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Comparing Energy Storage Methods

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Summary

- *Energy storage is a growing challenge for balancing supply and demand in energy networks, especially electricity networks. It is a crucial issue at a time of energy transition based on renewable energies and electric vehicles.*
- *By comparing energy storage methods, one can see that there are not really any ideal solutions, as their relevance depends on how they are used.*
- *It is therefore essential to support research into different energy storage technologies.*

Gérard Longuet, Senator
Gérard Leseul, Member of the National Assembly

Context

This briefing follows on from a previous Science and Technology Briefing on electricity storage.[1] It broadens the scope by looking at energy storage more comprehensively, while at the same time narrowing the issues involved, since the aim is not to present the different energy storage methods and their challenges, but to compare them. It also complements a previous Science and Technology Briefing on hydrogen production methods.[2]

Understanding the growing interest in energy storage

Energy storage is attracting increasing attention due to changes in the way we produce and consume energy, and how it enables us to adapt to these changes.

In the field of energy production, reducing the use of fossil fuels and developing renewable energy sources (mainly wind and solar energy) requires the identification of suitable storage solutions, particularly in view of their intermittent and uncontrollable nature. These solutions take the form of stationary storage systems and should enable us to stabilise production, compensate for insufficient production or peaks in demand at any given time, restore energy accumulated during production surpluses and, in cases other than those involving renewable energy sources, regulate the frequency of supply networks and deal with occasional shortfalls. Energy storage therefore plays a crucial role in balancing supply and demand on electricity grids.

Moreover, as far as energy consumption is concerned, people are becoming increasingly reliant on electrochemical storage solutions in their daily lives, particularly in relation to mobility and transport, such as the on-board power supply in smartphones, but also in electric vehicles. Lithium-ion batteries were one of the greatest scientific breakthroughs of the late 20th century, earning Stanley Whittingham, John Goodenough and Akira Yoshiro the Nobel Prize in Chemistry in 2019.

These two examples of electricity storage - stationary and on-board - illustrate the growing need for greater flexibility. Some technologies, such as batteries, can be used for both.

A wide range of energy storage solutions

Unlike fossil fuels (which are a form of carbon-based chemical storage), it is not possible to store electrical energy itself, so it must be converted into another form of energy before it can be stored. This form of energy is then converted back into electricity when needed (this is known as *Power to X to Power*).

However, electrical energy storage is not the only storage option: there is also thermal energy storage. The above-mentioned Science and Technology Briefing on electricity storage presented three storage methods (pumped-storage hydroelectricity, batteries and hydrogen), to which this briefing adds others. These different solutions, which will be compared in this briefing,[3] can be divided into four categories: mechanical storage, electrochemical storage, electromagnetic storage and, finally, storage via energy carriers, such as hydrogen, chemical or thermal.

- **Mechanical energy storage**

Gravity storage or pumped-storage hydroelectricity (PSH) is the most common and economical form of large-scale energy storage: by 2023, 80% of the world's stored energy will be pumped-storage hydroelectricity[4] (this percentage is declining as it was 95% before 2020, with batteries accounting for most of the remainder). Pumped storage power plants, also known as pumped-storage plants (PSP), take the form of two-way dams. A set of turbine-generators and pumps is placed between two reservoirs at different heights: when there is a surplus of electricity production (during periods of low demand), water is pumped upstream to fill the higher reservoir, and during periods of high demand, the water is allowed to flow back down to the lower reservoir (using gravity), where the potential energy of the water is converted into electrical energy as it passes through the turbines, thereby using the generators to produce electrical energy, which is then fed into the grid. Their efficiency ranges from 70 to 85%. They offer a large storage capacity - 188 GW worldwide by 2023, including 5.5 GW in France,[5] and have a long lifespan, in excess of 40 years. However, they require significant investments, a considerable amount of land and are highly dependent on the availability of suitable sites.

Compressed air energy storage (CAES) works in a similar way to pumped-storage hydroelectricity in that it is a two-way system, but it uses air rather than water to drive the turbines in the generators. Compressors are used to inject cooled compressed air into a storage space, such as an underground cavity.[6] The efficiency of CAES is variable (40 to 50%), much lower than pumped-storage power plants, and it also requires suitable geological sites, i.e. underground cavities.

Flywheel energy storage (FES) uses the kinetic energy of a high-speed cylinder in a vacuum chamber to generate electricity.[7] It is highly efficient in the short term, but declines with time and friction (85-90% efficiency at start-up, with a significant self-discharge rate: 78% after five hours and 45% after one day). This technology can provide a significant amount of power at a single point in time, but is energy-limited over time and is also very expensive. It can be used in addition to batteries to meet specific electricity grid needs (e.g. frequency regulation in the US).

- **Electrochemical energy storage**

This type of storage involves secondary batteries (or secondary cells) that store energy by means of reversible electrochemical reactions (if these reactions are not reversible, they are referred to as primary batteries or primary cells, more commonly known as single-use or disposable batteries[8]). Their physical principle is based on the difference in electrical potential between two ionic conductive materials forming electrodes. The two materials are deliberately chosen to ensure that a reversible oxidation-reduction reaction can take place. The electrons are exchanged using an external electrical circuit. The reaction is balanced internally by exchanging ions using an electrolyte. The battery is discharged when the two electrodes have been converted, making it impossible for the reaction to continue. To recharge the battery, a reverse electrochemical reaction is created by circulating a counter current between the electrodes.

There are a number of different technologies available, depending on the redox couple involved in the electrochemical reactions.

Lead-acid batteries are the oldest of these technologies (patented in France in 1859 by Gaston Planté) and are still in use today (for example, in starter batteries for internal combustion engines and other industrial applications). They are inexpensive, have average cyclability[9] and their efficiency, approximately 85%, is lower than that of lithium-ion or Li-ion batteries.

Although more expensive, Li-ion batteries have a longer lifespan and high energy density,[10] which is why this technology is becoming more widely used. Li-ion batteries take the lion's share when it comes to energy storage, accounting for 95% of the 20% of the world's energy storage that is not stored in PSPs. Their efficiency is approximately 90-95%. They can also be given a second life: their reuse in stationary applications is expected to become increasingly common.

Other solutions are available, but these are either obsolete or reserved for very specific applications (nickel-metal hydride or NiMH, nickel-cadmium or NiCd, nickel-iron, etc.). Emerging technologies are discussed below in terms of future prospects, as their lack of maturity makes their deployment more difficult. Progress in battery storage capacity has been particularly slow, tripling in a century and a half, mostly in the last 30 years, purely thanks to the development of lithium-ion batteries.[11]

Finally, supercapacitors are used to store energy in an electric field using the electrochemical double layer process, but they are more electrostatic than electrochemical. Their energy density is lower and their self-discharge rate higher, however their good efficiency (95%) and, above all, their power make them suitable for rapid charging and discharging (for use in rail transport, for example).

- **Electromagnetic energy storage**

Superconducting magnetic energy storage (SMES) involves passing an electric current through a coil of superconducting wire and then allowing the current, and therefore the electrons, to flow when the coil is closed (short-circuited), resulting in the formation of a stable magnetic field.[12] The absence of electrical resistance limits energy losses, which are mainly due to the connections and the power converter, resulting in high instantaneous power efficiencies of around 95%, as the energy is stored in the coil in both magnetic and electrical form and can be recovered immediately.

This technology is still relatively undeveloped and uncompetitive - superconductivity requires very low temperatures (close to absolute zero) - but it can be used to complement to batteries because it provides point-source power (as is the case with flywheel energy storage). However, combining two technologies always comes at a significant cost.

- **The use of an energy carrier: hydrogen, chemical energy storage and thermal energy storage**

Using an energy carrier means, for example, transforming electricity into hydrogen or, more rarely, into other molecules, in the form of gas[13] (*Power to Gas*) or liquid[14] (*Power to Fuel*).

The carbon footprint of this storage method is only good if decarbonised electricity is used to produce hydrogen through water electrolysis, which is not the case today, as pointed out in the Science and Technology Briefing on hydrogen production methods cited above: 99% of hydrogen production relies on fossil fuels (natural gas, oil and coal), with significant greenhouse gas (GHG) emissions, and the prospect of increasing the power of electrolysers will not be possible with renewable energy sources, as their intermittency is incompatible with the sensitivity of most electrolysers (alkalis) to variations in power.

As well as being dangerous, hydrogen has a low energy density in relation to its volume (in contrast to its high energy density in relation to its weight), which makes it difficult to store. Finally, the efficiency of this type of storage is very low: when converted back into electricity (*Power to H2 to Power*), it is a mere 30%, or even 20% if the gas has been stored in liquid form at a very low temperature, or 60 to 70% if the hydrogen is used directly.

In addition to hydrogen and fossil fuels, other chemical storage systems exist, but on a much smaller scale.[15] This can involve storing and releasing the energy of a reversible chemical reaction (endothermic when stored, exothermic when released).

Thermal energy storage, in the strict sense of the term, usually involves storing energy in the form of heat, which is particularly strategic given that half of the energy consumed is used for heating (or sometimes cooling). There are two types of thermal energy storage: sensible heat storage[16] and latent heat storage.[17] The first is simple and inexpensive, but generally takes up a lot of space. Its efficiency varies according to insulation and storage volume, but can be relatively high (70-80%). The second is particularly costly, sometimes risky and therefore not very well developed (with the exception of ice) or still in the experimental stage. In both cases, large-scale thermal energy storage experiments have yet to be developed to overcome their low cyclability. Carnot batteries, which can use both forms of thermal energy storage, are a promising way forward, based on the thermal conversion of electricity and then the conversion of this heat back into electricity in a *Power to Heat to Power* process.[18]

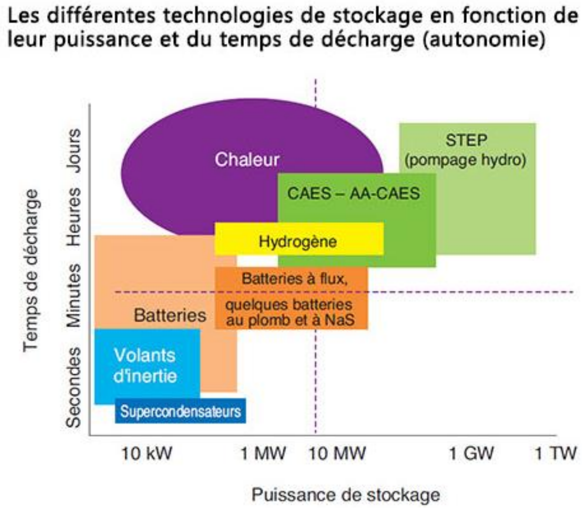
■ Results should be interpreted with caution, as the relevance of the solutions depends on how they are used

An evaluation of the costs of these storage methods, using a variety of methodologies,[19] shows that their costs are variable, complex and partly determined by the price of their components, as well as many other factors.[20] These storage systems can be more or less distributed or, conversely, centralised. They vary in terms of cost effectiveness, life span, safety, reliability, discharge time and, most importantly, environmental impact[21] and energy efficiency.[22]

Losses due to conversions (at least one to store electrical energy in another form, and another to generate electricity again) mean that direct use should be developed wherever possible. In the case of storage via energy carriers (hydrogen, heat, etc.), conversion, which is always optional, does not seem at all appropriate. The same applies, of course, to thermal energy storage, which must be used directly for heating or cooling.

Most importantly, these technologies operate on different timescales, with the time horizon for storage being a different issue to that of controllability in the context of intermittent energies use. FES, SMES and supercapacitors are suitable for very short-term power requirements, while batteries are ideal for short-term use (a few hours) and are particularly suited to mobile applications; PSPs and, to a lesser extent, CAES are an optimal storage solution for the longer term (a few days, weeks or even months between peak seasons); hydrogen may be an interesting option for longer-term use (at least a week) for energy conversion and recovery, as the only by-product of this conversion process is water.

When comparing the different types of energy storage, we can see that their relevance is determined by the conditions in which they are actually used. The following graph shows how these different storage methods complement each other.



Source: IFPEN

Opportunities for innovation

Technological innovations or new approaches to current technologies could change the criteria for these analyses and the results presented. There is still a lot of progress to be made, especially when it comes to batteries. In addition to the progress that will continue to be made (greater reliability, longer life, improved environmental performance), we can also expect to see significant improvements in lithium-ion batteries, particularly with the so-called "all-solid" batteries that could be on the market by 2030.[23]

We are also seeing the emergence of innovations that will allow us to move away from our dependence on critical materials such as lithium: sodium-ion or even potassium-ion technology, innovations that aim to do away not only with lithium but also with cobalt, nickel and manganese, which are particularly costly.[24]

Progress has also been announced in the development of lithium-sulphur and sodium-sulphur batteries, which are denser (in terms of mass), more environmentally friendly and slightly less expensive than lithium-ion batteries, but have a lower cyclability. In December 2022, a new version of the sodium-sulphur battery was presented by a team of Chinese and Australian scientists, with a higher capacity than lithium-ion batteries but half the capacity after 1,000 cycles.

Flow batteries, or redox flow batteries, are also worth mentioning, as their competitive cost, good performance and long life make them an attractive option, despite their lower efficiency of around 75% and the use of toxic heavy metals. Above all, these storage devices are bulky in mass and volume and can therefore only be used for stationary applications.[25]

Finally, energy storage systems will benefit from innovations in artificial intelligence and data science. For example, smart grids will consist of management systems that go from upstream, at the production stage, to downstream, at the final consumption stage, including on-board storage devices. So the batteries of the future will be more than just electrochemical systems, and will contain more and more electronics to make them intelligent.

Conclusions

There is no miracle solution when it comes to energy storage. The available storage technologies are adapted to each specific situation and should be chosen on the basis of a multi-criteria analysis within the framework of a given energy strategy that sets targets for the share of renewable energies in the energy mix.

A wide choice of technologies is therefore essential in this field, as requirements can vary greatly in terms of duration (a few seconds for frequency regulation, several minutes or hours for stabilising production, several months for storage between peak seasons), flexibility, power or energy (from a few kWh to several tens of GWh), and so on. It is therefore extremely important to ensure that we have a wide range of technological options available and that we diversify storage methods according to the value chain of the energy networks, from production to use, through transmission and distribution. In some cases, it makes sense to combine technologies to make them complementary, for example by combining batteries with supercapacitors or flywheels, albeit at a higher cost.

As long as the comparison of energy storage methods does not lead to a clear conclusion as to the existence of better solutions, since these depend on the applications and conditions of use, a diversified approach to basic and applied research should be pursued.

France has the advantage of being well positioned in most of these technologies. Innovative solutions aimed at industrial development should be particularly encouraged, even if, as stated in the Science and Technology Briefing cited above, the need for stationary storage will remain relatively limited in France due to the flexibility of the electricity system and its interconnection with the European system.

The Office's websites:
http://www.assemblee-nationale.fr/commissions/opecst-index.asp
http://www.senat.fr/opecst

Persons consulted

Jean-Marie Tarascon, Professor at the Collège de France, Chair of Solid State Chemistry and Energy, and member of the French Academy of Sciences

Lingai Luo, CNRS Research Director at the Heat and Energy Laboratory, University of Nantes

Pierre Odru, former Head of Energy Storage at the French National Research Agency (ANR - Agence nationale de la recherche) and former Senior Engineer at IFPEN

Thierry Priem, former Head of the Storage and Flexibility Solutions programme at the CEA's Energy Division

Aymeric Canton, Head of the Storage and Flexibility Solutions Programme in the CEA's Energy Division

Philippe Azaïs, Head of the Energy Efficiency of Complex Systems and Networks Programme in the CEA's Energy Division

Sébastien Patoux, Head of the Battery Technologies Department at the Laboratory for Innovation in New Energy Technologies and Nanomaterials (LITEN)

Laurent Torcheux, Advisor to EDF's Research and Development Department

Nesrine Darragi, Founder and CEO of Hive Electrics

Yannick Borthomieu, Head of the Battery Department at Saft

Note: Gérard Longuet states that he is a director of Cockerill.

Références

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[1] See the Science and Technology Briefing No. 11 (February 2019) on electricity storage, prepared by our colleague Senator Angèle Préville, which this briefing extends and supplements: https://www.senat.fr/fileadmin/import/files/fileadmin/Fichiers/Images/opecst/quatre_pages/OPECST_2019_0009_note_stockage_electricite.pdf

[2] See the Science and Technology Briefing No. 25 (April 2021) on hydrogen production methods, prepared by our colleague Senator Gérard Longuet, First Vice-Chairman of the Office: https://www.senat.fr/rap/r20-536/r20-5361.pdf

[3] One of the few French-language summaries on the subject was published by Pierre Odru: P. Odru (dir.), *Le Stockage de l'énergie*, Dunod, 2012.

A 2022 US report compares different storage methods, focusing on their relative costs and benefits: V. Viswanathan, K. Mongird, R. Franks, X. Li & V. Sprenkle, *Grid energy storage technology cost and performance assessment*, U.S Department of Energy (DOE). This follows on from another report published in 2019: K. Mongird, V. Viswanathan, P. J. Balducci, M. J. E. Alam, V. Fotedar, V. S. Koritarov & B. Hadjerioua, *Energy storage technology and cost characterization report*, U.S Department of Energy (DOE).

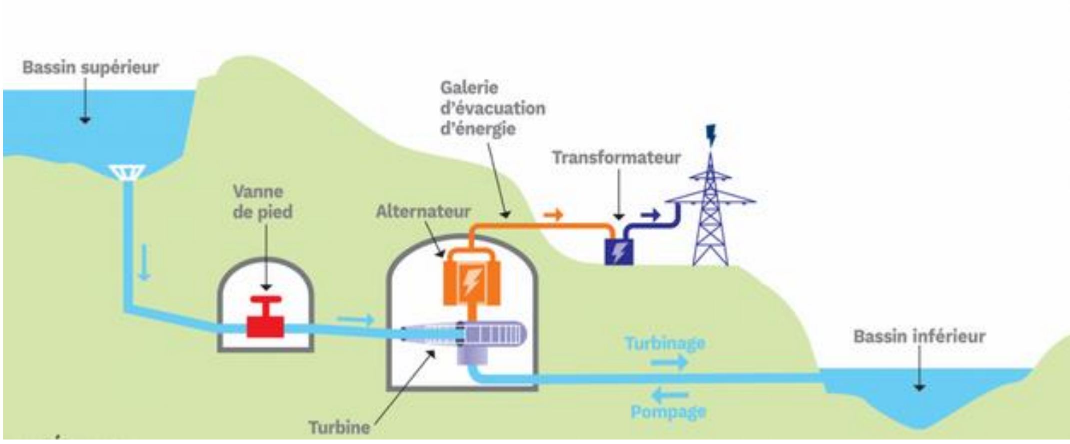
See also the following summary articles: R. Shan, J. Reagan, S. Castellanos, S. Kurtz & N. Kittner, "Evaluating emerging long-duration energy storage technologies", *Renewable and Sustainable Energy Review*, 2022; K. Mongird, V. Viswanathan, P. J. Balducci, M. J. E. Alam, V. Fotedar, V. S. Koritarov & B. Hadjerioua, "An evaluation of energy storage cost and performance characteristics", *Energies Review*, 2020; M. Rahman, A. O. Oni, E. Gemechu & A. Kumar, "Assessment of energy storage technologies: A review", *Energy Conversion and Management Review*, 2020; S. Koohi-Fayegh & M. A. Rosen, "A review of energy storage types, applications and recent developments review", Journal of Energy Storage, 2020; F. Nadeem, S. M. S. Hussain, P. K. Tiwari, A. K. Goswami & T. S. Ustun, "Comparative Review of energy storage systems, their roles, and impacts on future power systems", *IEEE Access Review*, 2019; A. Ahmed, A. Alsharif & N. Yasser, "Recent advances in energy storage technologies", International Journal of Electrical Engineering and Sustainability IJEES, 2023.

A publication of particular interest in this regard is a report published by the Royal Society in September 2023, which highlights the prospects for large-scale energy storage solutions in the UK: https://royalsociety.org/topics-policy/projects/low-carbon-energy-programme/large-scale-electricity-storage

[4] See the report presenting this recent data at the following link: https://static1.squarespace.com/static/55826ab6e4b0a6d2b0f53e3d/t/64a79c04263d091574985908/1688706054284/CNESA+White+Paper+2023.pdf

[5] PSPs, which represent 188 GW of installed pumped storage capacity, are mainly found in Europe, Asia (China, Japan, etc.) and North America. The largest in the world is in Bath County in the United States (3 GW), followed by the Chinese plants (Huizhou and Guangzhou, each with a capacity of around 2.5 GW). France has six high-power stations: Grand'Maison in Isère (with a capacity of 1.79 GW), Montézic in Aveyron (910 MW), Bissorte in Savoie (748 MW), Revin in the Ardennes (720 MW), Le Cheylas in Isère (480 MW) and La Coche in Savoie (370 MW). There are an estimated 500,000 potential sites for PSPs around the world, although the pace of construction remains moderate, with just three noteworthy plants inaugurated in 2022: Jinzhai in China (1.2 GW), Nant de Drance in the Canton of Valais in Switzerland (900 MW) and Tâmega in Portugal (which, with its three reservoirs Gouvães, Daivões and Alto Tâmega, aims to reach 1.16 GW by the end of its planned deployment in 2024).

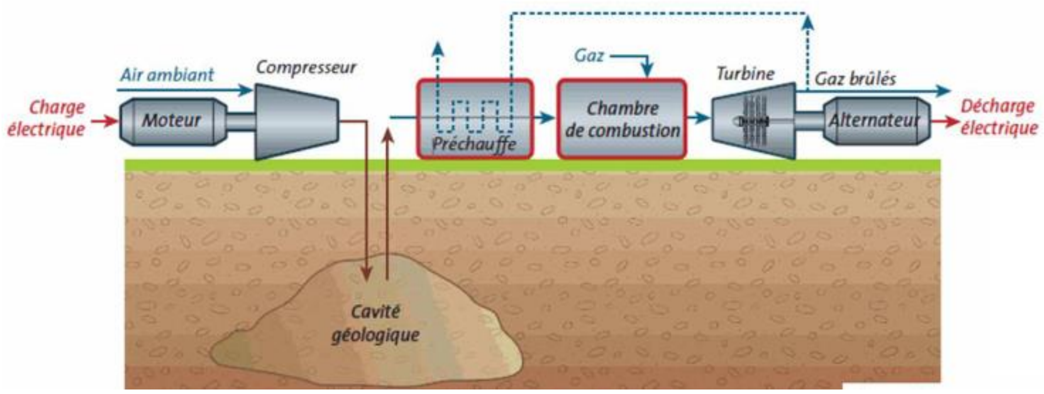
Diagram of a pumped-storage power plant (PSP)



Source: EDF

[6] Integrating heat storage during the compression phase to heat the air during expansion increases the efficiency of CAES systems, as shown in the following diagram showing a combustion chamber, although such a device is not always installed (in this case there is a direct transition from the preheating stage to the turbine).

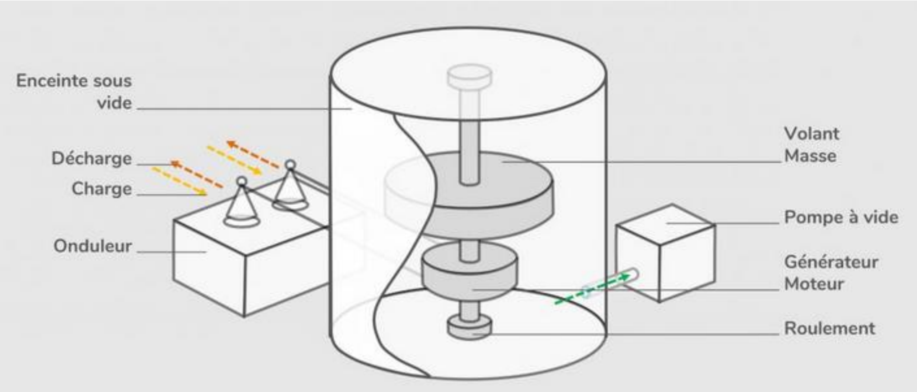
Diagram of a compressed air energy storage installation (CAES)



Source: Enea

[7]

Diagram of flywheel energy storage (FES)



Source: Bruxelles Environnement

[8] Confusion between disposable batteries (primary batteries) and rechargeable batteries (secondary batteries) is all the more common as the word "battery" is used in English to refer to both primary batteries (primary cells) and secondary batteries (secondary cells).

[9] Cyclability is the average number of charge/discharge cycles a battery can be subjected to.

[10] Different batteries are characterised by their potential differences, the amount of electricity stored in the electrodes and the rate at which they charge and discharge, which determines their available power, all of which depend on their mass and volume.

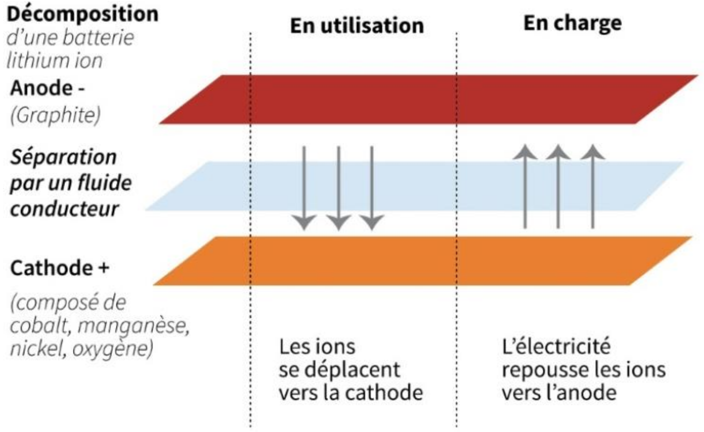
Other important characteristics are their lifespan in terms of the number of charge/discharge cycles they can withstand with limited degradation, their overall lifespan (including calendar storage), their self-discharge rate over time, their energy efficiency, their temperature sensitivity, etc.

Automotive and portable applications focus on the volume and mass density of the energy and power output, whereas stationary applications are less concerned with weight and more with the overall cost, i.e. investment, maintenance, useful life, efficiency, etc.

Lead-acid batteries, which are older and less expensive, have a specific energy output of around 30 Wh/kg, which is why they are still used to start combustion vehicles or for back-up systems, including in our nuclear power stations.

Lithium batteries are widely used for both mobile storage applications (mobile phones and laptops, electric vehicles, etc.) and stationary storage applications. They have a longer lifespan, a lower self-discharge rate, higher efficiency and, most importantly, their mass energy density is more than eight times that of lead-acid batteries, at around 250 Wh/kg, with a similar difference in volume energy density.

Diagram of a lithium-ion battery

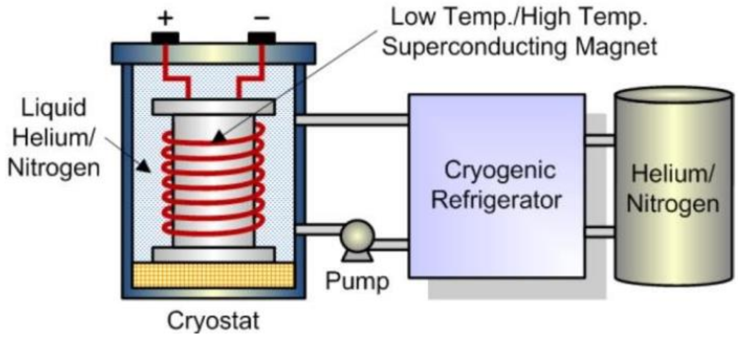


Source: Source: AFP, taken from batteryuniversity.com and livescience

[11] As Jean-Marie Tarascon, Professor at the Collège de France and winner of the 2022 CNRS gold medal for his research into batteries, explained at the hearing: "*It is worth mentioning Moore's Law. Unfortunately, these developments are in the field of chemistry, not electronics. Moore's Law predicts that memory capacity will double every 18 months. But it took two centuries for batteries to double or even triple in capacity. So, as you can see, we are definitely not on the same timescale. Lithium-ion is without doubt the most successful of these technologies. Sony's first lithium-ion battery, produced in 1991, had a mass energy density of 110 Wh/kg, whereas today we have reached 220, even 230 or 250 Wh/kg, a factor of 2.5 in 25 years.*" This density is as high as 300 Wh/kg for the best lithium-ion batteries available today. See the minutes of the Office's public hearing of 4 May 2023 on "The technological prospects of batteries: incremental progress or disruptive innovation?": https://www.senat.fr/compte-rendu-commissions/20230501/2023_05_04.html

[12] The following diagram illustrates the dependence of SMES on helium, nitrogen and very low temperatures:

Diagram of a superconducting magnetic energy storage device (SMES)



Source: M. G. Molina, 6th IEEE Power & Energy Society conference

[13] Biomass, which has a low carbon footprint, can even be used to store energy, as can CO_2 captured from industrial activities. The gas obtained by methanation (in the *Power to Gas* process) can also be combined with hydrogen to produce syngas, which can be converted into fuels.

[14] Most of these liquids take the form of synthetic fuels, also known as *e-fuels*, such as e-methanol, e-diesel, e-kerosene and paraffinic e-fuels. See the Senate's report on the development of sustainable fuels and hydrogen: https://www.senat.fr/notice-rapport/2022/r22-825-notice.html

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[15] Chemical storage often uses water as an energy carrier. In particular, it can take the form of sorption (adsorption, surface interaction between a solid and a gas, or absorption, volume interaction between a gas or a liquid that dissolves in another liquid).

Adsorption can be physiosorption (electrostatic surface interaction, often with silicas or zeolites for water vapour) or chemisorption (surface interaction with electron transfer and formation of new chemical bonds; in this case, adsorption produces approximately ten times more energy than physiosorption).

Absorption generally involves the absorption of water vapour into a solution to dilute or dissolve a material. Thermochemical storage techniques using sorption are theoretically capable of storing heat or cold for an infinite period of time, with a high volumetric energy density, but this method of storing energy in the form of its chemical potential is only at the research and prototype stage.

Chemical energy storage may also involve the use of chemical reactions to chemically decompose products in reversible reactions (e.g. blue hydrated copper crystals which decompose to water vapour and white anhydrous copper sulphate when heated).

[16] Sensible heat storage is based on the difference in thermal mass between a material stored at two different temperatures. This can be a solid or liquid material, such as hot or cold water, oils, stones, concrete or molten salts, which are used in certain thermodynamic solar power plants and have the advantage of high melting temperatures of several hundred degrees (sodium nitrite, sodium nitrate, potassium nitrate, calcium nitrate, etc.). This storage method is suitable for neighbourhoods or residential buildings, in particular via water tanks. It can also act as buffer storage for heating systems, as in the case of domestic hot water tanks, mainly from solar panels. A number of projects, such as borehole thermal energy storage (BTES) systems, combine sensible heat storage with geothermal energy.

[17] Latent heat storage uses the latent heat generated when a material changes phase, for example from solid to liquid. Such materials include ice, fatty acids or alcohols, paraffins, hydrated salts or polyols. The phase change in latent heat storage requires materials to be contained, either by encapsulation or by the use of an encapsulating agent (ice storage system or similar), or by compaction in a fixed bed, or by dispersion, impregnation or infiltration into another material (e.g. in the walls of a building).

[18] The principle of Carnot batteries is to use electricity to drive thermal energy storage devices (electro-thermal energy with sensible or latent heat), for example via high-temperature heat pumps, so that it can be released during periods of high demand by high-temperature turbines using a thermodynamic cycle (Rankine, Brayton or Joule cycle, etc.).

[19] Comparing the efficiency and costs of these technologies is a delicate task: certain parameters are intertwined, and some technologies generate specific costs that cannot be compared with those of other technologies. The consensus from research seems to be that there is no common framework for comparing the costs of energy storage devices. As a result, there are a number of different methodologies, often specific to a particular storage method. However, the most common recent framework for comparing them is the Levelised Cost Of Storage (LCOS), inspired by the Levelised Cost Of Energy (LCOE), which is based on the following equation: the sum of the costs incurred (installation, network adaptations + operational maintenance costs + load costs over one year) divided by the yield in MWh over one year. The capital costs, discussed in the research, cover different elements that vary according to the technology. Capital costs for electrochemical energy storage are generally expressed in dollars per kilowatt-hour ($/kWh), while those for FES, PHS and CAES are expressed in dollars per kilowatt ($/kW). More specifically, capital costs relate to the supply of energy storage units, including, for example, pumped hydro, hydroelectric dams, and the various pump and turbine-generator arrangements. For compressed air energy storage, the capital costs include creating underground storage cavities, preparing the ground, compressors, turbines and the required natural gas. The capital costs also include the cost of the Power Conversion System (PCS). These costs include the installation of control and monitoring systems for the technologies involved in the energy conversion, such as inverters in some cases. These costs also include solar cells, the technology responsible for converting solar energy into electrical energy. The costs of the containers and chambers surrounding the technology are often included in the cost of the PCS. The cost of balancing the system (referred to as BOP, or Balance Of Plant, in the literature) is the cost of all the supporting components and auxiliary systems of a power plant needed to deliver the energy, other than the generating unit itself. This can include transformers, inverters, but also personal protective equipment for workers, electrical cables, electrical connections and the assembly structure on which the conversion technology is based. These costs are also expressed in $/kW and are generally included in the capital costs. The construction and commissioning costs (referred to as C&C in the literature) correspond to the costs incurred in studying the site and its ideal architecture, evaluating the topology, the costs of transporting materials to the site where the storage technology is located, and the costs of labour and spare parts for installing the technology. Finally, fixed and variable operation and maintenance costs include all costs required to operate the technology over the long term. Fixed operation and maintenance costs (referred to in the literature as O&M) include the costs required to keep the storage technology operational throughout its economic life and do not vary according to energy use. Variable O&M costs include all costs required to operate the storage system over its economic lifetime, and are standardised against the annual discharge energy flow. This standardisation is expressed in cents/kWh.

In total, the cost calculations for energy storage technologies take into account the capital costs (PCS costs, storage costs, C&C costs and BOP costs), the fixed and variable operation and maintenance (O&M) costs, and any replacement costs that are not included in the maintenance costs. While some studies specify the value of the dollar at the time of the study, others do not, and some even index costs to inflation. There are other variables taken into account, and each study makes assumptions, especially in the case of predictive models. For example, it is often assumed that the capital costs of pumped-storage hydroelectricity, compressed air energy storage and flywheel energy storage will not change until 2025, as these technologies are more mature than others. These choices can therefore lead to very different results, even if the same

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methodology is used (often that of levelised costs or LCOS). Regarding the decision of some researchers not to use the LCOS standard, it should be noted that in reality similar methods are used and that a different name may even correspond to the dominant methodology. The latter is not perfect and does not take sufficient account of certain specific characteristics of a given technology, particularly in terms of its ability to rapidly ramp up or distribute power.

[20] The main findings of the American studies cited in endnote 3, based on the LCOS, are as follows:

- for energy storage of four hours or less, lithium batteries offer the best solution in terms of cost, performance, life span and technological maturity. These are also the technologies with the best efficiency (85%, but this declines over time) and the ability to distribute high voltage;
- supercapacitors are also particularly advantageous in terms of annual costs for certain specific needs;
- for longer-term storage, PSPs and CAES are the most cost-effective and have the lowest possible cost, at $165/kWh and $104/kWh respectively. Their efficiency is lower: pumped-storage hydroelectricity can recover more than 80% of the energy used, while compressed air can recover 50%. Pumped hydro therefore remains a more mature, more efficient and more widely used technology. Batteries are therefore only competitive with PSPs for short-term storage. Pumped storage becomes systematically more cost-effective for storage periods beyond approximately sixteen hours, although the exact break-even point remains unclear and depends on the installation.

Storage time is therefore the primary determinant of the superiority of one technology over another. These studies also show that, while lithium batteries remain the best batteries for short-term storage, flow batteries open up interesting prospects in terms of cost, performance and lifespan, despite a lower efficiency of 75%. The lifespan of lead-acid batteries is too short for them to remain cost-effective and competitive. As for other systems, researchers seem to doubt the possibility of major innovations in PSPs, CAES or FES (adiabatic compressed air energy storage, or A-CAES, is expected to reach 75% efficiency). It is therefore unlikely that there will be a significant reduction in the cost of these three technologies.

[21] In terms of environmental impact, the issue of recycling is essential and requires the use of life cycle analyses (LCA). For example, while it is well known that it takes 320 to 350 kWh of electricity to supply 1 kWh of battery power, which equates to 90 kg of CO_2 emissions, it is less well known that an electric vehicle uses six times more materials and chemical elements than a traditional internal combustion engine vehicle. The CEA (French Alternative Energies and Atomic Energy Commission) has developed a multi-criteria analysis methodology for comparing energy solutions, taking into account their technical, economic, environmental (life cycle analysis, etc.), regulatory and societal (changes in use, etc.) aspects.

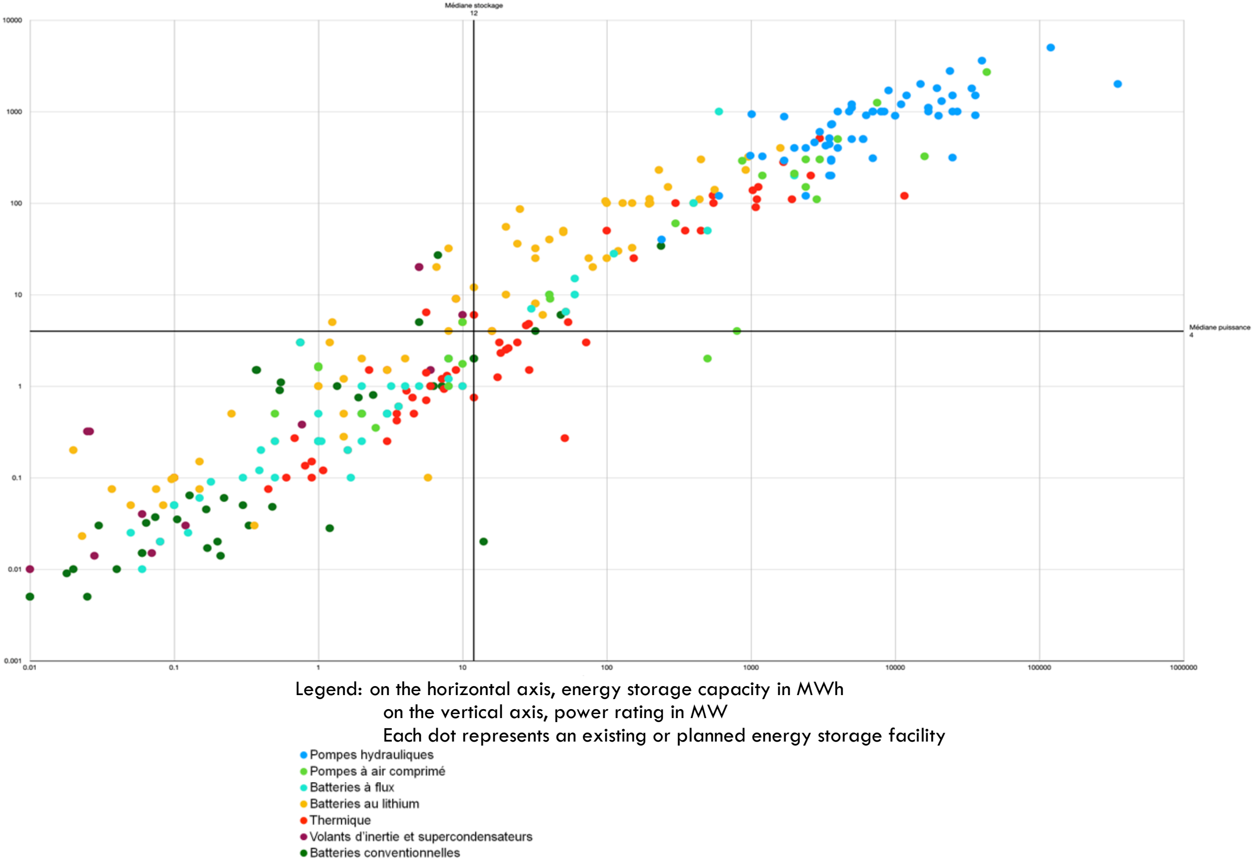
[22] Efficiencies are most often expressed in terms of RTE, or round-trip efficiency. This term refers to the balance between the net amount of energy required to charge and operate the storage system and the amount of energy retrieved from it. There are always losses during these charging and discharging processes. These losses can be broken down as follows:

- batteries, for example, gradually lose their capacity to discharge the same amount of energy. This is particularly true of lithium batteries, and although the losses from one cycle to the next are negligible, the efficiency of the battery gradually decreases over time (this is one of the reasons why the batteries in our mobile phones need to be recharged more often over time);
- internal resistance during discharge can cause very slight losses;
- finally, and most importantly, the energy required to heat, cool, control or manage the state of the system is not recovered but consumed in its entirety, which accounts for the vast majority of energy losses between charging and discharging.

In addition to RTE, the energy-to-power ratio can also be useful in understanding these efficiencies. Energy storage technologies are generally measured against two criteria: their power rating and their energy rating, or energy capacity. Their power rating is expressed in MW and measures the instantaneous demand that these technologies are capable of satisfying. If you add up the power ratings of all the household appliances connected to an energy storage module, their combined power rating must be equal to or less than the power rating of the module. Their energy capacity, expressed in MWh, indicates the total amount of energy that the storage system is capable of supplying over time. By dividing the energy capacity (in MWh) by the power rating (in MW), we can determine the duration (in hours, minutes or seconds) over which a storage system can operate while supplying maximum power. This duration is known as the energy-to-power ratio, sometimes referred to as discharge time. For example, a storage system with a power rating of 100 MW and an energy capacity of 50 MWh has an energy-to-power ratio of 30 minutes. The different energy storage methods perform well in one dimension or another. While some energy storage technologies, such as supercapacitors, are well suited to providing high power for a few seconds or minutes, others, such as PSPs, are capable of providing energy for longer periods of time.

The following graph shows 355 energy storage systems around the world (existing or planned) that have been analysed by the Office. It summarises the capacity-to-power ratio data for several technologies (PSP in blue, CAES in light green, lithium batteries in yellow, thermal energy storage in red, flow batteries in turquoise, conventional batteries in dark green and SMES in purple), which empirically confirms the variability in performance between storage technologies.

The range of capacity-to-power ratios of different energy storage methods



Legend: on the horizontal axis, energy storage capacity in MWh
on the vertical axis, power rating in MW
Each dot represents an existing or planned energy storage facility

Source: Opecst

The following table summarises information on the main storage technologies:

Technology	PSP	CAES	Sensible heat	Hydrogen	Batteries	Supercapacitors	FES	SMES
Charging method	Pumped water	Compressed air	Heat	Steam reforming - sometimes water electrolysis	Displacement of ions towards the negative electrode	The accumulation of ions on each electrode	Driving the flywheel	Electrification of the coil
Principle, potential or energy carrier	Gravitational energy *Difference in speed*	Compressed air *Difference in pressure*	Various materials *Difference in temperature*	H_2	Exchange of electrons between two electrodes *Difference in electrical potential*	Exchange of electrons between two electrodes *Difference in electrical potential*	Kinetic energy *Difference in speed*	Magnetic field *Difference in inductance*
Discharging method	Water drives a turbine	Air expanded to drive a turbine	Heat transfer	Fuel cell or combustion	Displacement of ions towards the positive electrode	The release of ions from each electrode	Deceleration of the flywheel	Recovered by an inverter
Efficiency	70-85 %	40-50 %	70-80 %	20-50 %	90-95 % Li-ion	95 %	85-90 %	95 %
Maturity	+++	+	++	+	+++	—	++	—

Source: Opecst

[23] See the short article by Patrick Bernard, Director of Research at Saft, "Trois technologies de batterie qui pourraient révolutionner notre avenir" ("Three battery technologies that could revolutionise our future"), which, following on from the new generations of lithium-ion batteries and lithium-sulphur batteries, focuses on all-solid batteries, the first generation of which could be based on graphite anodes, which offer better energy performance and greater safety but are heavier, paving the way for the marketing of lighter all-solid batteries with lithium metal anodes: https://www.saft.com/fr/m%C3%A9dias-et-ressources/nos-histoires/trois-technologies-de-batterie-qui-pourraient-r%C3%A9volutionner-notre

[24] The CEA-CNRS Sodium-Ion Technology Task Force, launched in 2012 by Jean-Marie Tarascon, is working on various projects and cell formats, such as the Naïades stationary battery in 2020 and the Naïma stationary battery in 2022. It has already led to the creation of the start-up Tiamat in Amiens in 2018, which announced the commercialisation of sodium-ion technology in April 2023, a world first. Another French start-up, Hive Electric, founded in Lille in 2019, is working on aluminium-based metal-ion cells that do not contain lithium, cobalt, nickel or manganese, as well as lithium-iron-phosphate (LFP) technology, which does not contain cobalt, nickel or manganese. See the minutes of the public hearing cited above.

[25] In addition to their reliability, which remains to be confirmed, redox flow batteries have a low energy density and require a proton exchange membrane (which allows ions to be exchanged between the two liquid electrolytes).