND ASIA

At the end of 2015, according to the *iha (international hydropower association)*, the world installed hydropower capacity was about 1211 GW of which 145 GW were from pumped storage as it is visible in the next depict from the mentioned *iha* source.[29]

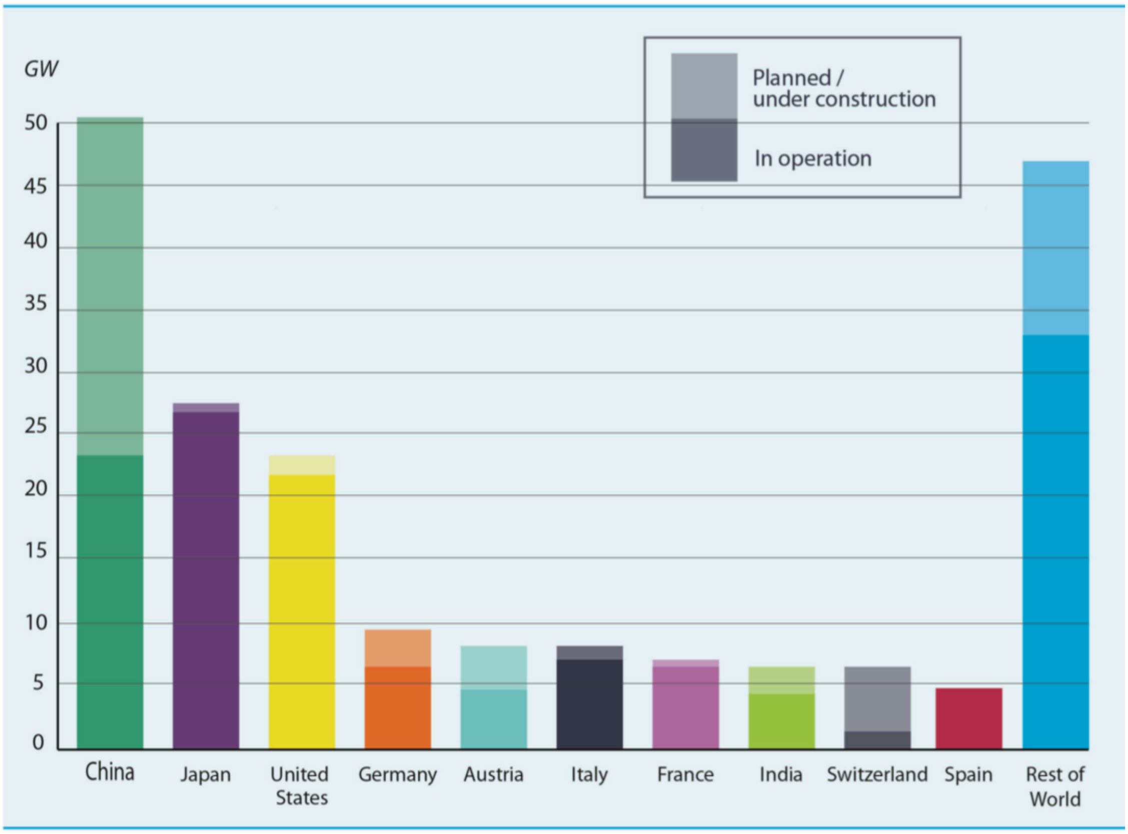


Figure 6.1.- Worldwide PHES plants location (GW) at the end of 2015 [29]

This research wants to represent the growth that pumped storage is having nowadays. As it is going to be explained later, the last update that the Department of Energy from the United States (DOE) has made was in February 2016, and it shows that there are a total of PHES installed capacity of about 180 GW, which comparing with the 145 GW at the end of 2015, represent an important growing trend.

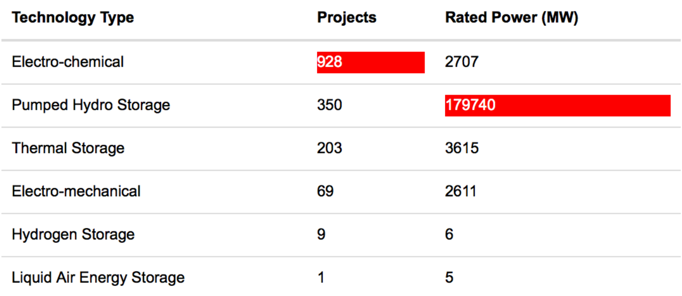
The Department of Energy from the United States [30] is responsible for the technology investigation and improvement in the energy situation in the United States. The Office of Electricity Delivery & Energy Reliability website has a search facility of worldwide Energy Storage Plants. This page allows the user to select the information he needs, which was a great benefit to this project. In this case, all the information related with the pump hydro energy storage plants were studied. The analysis performed from the information available is shown in the graphs and images below.

In the Figure 6.2, is clearly visible how most of the Pumped Hydro Energy Storage plants are located in the European and Asian continents.

Figure 6.2.- Map of locations of PHES plants 2016

Comparing the different existing energy storage technologies from Figure 6.3, even though there are fewer PHES projects, these plants are the ones which offer greater energy capacity in the world, with a total of 350 projects and about 180 GW of rated power.

More than 1/3 of this total rated power is supplied by the plants from Asia, whereas 1/3 is supplied by the plants from Europe and the other 1/3 is supplied by the rest of the world as it is going to be calculated later.



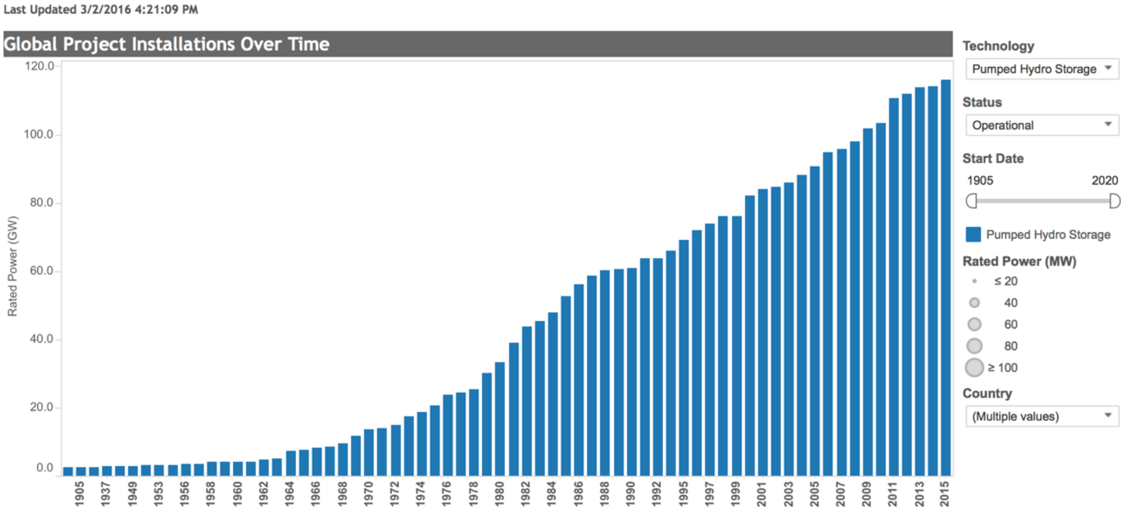
Technology Type	Projects	Rated Power (MW)
Electro-chemical	928	2707
Pumped Hydro Storage	350	179740
Thermal Storage	203	3615
Electro-mechanical	69	2611
Hydrogen Storage	9	6
Liquid Air Energy Storage	1	5

Figure 6.3.- Different types of technology

This project’s aim is to make a comparison between the situation of the PHES plants in Asia and Europe. Similarities and differences between both continents will be explained and analysed in the following sections.

6.1 Operational Europe & Asia

The following chart shows the evolution over the years of currently operative PHES plants in Europe and in Asia, reaching a total of 240 projects and 115.24 GW of power. It can be noticed how it increases by roughly 20% every ten years, which suggests it has a fairly constant and positive growing trend.



Last Updated 3/2/2016 4:21:09 PM

Technology: Pumped Hydro Storage

Status: Operational

Start Date: 1905 – 2020

Country: (Multiple values)

Figure 6.4.- Bar chart of growth of rated power of operational PHES in Europe and in Asia

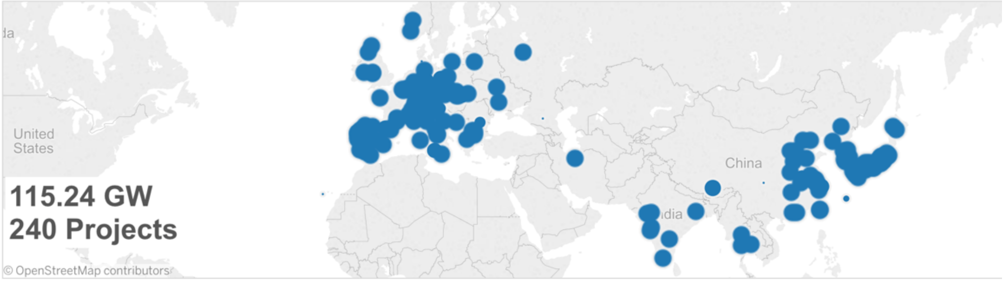


Figure 6.5.- Operative PHES plants geographical distribution in Europe and in Asia

From the total chart, by selecting the European countries, it is possible to know the geographical distribution of plants in Europe, as well as the total number of them and its rated power. The growing trend is also more or less constant but reaching a lower power than the Asian as it will be discussed afterwards. The summation of plants gives us a value of 151 projects and a total capacity of 50.17 GW.

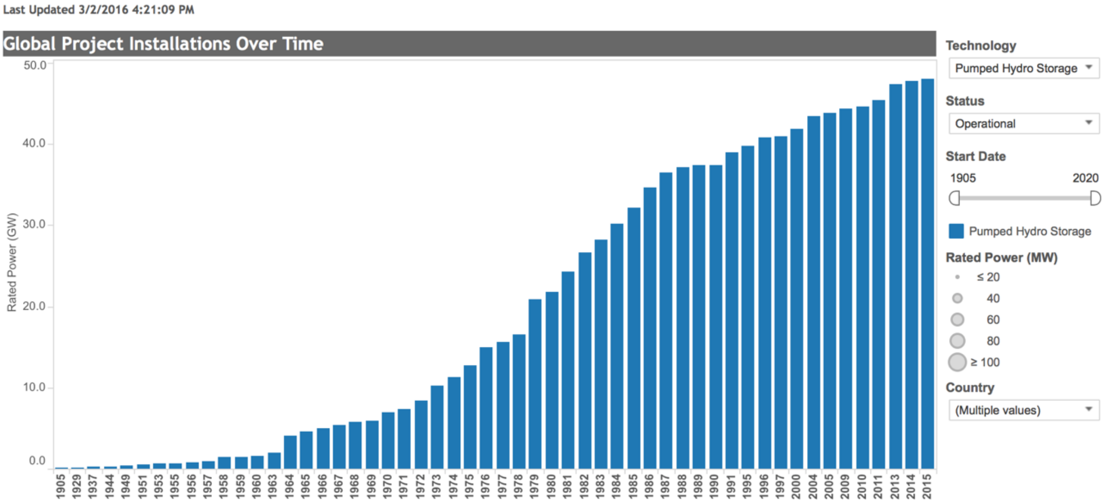


Figure 6.6.- Bar chart of growth of rated power of operational PHES in Europe

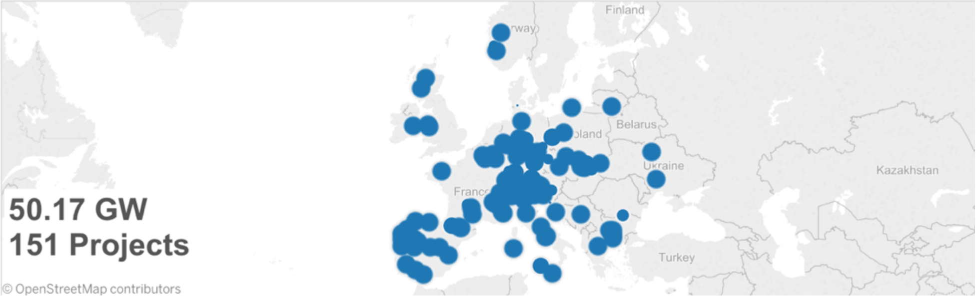


Figure 6.7.- Operative PHES plants geographical distribution in Europe

In the image provided by the DOE, we can see how in the central European area there is a large part of the mentioned projects.

From Figure 6.7 we can see that there is 0.33 GW/operational project in Europe.

The growing trend in Asia is, as well as in Europe, more or less constant and positive but reaching more rated power.

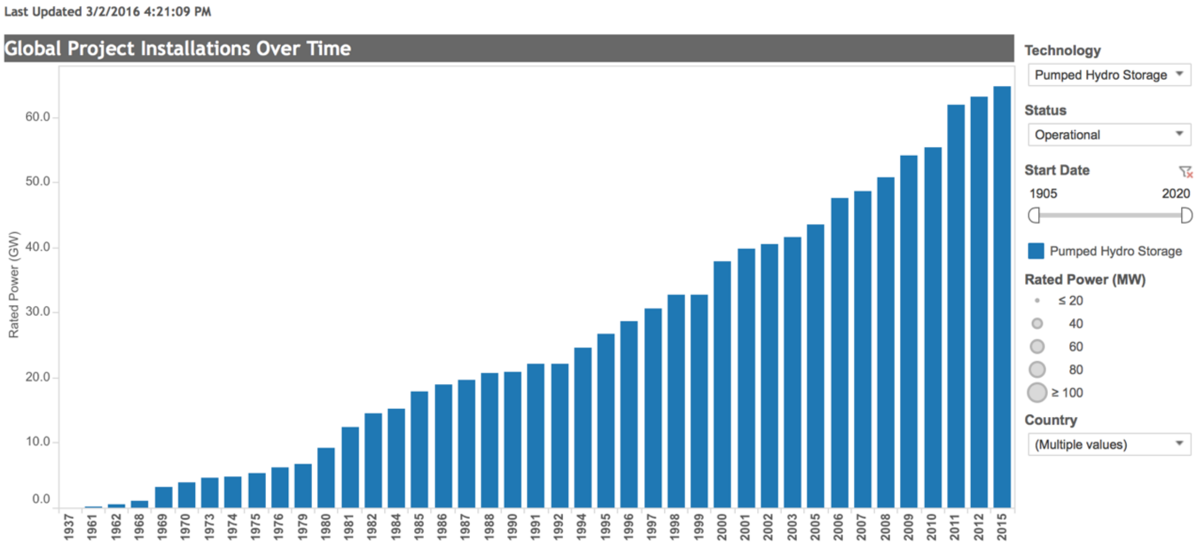


Figure 6.8.- Bar chart of growth of rated power of operational PHES in Asia

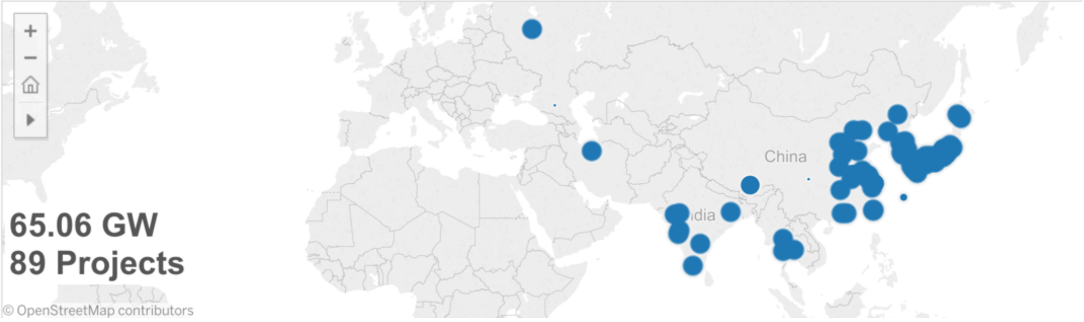


Figure 6.9.- Geographical distribution of operative PHES plants in Asia

Although there are fewer plants in Asia in operation (89 projects), as seen in the chart before, in the recent years a large growth of pump storage energy plants has emerged on this continent, reaching to provide a higher capacity than the European ones, thus its power average is higher, reaching a total of 65.06 GW comparing with the 50.17 GW from Europe.

Furthermore, from Figure 6.9 we can see that there is 0.73 GW/operational project in Asia, which are more than the double of the European ones.

6.2 Under construction Europe & Asia

This chapter shows the projects which are under construction and that are predicted to be operative in the coming years. Just as in the previous case, the plants from Europe and Asia are displayed together to know how many they are and the total capacity they represent. Afterwards each continent will be analysed separately.

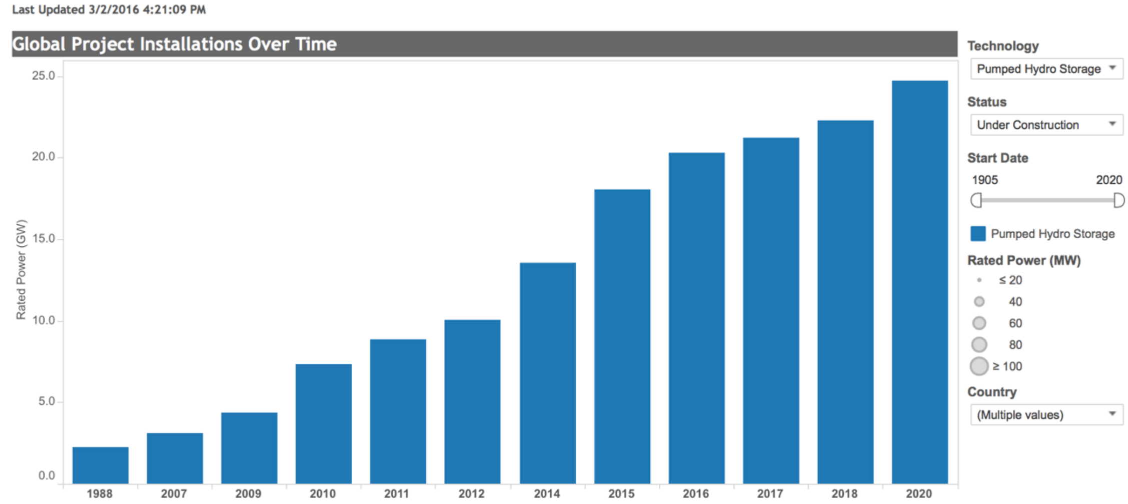


Figure 6.10.- Bar chart of growth of rated power of under construction PHES in Europe and in Asia

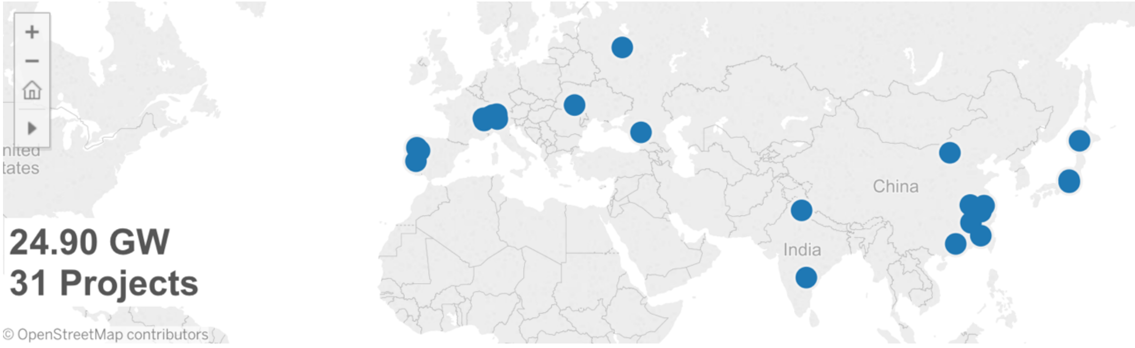


Figure 6.11.- Geographical distribution of under construction PHES plants in Europe and in Asia

From 2015 to 2020 an important increase of PHES plants in both continents is predicted.

Europe and Asia have a total of 31 PHES plants and a power capacity of 24.90 GW.

As it can be seen on the map, there are several projects in Europe in the area of the Alps due to the existence of many lakes and mountains which have the optimal conditions to create water reservoirs.

It is anticipated that by 2017 there is going to be 13 projects more which will be a considerable increase in rated power in Europe of 8.34 GW.

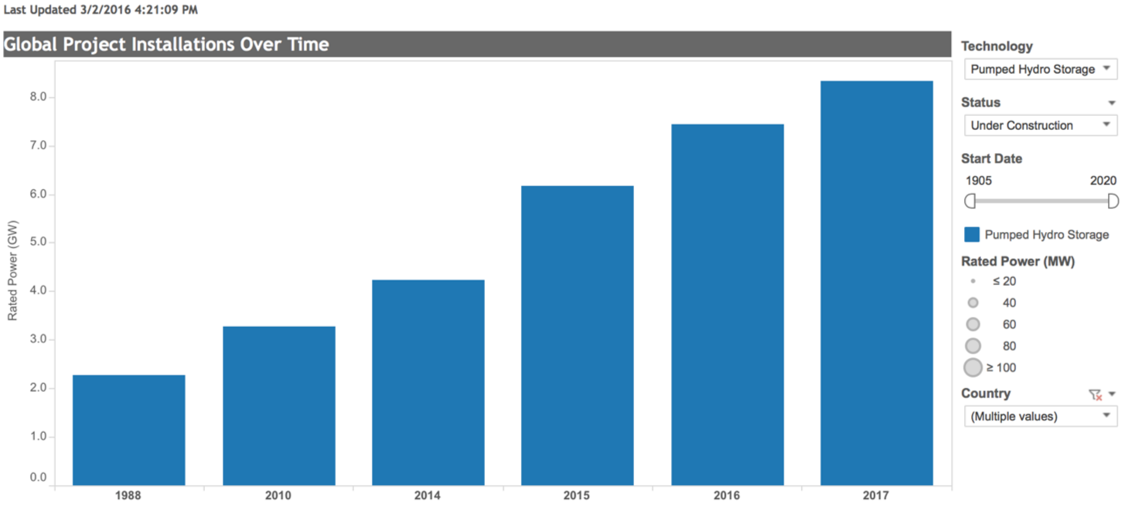


Figure 6.12.- Bar chart of growth of rated power of under construction PHES in Europe

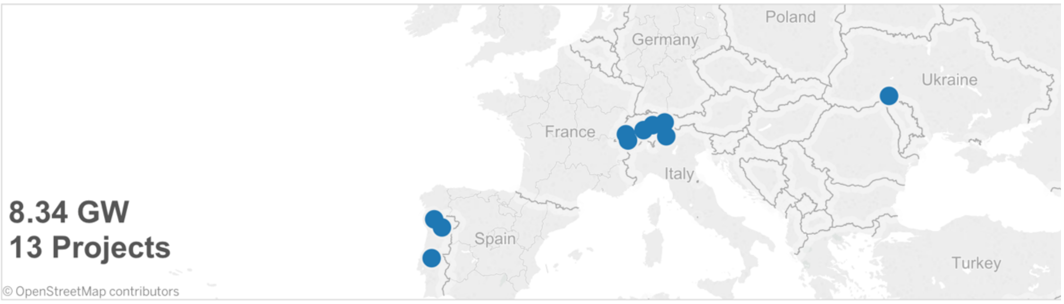


Figure 6.13.- Geographical distribution of under construction PHES plants in Europe

From Figure 6.13 we can see that there is 0.64 GW/under construction project in Europe which will be added to the grid.

In Asia it can be noticed that the trend is growing positive, reaching by 2020 a number of 18 new projects which gives 16.56 GW more to the global grid. (Average of rated power per new project included).

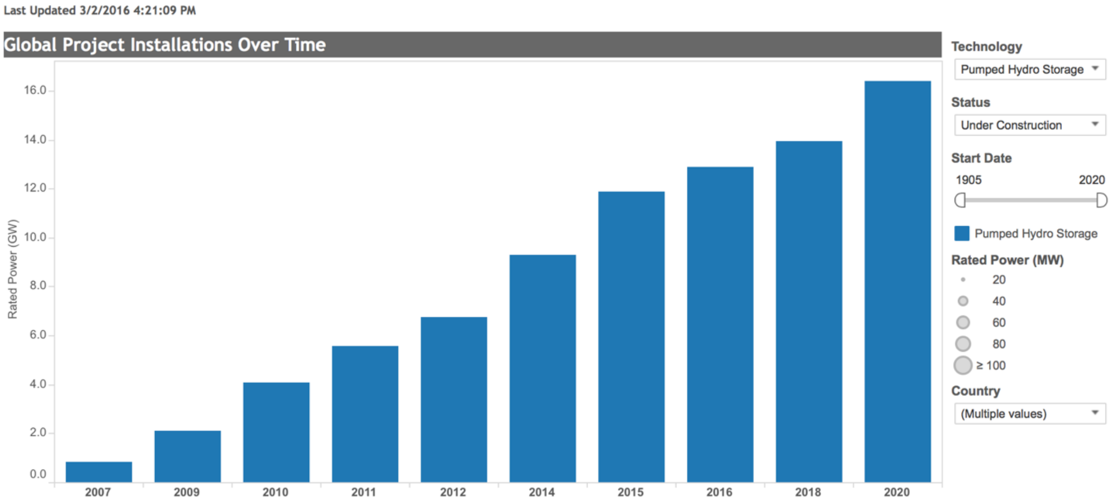


Figure 6.14.- Bar chart of growth of rated power of under construction PHES in Asia

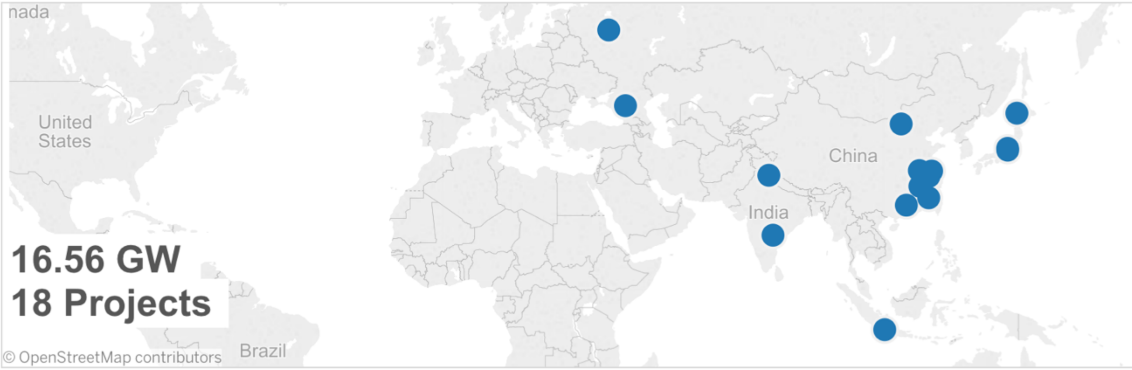


Figure 6.15.- Geographical distribution of under construction PHES plants in Asia

From Figure 6.15 we can see that there is 0.92 GW/under construction project in Asia which will add more power than Europe. Moreover, it could be seen that the number of projects expected to be built in the following years in Asia are higher than the European ones, most of them concentrated in the area of China. The capacity of them are about the double of their Europe counterparts.

6.3 Top 10 Countries by Installed Capacity

6.3.1 Pumped storage (Operational)

Table 6.1.- Top 20 Countries by Installed Capacity

Country	Nº of PHES plants	Rated Power (GW)	Average power consumption (GW)	Ratio (Rated power/ Average power consumption)
Japan	38	25.37	113.90	0.22
China	27	23.64	584.70	0.04
United States	36	20.36	469.16	0.04
Italy	18	7.07	35.47	0.20
Spain	20	6.89	28.65	0.24
Germany	27	6.23	65.81	0.09
France	10	5.81	55.53	0.10
India	8	5.07	111.74	0.05
Austria	17	4.81	8.24	0.58
South Korea	7	4.70	59.78	0.17
United Kingdom	4	2.83	39.58	0.07
Switzerland	12	2.69	7.21	0.37
Taiwan	2	2.61	27.94	0.09
Australia	6	2.54	26.74	0.09
Poland	6	1.75	17.10	0.10
Portugal	7	1.59	5.59	0.29
South Africa	3	1.58	26.26	0.06
Thailand	3	1.39	19.03	0.07

In the Key World Energy Statistics of 2015 we can see the total consumed energy by these countries in that year. From the total consumed energy we can easily obtain an average consumption power. By dividing the average power of PHES of each country by its average consumption power, we obtain a ratio that tells us how much demand power can be supplied by PHES.[31]

The case of Austria is one of the most relevant of this study as even though it has a lower power rate and number of operative plants than Japan for instance, the ratio calculated shows that the PHES plants could supply 50% of its electricity demand. But it should be mentioned that some of this energy supplied by Austria is exported to Germany, so finally this percentage does not represent the amount of energy that Austria is using from the PHES plants.

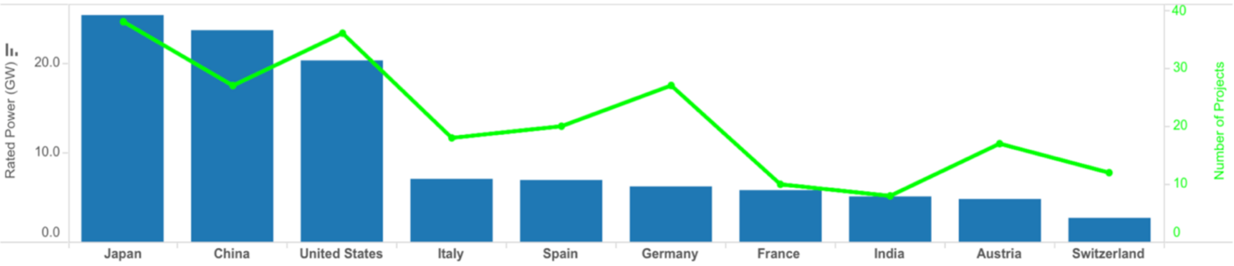


Figure 6.16.- Bar chart which relates the top installed capacity countries rated power and the number of PHES plants operative in each one

The graphic shows the countries mentioned in the table above by their rated power in bars and the green line which represents the number of projects per country. Japan apart from having the higher rated power registered, is the one which has the highest number of projects followed by China and the United States.

6.3.2 Pumped storage (Under construction)

Table 6.2.- Top 10 Countries by Installed Capacity. PHES projects under construction

Country	Number of projects	Rated Power (GW)
China	7	9.56
Switzerland	5	3.74
Japan	6	3.28
Ukraine	1	2.27
Portugal	5	1.95
India	2	1.70
South Africa	1	1.33
Indonesia	1	1.04
Russia	2	0.98
Austria	2	0.37

The table shows the top 10 countries which have the most PHES that will be built in the near future by the installed capacity. China is at the top of the list with 7 future plants with 9.56 GW followed by Switzerland with 5 projects in the Alps region as mentioned before.

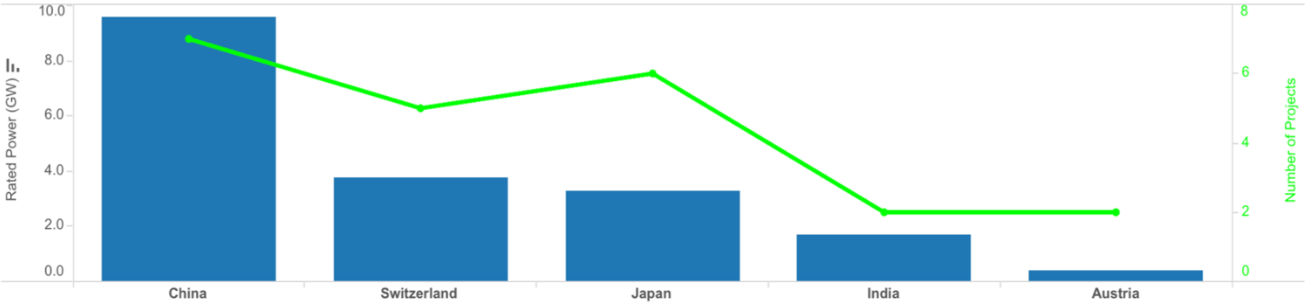


Figure 6.17.- Bar chart which relates the Top installed capacity countries rated power and the number of PHES plants operative in each one

Once again the graphic shows the countries mentioned in the table above by their rated power in bars and the green line which represents the number of projects per country. This time China has the highest number of projects as well as the highest level of rated power.

6.4 Top Use Cases

6.4.1 Uses in operational plants

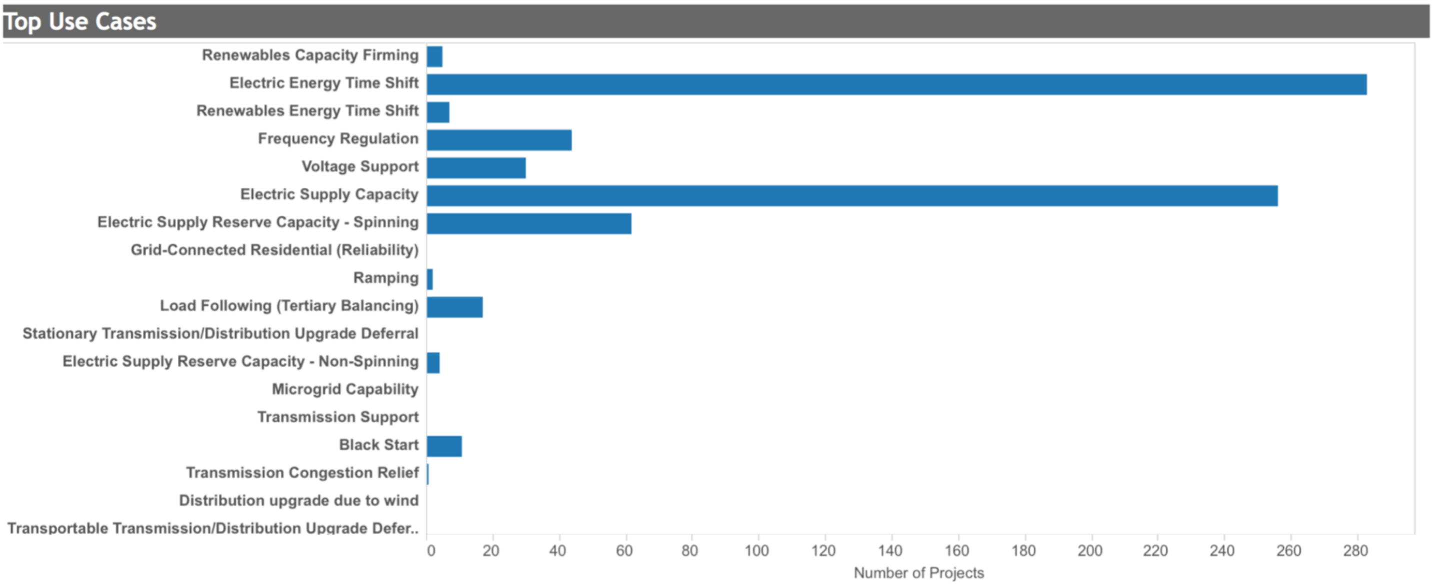


Figure 6.18.- Chart of the main use cases from operational PHES plants and the number of plants which cover nowadays each function

6.4.2 Uses in under construction plants

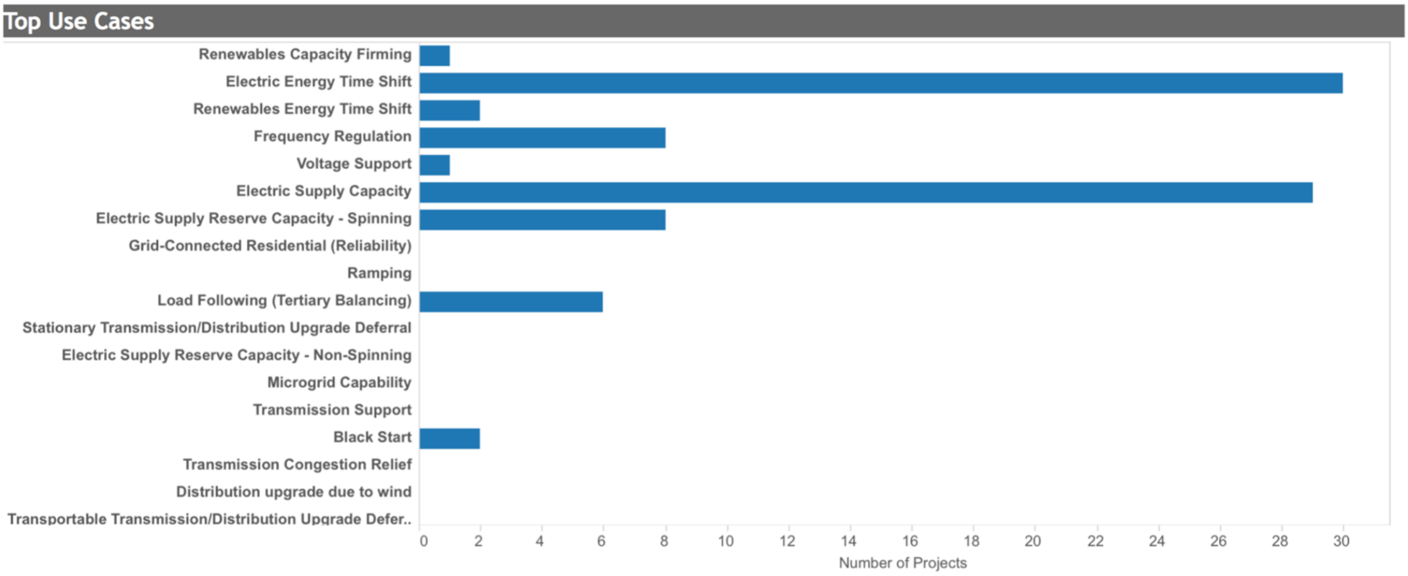


Figure 6.19.- Chart of the main use cases from under construction PHES plants and the number of plants which will cover each function

As shown in the graphs, current operating plants as well as those under construction, in addition to serving as energy storage, they mainly base their operation on tasks like electric energy time shift, electric supply capacity, frequency regulation and black start, which were explained in the chapters before.

6.4.3 Uses in announced plants

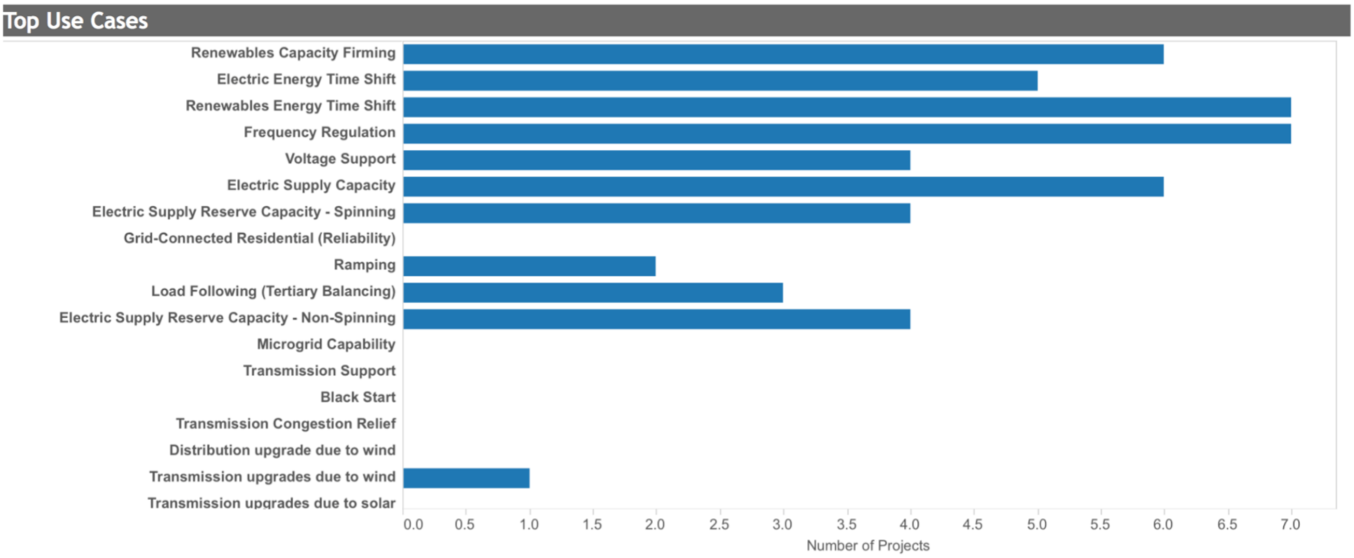


Figure 6.20.- Chart of the main use cases that the new PHES plants will have and the number of plants which will cover each function

By analysing the use cases for announced plants, the results suggest an increase of plants which cover more functions apart from the ones they have nowadays. The new PHES plants are expected to be widely used for all kinds of applications, highlighting for instance the renewables energy time shift, voltage support, ramping and transmission upgrades due to wind.

7 COSTS

Some authors mention cost overruns as a major reason why these plants are not really profitable in their opinion. For them, these costs overrun appear in three out of every four large reservoirs, and they are about the double for two out of ten large reservoirs, being more than the triple for one out of every ten which make these PHES plants not profitable.[32]

Furthermore, other authors support the idea that these plants are the largest and the most cost-efficient system for energy storage among all the technologies available currently.

It should be mentioned that these costs depend on various factors. One of these aspects is the height between the two reservoirs: if the height is low between reservoirs, the reservoir should be bigger to compensate the desired capacity, whereby the cost will be increased.

In case of an a FLES plant, the maintenance costs will be increased due to being an underground installation, but the costs of the water pipe lines like the penstock, will be reduced.

Although the investment cost is very high, it is known that the maintenance costs of PHES are not very large compared with other storage technologies. According to an article recently published, the energy capital cost is about 2000-4300 $/kW but considering that its lifetime is about 60 years, this cost pays itself over time. [33]

Operating costs per unit of energy for pump storage are usually the lowest compared with the existing technologies, however civil engineering costs for the construction of reservoirs and ducts are significantly higher. This makes the decision difficult as to whether or not to build, being that they can only be profitable after more than ten years.

As a conclusion we could say that despite the really important investment at the beginning of the project, the intended lifetime (around 60 years) and its low cost in the maintenance and operation field, makes PHES an interesting and cost efficiency solution for energy storage.

8 NEW POSSIBLE LINE OF RESEARCH: COULD BATTERIES BE COMPETITIVE WITH PHES PLANTS?

It would be difficult to answer this question without further investigation, but a small summary is made of information gathered so far. As stated by the title of the section, it could be a new line of research that this project could take in the future.

According to a recent study from City Bank[34], the most important handicap for the development of the batteries facing land scale storage operations is the cost. It is estimated that the storage batteries investment cost is around $5,000/kWh.

Table 8.1.- Grid-introduction cost comparison between Batteries and PHES

The grid-introduction cost for storage battery systems	**$5,000/kWh**
PHES grid cost	**$230/kWh**

Comparing this cost with the one from PHES plants, which they estimated at $230/kWh, it means that the batteries costs is almost 20 times the PHES ones.

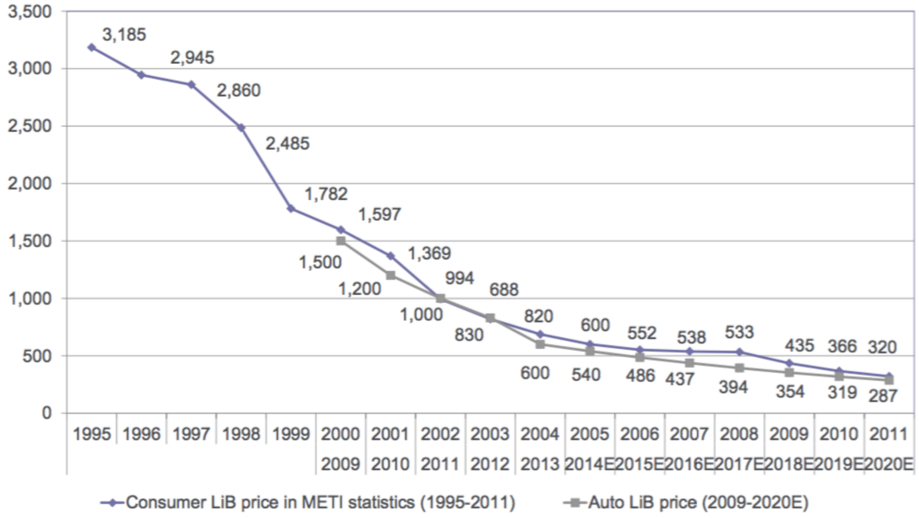


Figure 8.1.- Price decline of automovile Lithium Ion batteries

An interesting thing to consider is the decreasing cost of the batteries from electric cars industry. As it is shown in Figure 8.1, it is becoming cheaper and cheaper every year.

Initially, the cost was more than $2000/kWh and they were only used in high-end products. Eventually, mobile phone market expansion resulted in the cost falling at an annual rate of more than 10%, and now lithium-ion batteries used in low-end handsets cost less than $200/kWh.

As it can be shown by the chart, at the beginning the Lithium Ion batteries cost was around $2000/kWh that is why they where only used in high quality and expensive applications. Nevertheless, after the mobile phone boom, these prices became lower little by little, reaching the $200/kWh cost and being used in low cost mobile phones. The same happened with the electric vehicles: they noticed a cost decrease from $1000/kWh to the currently $500/kWh cost.

So if the future trend is to decrease batteries costs, large scale batteries could also benefit from this and might have their price declining below $230/kWh. According to this City Bank study, it could be reached in 7-8 years. [34]

In this case, the batteries would become the biggest competitors and possible substitutes for PHES.

9 CONCLUSIONS

Due to the development of technology, and the need to produce more electricity because of the growth of the global population (especially in Asia), and besides the global warming problem which concerns all the world nowadays, new renewable sources such as wind and solar power have appeared.

These sources have an intermittent behaviour and here resides the boom of the Pumped Hydro Energy Storage plants, to face these fluctuations with the aim of improving the power grid quality, allowing the renewable energy sources to join the power system network.

In view of the above, Asian growth is faster than the European one becoming the continent which provides the most rated power by PHES plants into the grid.

Despite the high investment cost at the beginning of the project, the intended lifetime (around 60 years) and its low cost in maintenance and operation field, makes the Pumped Hydro Energy Storage technology the currently best solution for storing the energy.

If the prices decrease enough to match the ones of the PHES, batteries could become their strongest competitor, and eventually their substitute.

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