Chapter 2

The Importance of Energy Storage for Sustainable Heat and Power

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Abstract

The impact of energy storage is far-reaching, as not only does it address the issues that have limited renewable energy's penetration, it fundamentally alters the longstanding relationship between utilities and their customers. The disruptive potential of storage is unlike other energy technologies in that it pervasively extends across the value chain in a way that stakeholders will impact and be impacted by its adoption. Energy storage can play an important role in the present, in the short-term and in the medium- term future energy scenario. Both stationary and automotive applications will be considered and the main features required by each of them for an energy storage system will be explained. A very brief description of the proven and most promising storage technologies will be given with the aim of providing an overview of the peculiarities of each one and consequently its better-suited applications. Finally, the state-of-the-art, the opportunities and the barriers to the spread of energy storage systems will be summarized.

1. Introduction

Energy efficient thermal energy storage (TES) system constitutes a crucial instrument in thermal distribution networks today. Due to the thermal management of urban and industrial landscapes becomes increasingly important, so too does the impact of carefully planned and designed TES systems [1-5]. TES systems, for the most part, do not specifically generate nor consume thermal energy and their role in the thermal distribution landscape is essentially analogous to that of a battery or capacitor in a power distribution network. They allow supply to meet demand by bridging the gaps between the two [6-8]. In most manifestations of TES systems, this gap is often a time gap, where the surplus thermal energy generated is preserved in the TES for a future period when the demand for it is greater or more

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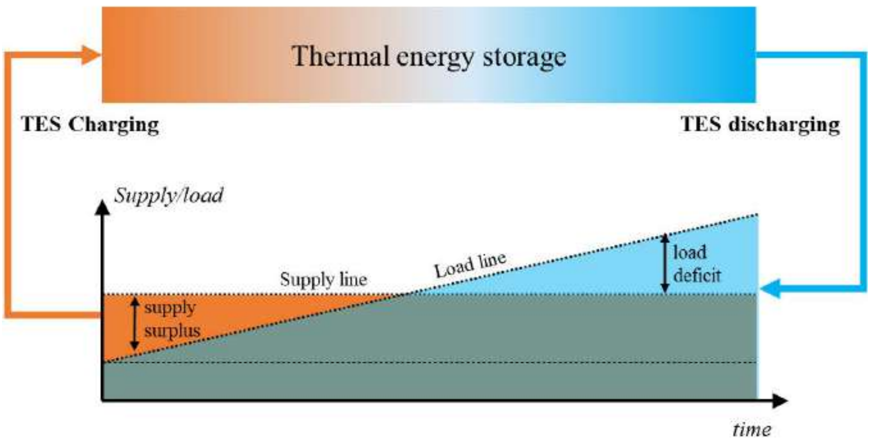
appropriate, such as with hot water storage for night-time heating, or even across longer periods of time like seasonal TES systems which store heat during summer and discharge during winter [9-11]. The "storage" phase of the TES is often coined as the "charging" phase in the literature, while the utility phase of the TES process is considered as the "discharging phase". Hence, TES systems play important roles in creating efficient and resilient thermal distribution networks by allowing load matching to take place as needed. Figure 1 illustrates how TES is applied to bridge the gap between demand and supply needs [12-15].

Fig. 1. TES meet load deficits by bridging the time gap between supply-side and demand-side utilities.

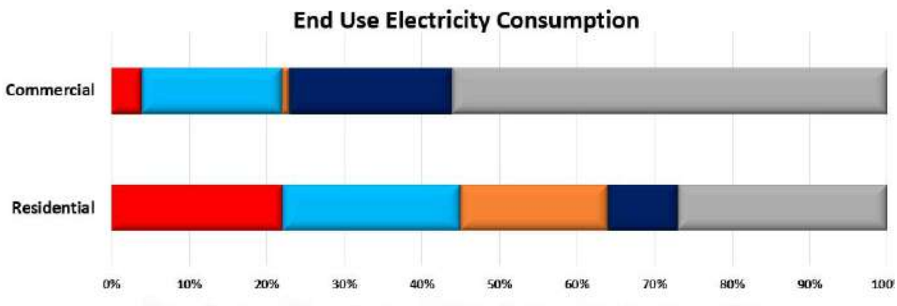


The energy scenario has significantly changed in the last decade for a variety of factors. The first one is the increase in the amount of electrical capacity supplied by variable and non-predictable renewable sources [1-3]. In recent years, the growing awareness at both the public and institutional levels of the "energy issue" has led to a series of initiatives aimed at promoting the use of renewable energy sources (RESs) [4]. Definitely, their use often results in a lower environmental impact in terms of a reduction of both resources consumption and emissions, with special regard to carbon dioxide, which is responsible for the greenhouse effect. The comparison between the installed capacity and energy production allows us to evaluate the load factor of such plants, expressing the ratio between the energy actually produced and that theoretically producible if the plant would run throughout the year at its design power: the value is low and around 22% for wind power and 12% for solar. This is due to the extreme variability of the sun and of the wind over the year and even in a single day, so that the plant can operate at design load only for a limited number of hours per year. In addition, the low predictability of these variations makes production scheduling more difficult, especially for wind power even in the very short term [2, 3].

A second aspect is due to the progressive deregulation of the energy market carried out in many developed countries aims to separate the activities of generation, transmission and distribution of electricity and where for every hour of the year the price of energy is determined by the intersection between supply and demand curves. The main goal of deregulation is the promotion of fair competition in the production and sale of electricity in order to reduce energy costs and increase the efficiency of the system [4]. The first consequence has been the significant and rapid growth of the installed generation capacity in OECD countries, the power plants had a total installed capacity of 2,680 GW, of which 1,811 GW was from thermal power plants in 2020. But in some countries, this expansion has been even greater [5, 6].

The stability of the power grid depends on various actors working in concert to maintain a balance between electricity supply and demand. Traditionally, electricity assets are categorized based on their function; i.e., generation, transmission, or distribution. Storage systems differ in that they have the ability to balance supply and demand across the segments that comprise the value chain. The new control points offered by storage systems enable operators to selectively respond to fluctuations in grid inputs and outputs. Such functionality is essential to realizing the vision of "smart cities" where producers and consumers are equally informed and equipped to respond to market dynamics in real time. However, many electrical grids were not originally designed to accommodate assets that can both generate and consume electricity. The implications of two-way power flow and the role of energy storage within a modern electricity ecosystem have been studied by many institutions. Potential applications and appropriate storage technologies within each segment of the value chain are illustrated in Figure 2.

Figure 2. End use electricity consumption



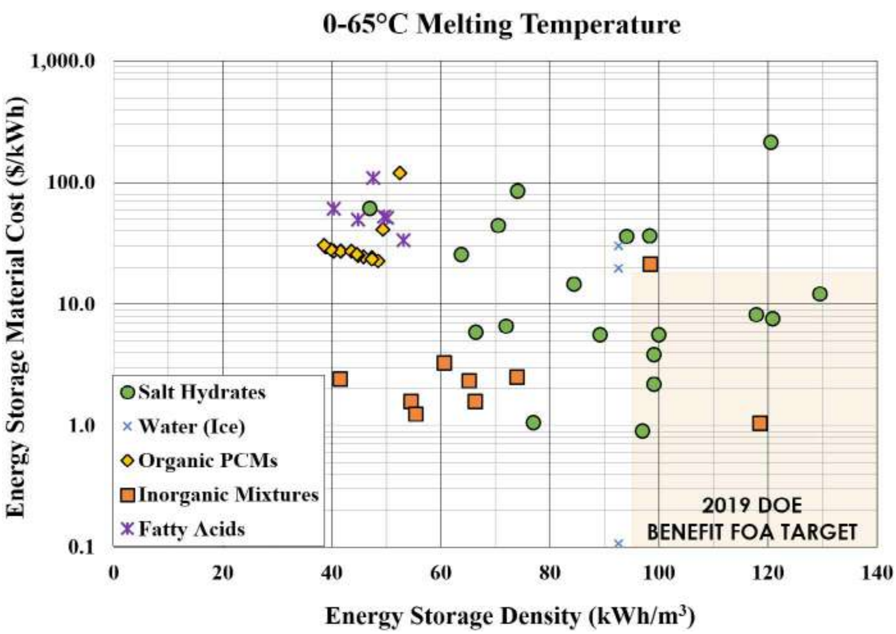
In almost all the developed countries, in a more or less marked way, the combined effects of the aforementioned factors have created a situation where the installed capacity is overabundant with respect to the users' peak demand, and where quite a high fraction of power is made available by variable and difficult to predict renewable sources. This condition definitely implies a significant saving of fossil fuels and the reduction of emissions, but introduces some critical elements into the market [10-15]. In addition, the advent of generators powered by renewable sources has drastically changed the structure of the electricity network with the presence of a large number of small power production facilities spread over the country in the vicinity of the users and of the available sources, instead of a classic structure with "a few" large facilities concentrated in the industrial zones of the country [7-9].

It is important to remember that the power grid is a very complex system that transmits and distributes electricity generated from the production plants to users through a set of power lines, transformer stations, isolation, protection systems, and is subject to very stringent technical constraints, in particular [1-4]:

- An instantaneous and continuous balance between the amount of energy released and that required by the network is necessary, taking into account the losses due to transformers, transport and distribution.
- The frequency and voltage must be kept within a very narrow range of values is essential to protect the safety of the generation and end-user facilities.
- It must always be ensured that the energy flow in each power line does not exceed the maximum permissible load on the power line itself.

The change of any one of the abovementioned parameters, even if minor and/or of very short duration, can rapidly induce a state of crisis into the entire local electrical system and subsequently, because of a "domino" effect, to a possible blackout of the entire network. For example, the sudden drop in power available from wind turbines caused by an unexpected reduction of the wind speed can cause stability problems to the network when the share of energy provided by these systems is significant [2, 3, 5]. Therefore, when thermal plants are called upon to operate, sometimes suddenly, they impose a high price on the market, which partly offsets the higher costs associated with frequent stops and part-load operation. This great variability on the supply side has enhanced the role and the value of the markets for ancillary service and has led to a major diffusion and increased importance of the capacity markets have to ensure supply will be available when it is needed [7, 9, 1]. Figure 3 shows the energy storage density of the phase change materials.

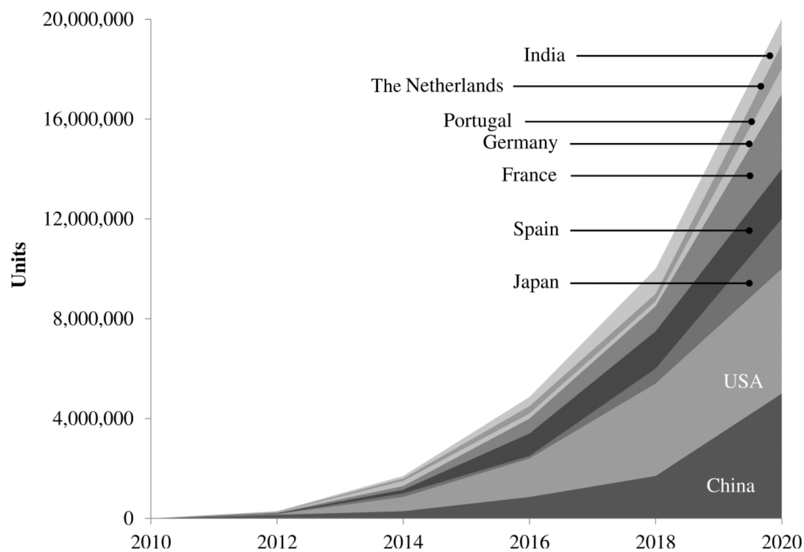
Figure 3. Energy storage density of phase change materials for energy storage material cost ($/kWh)



As a final issue, the transport sector is also undergoing many changes. The most important driver is the requirement to reduce pollutants, mainly particulates, in urban areas. This issue demands new transportation solutions: one of the most promising and studied is that of pure electric and hybrid vehicles, combining a traditional fossil-fueled engine with an electric propulsion system. These vehicles are powered by the energy stored in an onboard battery, which will be recharged at the so-called “charging points” usually connected to the grid. With a proper operation strategy, these charging stations can be managed as users with flexible demand and are able to dampen the peaks and gaps in energy supply [1-3].

The combination of all these elements has led therefore to the need to rethink the arrangements for managing both the electricity network as a whole, as well as individual plants. The main target is to supply energy with high efficiency, low cost, high reliability, and low environmental impact. As a last point, it is important to note that in developing countries or for communities looking for energy self-sufficiency, the exploitation of renewable sources is an opportunity to increase the number of people who have access to electricity with an adequate degree of availability and reliability. In such countries, the number of renewable energy or hybrid power plants is increasing. In this case, the systems are not grid-connected and it is even more important to arrange power units able to meet the demand in spite of the intermittency of variable energy sources. Figure 4 shows the electric vehicle stock target.

Figure 4. Electric vehicle (EV) stock target [8].



The new situation needs to be addressed with adequate instruments. Possible areas of research and application are manifold and involve very different aspects:

- Thermal plant flexibility, partial load efficiency and start-up and shutdown speed.
- Emission control and removal, including carbon capture and storage technology.
- New technologies for the exploitation of low-quality energy sources with high efficiency.
- Control systems and smart grids.
- Policies that are able to promote the use of renewable sources and energy efficiency without distorting the market.
- Energy storage permits the separation of energy production from its consumption.

2. The Main Characteristics

As mentioned previously, energy storage is a challenge for the electricity system where the optimum efficiency can still be improved. Briefly, the aim is to separate the supply and demand for energy. However, each storage technology has specific features, which make it better suited for some applications than for others.

For this reason, before explaining the role of energy storage in actual and future markets, the most important characteristics of energy storage units are outlined below [9–14]:

- *Storage capacity (C):* This represents the maximum amount of energy that can be stored. For some technologies, due to the presence of a maximum allowable depth of discharge, it differs from the usable energy.
- *Charging and discharging rating power (P):* This is the nominal charge–discharge power, usually that of maximum efficiency. For some systems, the charge and discharge powers have the same value, while in other cases, they differ (for example if different devices are used for the two phases and/or for specific users' needs). Usually, the actual power can differ from the rating value and varies from a maximum to a minimum value.
- *Specific energy and specific power (Es and Ps):* They quantify the density of energy or power, and are defined as E/V and P/V , where V is the volume of the storage. The higher these values, the lower the volume

at constant energy or power. Sometimes, these values are supplied per mass unit.

- *Round trip efficiency (η):* This is the ratio of the discharged to the charged electricity. Its value is related to the losses both during the charge–discharge cycle itself and the self-discharge during the storage period. It usually differs from the cycle efficiency, considering only the charge and discharge phases.
- *Rated discharge time (T):* This represents the duration of the discharge time at the rated discharge power starting from full storage, and can be defined as C/P. Obviously, the actual value of the rated discharge time depends on the actual discharge power and on the energy stored.
- *Response time (tr):* This is the time between the request to change the operation and the system response.
- *Inversion time (ti):* This is the time needed to pass from the charge to the discharge phase or vice versa. Here, tr and ti represent the ability of a system to vary the power and to quickly respond to the grid operation regulation signal.
- *Expected lifetime (L):* This value can be defined in terms of a lifetime or as the number of charge and discharge cycles.
- *Reliability:* This gives an idea about the robustness of the storage units operation.
- *Environmental impact:* This point is very important and public acceptability is closely related to it. The main impact can be during the building phase (for example, due to the use of materials in short supply), during the operation (due to pollutants) or during the decommissioning (if potentially dangerous substances must be disposed of). The location of the storage system and its size influence this aspect.
- *Levelized unit electricity cost (LUEC):* This is the price at which the electricity should be sold in order to cover all the costs related to the building, operation and decommissioning costs and to assure a return on the investment. This value depends on many factors, such as the size, location, charge and discharge history of the storage unit, and also it is related to the market and the incentives policy. In any case, this value is fundamental in order to evaluate the feasibility of a storage solution.

As a last remark, for some technologies, the performance indices (C, P, η, T) are almost constant during the lifetime of the storage system, while for others, they decrease due to different deterioration phenomena. Other aspects can be important for the selection of storage technology, for example, its commercial maturity, the constraints required by the installation site, or the operational constraints (pressure, temperature), plus safety problems.

3. The role of energy storage in the energy scenario

The traditional role of storage systems was to store energy when the demand, and consequently its cost, were low, typically at night, and to make the energy available during the hours of peak demand. In this way, the inflexible thermoelectric plants could work all day at almost constant power and an energy reserve for peak hours was assured. In these systems, the main requirement for energy storage was the ability to exchange power with a rated discharge time of several hours [1-5].

In the new scenario, the energy storage system is also required to provide, in a very short time, power to overcome the intermittence of renewable sources and contribute to the regulation of the mains voltage: in this case, the amount of energy that can be stored is less important, but the response speed is critical. Therefore, depending on the application, different features are required. The most evident application difference is between stationary and automotive storage.

3.1 Stationary Applications

For stationary applications, storage units can either be connected to the grid or work in isolated areas for stand-alone energy systems. In the first case, they can operate as independent units to serve the grid or may be connected to a RES plant or to an end-user to provide the needed support [13-15]. Generally, the so-called "energy performance" storage systems are able to provide power for many operation hours and have a low value of P/C, are suitable for energy management applications that include moving power over long timescales, and generally require continuous discharge ratings of several hours or more. Typically, one or a few cycles/day are required.

The traditional service of this kind to the grid is the time-shift or energy arbitrage. Storage systems are used to decouple synchronization between power generation and consumption. A typical application is load leveling, which implies storing up energy during off-peak hours and using the stored energy during peak hours. This is convenient if the ratio between peak and base load prices is lower than the round-trip efficiency of the system. In this case, the storage system is required to have high-rated discharge times (from some hours to days) and capacity (from 10 MWh to about 10,000 MWh).

To the time shift service, the peak shaving service is often added, which helps decrease the number of shut-down/start-ups of traditional plants, the operation hours of more expensive/less efficient power plants, and the high line loss rates that occur during peak demand. Another service for the grid is the not-programmable sources integration helps boost the penetration of RES, decreases the energy losses from power plants, compensates for the power fluctuations and provides a more regular and predictable power profile.

Deferral of grid investments and congestion relief is another benefit that energy storage can guarantee. Distribution systems must be sized for peak demand; as demand grows, new systems must be installed, often only to meet the peak demand for a few hours per year. New distribution lines may be difficult or expensive to build, and can be avoided or deferred by deploying distributed storage located near the load. Response in minutes to hours is required plus a rated discharge time of some hours. The power performance of the storage technologies, able to supply high power for relatively short periods are suitable for providing grid ancillary services.

The "fast response" (in seconds to minutes from null to rated power) nature of these energy storage technologies makes them ideally suited to meet grid stability and reliability challenges. Among these services is the contribution to primary frequency control, which also requires a low inversion time to guarantee a high regulation band, and a good round trip efficiency. Some tens of cycles/day are usually required [7, 9]. Similar features are required of energy storage systems to contribute to secondary and tertiary frequency control. Black start is the restart of electricity supply after a major power system disturbance, and requires capacity and energy after a system failure restart and must provide a reference frequency for synchronization. It requires several minutes to over an hour of response time, plus several hours of discharge time. Usually, cycling is very low. For contingency reserve, stored energy is used for seconds to minutes to ensure service continuity when switching from one source of electricity to another. Discharge times in the range of up to about an hour are usually required. Far less cycling is required than for power-quality applications [3-5].

Another benefit that energy storage can provide to the grid is the power quality control: stored energy is only used for a few seconds or less to ensure the quality of power delivered. Power quality applications require rapid response and include transient stability and frequency and voltage regulation. As with the other applications, the timescales of discharge may vary; but this kind of services typically requires discharge times of up to about 10 min and nearly continuous cycling (hundreds of cycles per day).

The features required for the storage system depend on the size of the RES plant, but usually a continuous discharge of several hours and a response of minutes are required. In conclusion, the presence of energy storage units provides benefits for:

- The traditional production facilities, which can work at nearly constant load, plan their production and limit the number of on/off switches.
- The renewable source plants, whose production can be entirely and profitably used.
- The grid, whose stability and reliability are enhanced.
- The users, who are ensured a safer and more reliable electric service.

3.2 Automotive Applications

The main constraint for energy storage units for EVs and plug-in hybrid electric vehicles (PHEVs) is the necessity to remain on board the vehicle. Therefore, high volume and mass energy densities are paramount. Batteries are the most suitable technology for vehicles. For EVs they need to be designed to optimize their energy storage capacity, while for PHEVs they typically need to have higher power densities. Other important requirements are the rated discharge time, the fast charging, a high life expectancy, plus a low-temperature sensitivity [8]. On the other hand, the charging of EVs can potentially be controlled, and provides a source of planned demand and demand response. Controlled charging can be timed to periods of greatest RES energy production, while charging rates can be controlled to provide contingency reserves or frequency regulation reserves. EVs could potentially provide the grid services discussed previously.

4. Energy Storage Technologies

In this section, only a very brief summary of the main characteristics of each technology will be given. The following sections provide a more complete description of many of these storage technologies [9-15]:

4.1 Pumped-Hydro Energy Storage (PHES)

In brief, water is pumped into an upper reservoir and stored there; when energy is required by the grid or the price of electricity is high, water is released through one (or more) turbines to a lower reservoir and the electricity produced is sold. PHES is a proven technology, suitable for large-scale storage. It is very efficient and flexible in power, has a short response time, can ramp up to full production capacity within minutes providing a quick response for peak-load energy supply and is already used for both primary and secondary regulations. On the other hand, it needs to be located in suitable geological sites, containing a geodetic head and natural upper and lower basins or at least the possibility of building artificial reservoirs. This requires relatively high initial costs. The environmental impact can also be non-negligible, in terms of land occupation and modification, disturbance of the aquatic life, and modification of the natural water flow.

4.2 CAES

In these storage systems, the air is compressed during charging and then stored in an underground cavern or other pressure vessel. When electricity is required, the air is heated to avoid freezing and then expands in a turbine. If the heat generated during compression is stored and then used to preheat the air in order to increase the round-trip efficiency, the process is called adiabatic. If external heat input by means of combustion is used to preheat the air, the process is called diabetic. Despite the large interest of this technology, there are only two plants in operation around the world. CAES is basically suitable for medium and large energy storage for energy applications. Recently, many studies are related to its use in small systems. The use in direct connection to wind farms or other non-programmable RES plants, or for distribution grid support seems to be very promising. At present, the main drawback is the cost.

4.3 Flywheels (FWs)

Flywheels store energy in the form of kinetic energy. The storage unit is composed of FWs driven by an electric motor able to work either as a generator or as a motor and located inside a housing. If the motor provides a positive torque, the FW increases its rotation speed and energy is stored. When energy is needed from the FW, the electrical machine applies a negative torque and the stored energy is released. This technology is already mature and is suitable for high-power applications. In addition, FWs present long cycling expected life and short response and inversion times. On the other side, mainly due to friction losses, the round-trip efficiency strongly and speedily decreases during the operation. For this reason, the FWs are suitable only for short-term storage and, at present, are mainly used as voltage and frequency control, as support for wind farms or in transportation to increase the efficiency of trains, ferries or large EVs.

4.4 Fuel Cell Hydrogen (FC-HES)

Chemical energy storage is the transformation of electrical energy into chemical energy carriers (the so-called power-to-gas or P2G). At present, the most promising energy vector is hydrogen. Hydrogen is produced by means of water electrolysis which is a process consuming electricity. Then, hydrogen is stored as a liquid at cryogenic temperature, or as a gas at very high pressure or as a solid in hydrides. Finally, the stored hydrogen may be used to produce electricity. The most common solution is by means of fuel cells. There are many different kinds of fuel cells, which mainly differ in the electrolyte used and the operating temperature. Note that the use of hydrogen in fuel cells produces only water and does not emit any pollutants or greenhouse gas. This technology has a high energy density and the possibility of storing very large quantities of hydrogen for a long time. Hydrogen can also be transmitted from one location to another. These features make chemical storage suitable for energy management applications, even for seasonal storage. At the same time, electrolysis has a short response time. The main drawbacks are the excessive costs, the low round trip efficiency and the short lifetime expectancy.

4.5 Electrochemical Batteries (EBES)

Batteries, or accumulators, are based on a single device with the functions of energy storage and discharge of electricity. The basic element is an electrochemical cell having voltages from below 1-4 Volt; many cells can be put in series in order to reach higher voltages. Electricity is produced by an oxidation–reduction reaction where a flow of electrons is created from a chemical species (anode) to another one (cathode) in contact by means of an electrolyte. The reverse process can recharge the battery. Many different batteries are available on the market, and others are under study: they differ for the materials used for the anode, the cathode and the electrolyte, and in the design. Batteries have a high technological maturity, high energy density, good round trip efficiency, and great modularity that permits them to be tailored to users' requirements. Their main inconvenience is their relatively low life for large-amplitude cycling. During their operation they do not emit pollutants or noise. However, their disposal can present a significant environmental impact due to the materials used for the electrodes and/or the electrolyte.

4.6 Supercapacitors (ECES)

Supercapacitors or electrochemical capacitors (ECs) or also electric double- layer capacitors (EDLCs), store electrical energy in an electric field between two electrodes separated by a dielectric and immersed in a liquid electrolyte. The electrodes are characterized by a very large useful surface and the distance between the electrodes is very small. The process is easily reversible. ECs are suitable for high-power applications since they have a very fast response time, high round trip efficiency, high power density, but low energy density, long expected lifetime and can guarantee a very high number of charge–discharge cycles. They are an interesting solution also for electric transportation both for brake energy recovery and for propulsion over very short stretches of roads without electric connection. Supercapacitors have not yet reached commercial maturity, but they are expected to improve their performances in the near future.

4.7. Magnetic Superconductors (SMES)

In magnetic superconductors, energy is stored in the magnetic field of one or more superconducting coils characterized by very low losses. To reach this condition, they must work at very low temperatures (near absolute zero). At present, they have no commercial market, but are still in the research phase and are considered a promising technology. The main problem is the necessity of a cryogenic temperature with the related prohibitive cost and high energy requirement. This brings a low energy density and low round-trip efficiency. However, they have very interesting characteristics, such as very fast delivery of high power at high cycle efficiency. For this reason, they are suitable for power applications, requiring continuous operation with many charge and discharge cycles.

4.8. Thermal Storage (TES)

Thermal energy storage (TES) includes many technologies where energy is stored in the form of heat. Heat can be stored as:

- Sensible heat: if storage is achieved by increasing or decreasing the temperature of a storage material. In this case, the amount of stored energy is proportional to the temperature difference.
- Latent heat: if storage is connected to a phase transition of the storage material, usually from solid to liquid and vice versa. In this case, the

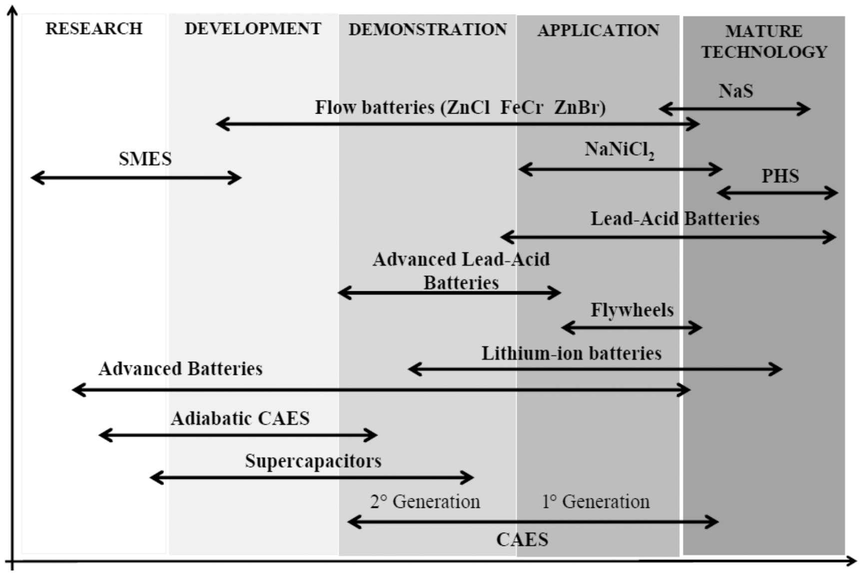
temperature remains constant and the stored energy depends on the latent heat of fusion of the material.

- Thermochemical heat: if heat is stored as chemical compounds created by an endothermic reaction and it is recovered again by recombining the compounds in an exothermic reaction. The stored energy is equivalent to the heat of the reaction.

These technologies are used for many heating and cooling applications. For example, where heat supply and demand are often not simultaneous, as for solar heating systems, or to utilize peak shaving of heating demand. Energy storage in these applications can be very long-term storage, even seasonal. Nowadays, TES is also used for electric applications as support of renewable energy plants. For concentrated solar power plants, energy from the sun is stored by means of molten salt and then released, when needed, to steam which operates a Rankine steam power plant. Further support to the grid can be given by storing heat from electric boilers working as a fast balancing service, or helping limit the demand for electrical power from electric boilers where the need for heat is not continuous and varies in intensity. As a last remark, recently many researchers are studying the possibility of combining different energy storage technologies in the same system in order to exploit the synergy among their different features: for example, the use of batteries together with FWs can increase the life of the batteries.

The power technologies are those with low discharging time and low rating power that fit well with the power quality applications. Some examples are batteries and FWs. The energy technologies are those with high discharging time and high rating power. These technologies fit well with applications like time shift, peak shaving and capacity reserve. Some examples are Pumped-Hydro Storage and CAES technologies. Figure 5 shows the different maturity levels of the main energy storage Technologies [17]. The present level (left end of each arrow representing a technology) and the expected level in 2030 (right end of the arrow) are reported. Some of them are still in a first research phase, others are already proven technologies. Nevertheless, improvements are expected for all of them. Note that for some of them, the expected development is really important.

Fig. 5. State-of-the-art and forecast development of the most promising energy storage technologies.



5. State-of-the-Art and Projects

At present (2020), the worldwide capacity of operating storage systems is estimated at nearly 245 GW and is equivalent to about 2% of the overall electric installed capacity. Many of these systems were built between the late 1970s and 1980s when the increasing price of oil and natural gas drove the construction and operation of many coal and nuclear power plants, which need to work at a steady base load and are not very flexible [14, 15]. Starting from the late 1990s, with the development and the large spread of Combined Cycle Gas Turbines, which are very efficient and flexible, the necessity for energy storage decreased until the last ten years, as explained in the Introduction. Batteries are mainly used for stand-alone applications: only two big grid-connected systems are installed, in Japan and Abu Dhabi, respectively. Also, only one CAES plant in the USA and another one in Germany are operating [1-6].

The International Energy Agency (IEA) has estimated that an additional 310 GW of grid-connected electricity capacity would be needed in the United States, Europe, China and India to support electricity sector decarbonization [1-5]. The estimated worldwide installed capacity in 2050 is about 400 GW: the main contribution is expected from countries where there are (or are planned) many solar and wind power plants, or where geodetic heads available for PHES are present. Regarding this point, mountainous places are the most suitable, but there is an increasing interest, supported by a technological development for seawater pumped-energy storage systems, which exploit the geodetic head connected to high coasts and use the sea as the lower reservoir.

Even if it is possible to find many studies about energy storage all over the world, at present only a few official technology roadmaps are in force. In any case, most of the international and national administrations have put energy storage as a key objective of their respective work programs about energy [12]. On the other hand, Japan, European Union and IEA elaborated the strategy about energy storage together with other energy technology roadmaps. In the United States, a federal map was not published, but some States have done so. California is the main example. In 2050, it is estimated that there will be an installed storage capacity of about 150 GWin the US, primarily achieved by means of the addition of new CAES plants [1-7].

In developing countries, the main contribution to energy storage in the short–medium term is expected to be small-scale stand-alone systems: many projects of renewable energy or hybrid plants integrated with the use of batteries, hydrogen or small PHES have been presented. Often, these systems require a pumping station for access to water. From the studies of many different agencies, it seems that in the short–medium term, batteries will be the winner for small-scale storage plants, while for large scale, probably CAES and Power to gas should be an attractive alternative to PHES, but they still need some improvements. It also calls attention to the importance that there is diversity in energy storage in order to exploit the suitable characteristics of each technology.

6. Barriers to Diffusion

As mentioned earlier, even if energy storage has a long history and much research and many improvements have been recently achieved, further efforts are needed in order to fulfill the new energy market needs [1]. The main challenges for storage concern the technologies, the market regulatory issues, and the strategies [2-4]. With regard to the technological aspects, improvements are required to increase the capacity, efficiency, autonomy, lifetime and reliability of the existing technologies. For proven technologies, the improvements should mainly consist in the upgrading of the existing devices, while for new and developing ones, they will also involve new storage concepts or important modifications of the present design, such as the use of different materials or working pressures and temperatures or innovative cycles. In any case, the key point for each improvement is the reduction of the LUEC. Since the LUEC is also a function of the operating history of the storage unit, it is essential that the development paths are tailored to the specific applications [5-8].

Improvements are also required to the control and regulation systems of the grids where storage units are connected. Note that when the share of non-programmable RES electricity exceeds 20–25% energy storage could enable bi-directional energy flows in the grid, and this eventuality must be predicted. For batteries used in the EVs, the major challenge is the increase of energy density and the reduction of charging times [4]. This last point also requires development of the devices used in the recharging stations. Great attention must also be paid to the environmental impact of the storage units: for many technologies, such as EBES, FC-HES and ECES, the major targets are the sustainable use of resources, the prevention of dangerous wastes and the possibility of recycling, for PHS the use of existing reservoirs and the minimization of the interference with the natural streams of water and of land use, for FWs, the main issue is noise control. In the analysis of the environmental impact of a storage unit, a life cycle approach must be used and the impact for each useful energy unit supplied must be evaluated [5-8].

Finally, improvements to the safety requirements for people living near the energy storage systems, and also the surrounding devices, have to be carried out: dangerous materials which can lead to explosions, toxic emissions, and corrosion are used in some technologies (EBES, SMES, ECES), failure of the rotating wheel is possible for FW, high pressure (CAES) or temperature (FC-HES) are required by some cycles, electrical hazards must be considered for all the technologies; for EVs also recharging security is a concern to be studied. Note that the perceived environmental impact and safety of storage technologies is an important social barrier to the spread of energy storage, so this point needs particular attention [1-4].

A second important challenge for the diffusion of energy storage is the creation of a market able to incentivize the connection to the grid of storage capacity and the supplying of storage services [22]. Since the value of energy arbitrage alone is not sufficient to justify the building of new plants, the market must recognize and pay for the help that an additional offered capacity gives to the grid in terms of flexibility, service safety and reliability. It should be paramount that the price paid by the final users is not increased. So, a preliminary detailed cost–benefits analysis is very important. To attract investment in fast response energy storage technologies, the market must be willing to pay for the value of the speed and accuracy that energy storage provides to the grid, reducing the overall need for, and cost of, regulation services. So the payment can be composed of two different terms: the first one based on the speed and amount of energy transferred by the resource in response to a control signal, and the second one based on the capacity that a unit makes available to provide regulation. Another interesting approach can be the employment of a regulation dispatch algorithm that selects fast response resources before slow response resources in order to minimize the total amount of regulation capacity required in the balancing area [8-12].

The difficulty in defining the rules for the proper support of energy storage systems is increased by the complexity due to the different functions that the same energy storage unit can assume in-service to the grid and to the different features that its function requires. When a unit is in the direct service of an RES plant or of final users, the possible presence of different owners and stakeholders makes the regulation more complicated. Another important issue is that the market rules must be clear and well defined in the short–medium term since the costs for a storage unit are often very high and investors need to plan their investments with a certain degree of confidence. This is paramount for Europe where a common balancing market must be built up [1-3].

In the United Stated, there is already a quite favorable environment for energy storage due to the well-developed ancillary services market: energy storage is allowed to participate and provide services that account for both its qualities and shortcomings [6−8]. Finally, it is important to note that the presence of energy storage also involves other markets such as the gas market (P2G), local districting heating markets (TES), and the transportation sector. A common development strategy must be implemented. It is clear that some strategic issues also have to be faced. The development of energy storage systems is linked to the progress of the whole energy system. Therefore, it is important that a systemic approach is employed, where technical, regulatory, market and political aspects are combined.

Some points are particularly related to the spread of energy storage systems:

- The regulatory framework for the reduction of CO2 emissions, which can strongly encourage the growth of RES.
- The penetration of EVs, which is connected to the evolution of the automotive industry and to the motivation for change in the behavior of users.

- The development of smart grids, which support the diffusion of small-scale energy storage and also of EVs as storage units.
- The upgrade of the Transmission and Distribution grids with the construction of new cables, connecting areas where large amounts of RES are available to areas where electricity is needed. This includes both new long cables in large geographic areas and an increase of the number of interconnections between different smart energy grids.

It is clear that strong public engagement is needed, which depends on investment priorities. Public investments are required to develop new projects and to help the construction of large test case facilities to validate the effective features of the storage technologies. It is important, at this development stage, that technology diversity is encouraged and promoted. A mix of all solutions is needed, tailored for each region and system architecture.

7. Conclusions

In this chapter, a general overview of TES systems, their importance to the thermal systems design, and their rising importance was discussed. A brief breakdown of their various manifestations and embodiments was also conducted with an emphasis on recent developments. The core thrusts of TES study, namely, material, design, and system integration, were defined and their research directions were briefly reviewed. The subsequent chapters will provide greater details on different forms of TES, starting from the fundamentals to present-day case studies.

As the energy landscape continues to evolve with higher levels of variability from climate change and renewable energy sources, the progress of TES systems is expected to grow significantly including various approaches to better manage thermal systems. While heat storage was central to the thermal management of the past systems, rising global temperatures have led to the growing need for cold TES systems in places where ambient temperatures continue to appreciate. Accordingly, a certain degree of emphasis will be placed on cold-TES systems in a subsequent chapter.

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Nomenclature

C = Storage capacity

E_s = Specific energy

L = Expected lifetime

P = Charging/discharging rating power

P_s = Specific power

T = Rated discharge time

V = volume

t_i = Inversion time

t_r = Response time

η = Round trip efficiency

CAES = Compressed air energy storage

EBES = Electrochemical battery energy storage

ECES = Supercapacitors energy storage

EDCL = Electric double layer capacitor

EV = Electric vehicle

FC-HES = Fuel cell hydrogen energy storage

FW = Flywheel

LUEC = Levelized unit electricity cost

PHES = Pumped-hydro energy storage

PHEV = Plug-in hybrid electric vehicle

RES = Renewable energy source

SMES = Superconductors magnetic energy system

TES = Thermal energy storage