




A Survey on Energy Storage: Techniques and Challenges

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Abstract: Intermittent renewable energy is becoming increasingly popular, as storing stationary and mobile energy remains a critical focus of attention. Although electricity cannot be stored on any scale, it can be converted to other kinds of energies that can be stored and then reconverted to electricity on demand. Such energy storage systems can be based on batteries, supercapacitors, flywheels, thermal modules, compressed air, and hydro storage. This survey article explores several aspects of energy storage. First, we define the primary difficulties and goals associated with energy storage. Second, we discuss several strategies employed for energy storage and the criteria used to identify the most appropriate technology. In addition, we address the current issues and limitations of energy storage approaches. Third, we shed light on the battery technologies, which are most frequently used in a wide range of applications for energy storage. The usage and types of batteries are described alongside their market shares and social and environmental aspects. Moreover, the recent advances in battery state estimation and cell-balancing mechanisms are reviewed.

Keywords: electricity; energy storage techniques; challenges; importance; batteries; state estimation



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1. Introduction

Electricity, corresponding to the movement of electrons in conductive materials, is an energy vector that allows energy to be transported between a source (generator) and a device designed for its use [1]. The specificity of electricity lies in the diversity of services that it can render through numerous technical devices, and it can easily facilitate the production of heat, cold temperatures, light, or driving forces (thanks to the electric motor) [2]. Unavailable in a usable form in its natural state, electricity is a so-called “secondary” form of energy, i.e., resulting from the transformation of primary points. The latter can be fossil-based (oil, gas, and coal) [3], nuclear [4,5], or renewable (from solar radiation, wind, the water cycle, biomass, etc.) [6–8].

Using renewable energies to produce electricity is an alternative to most current energy plans. However, unlike fossil resources, electricity, which only exists if used, cannot be stored, and must be converted into another energy to be reused later. Although various means of storage exist, they are vastly insufficient to meet the growing global need for electricity, which constitutes a significant challenge for research, innovation, and industrial development. The studies in this field are numerous, varied, and fruitful [9–13].

Most primary energies (gas, oil, or coal) are easily stored. Storing electricity in large quantities, on the other hand, first requires its conversion into other forms of intermediate and storable energy (potential, kinetic, chemical, or thermal) and its subsequent restoration for use. It should also be noted that the evolution of the global energy situation is characterized by the following significant findings:

- The use of electrical energy will increase sharply in the coming decades due to the simplicity and flexibility that this energy vector provides to users, as well as to reduce the overall use of fossil energies (mainly oil and coal); it also offers many possibilities for remote control [14,15].
- The share of renewable energies in the production of electrical energy will increase sharply to meet the objectives of reducing greenhouse gas emissions (mainly water vapor (H₂O), carbon dioxide (CO₂), methane (CH₄), nitrous oxide (or N₂O), and ozone (O₃), whose increased concentrations in the Earth's atmosphere are considered to constitute the major cause of global warming). Among these renewable energies, wind and solar are intermittent; hydro, geothermal, and biomass can provide production on demand in most cases [16,17].
- The intensity of electricity demand peaks should increase sharply, which is mainly due to the ongoing increase in the earth's population and rising individual and collective needs, even if significant awareness-raising efforts are undertaken to avoid waste [18,19].

The permanent balance between supply and demand, which determines the stability of electricity distribution networks, necessitates the integration of storage facilities acting as buffers between intermittent production for the ensured share offered by wind and solar power and an evolving demand, whose fluctuations are in no way in phase with the periods of production of renewable energies, into the production and distribution systems [20,21].

Energy storage is a major strategic issue on a global scale. Reducing the production of greenhouse gases entails, for example, the use of renewable energies. Due to the intermittency of some of these renewable energies (wind, solar power (particularly photovoltaics), etc.), storage is thus the only way to operate in accordance with the time lag between the production of electricity (by solar panels working only during the day) and the satisfaction of demand (lighting at night). Today, the most widely used system for storing large quantities of primary energy during overproduction is hydraulic storage by pumping water uphill from a downstream dam, and then pouring it into the latter's reservoir [22,23].

Of the other means of storage that exist (such as thermal storage, the creation of compressed air reserves, kinetic storage by a flywheel, etc.), the most widely used form of all the applications combined is undoubtedly electrochemical storage through batteries. Their considerable advantages partly explain these batteries' success compared to other mobility solutions [24,25].

Therefore, the development of high-performance electrochemical generators is of particular importance with regard to portable applications (computers, mobile phones, tools, etc.) [26,27], particularly in the transport sector due to the development of hybrid and all-electric vehicles [28,29] or even the growing electrification of functions on board aircraft. However, mobility is not the only advantage offered since another characteristic of these energy storage systems is their cyclability, which is their ability to store and discharge energy reversibly for several hundred cycles. This cyclability, which is accompanied moreover by an energy efficiency greater than 97%, renders batteries extremely interesting in stationary applications, such as the storage of electricity from primary renewable energies to balance supply and demand in local electrical networks (on the scale of buildings or a district) [30–34].

To ensure the dependability and efficiency of power networks, the implementation of a coordinated and optimal charging procedure for large-scale electric vehicle (EV) fleets is essential [35]. Additionally, EVs and renewable energy sources are promising strategies with which to lower the use of fossil fuels and their negative effects on the environment. It is simple to imagine a future where all vehicles will be electric as more manufacturers create and release EV models [36]. However, the viability of EVs depends largely on their driving range, which is determined by the size of their batteries. The batteries in EVs must be compact and lightweight, able to recharge quickly and frequently, and have enough power to transport an individual to their desired location [37]. Lithium-ion batteries are commonplace in modern EV applications. In EVs, the most energy-dense form of lithium chemistry, Lithium Cobalt Oxide (LCO), is typically used.

In this study, we explore a variety of facets regarding the storage of energy. The primary concerns and goals that are associated with energy storage are outlined in the first part. In the second part of this article, we discuss various methods currently in use for the storage of electrical energy, as well as the criteria that have been applied in order to select the methods that are most suitable. In the third section, we shed some light on the history of the development of technology for rechargeable batteries. In addition, we highlight some of the open problems and restrictions that are associated with energy storage. To the best of our knowledge, these different aspects have not been overviewed in the same paper in any previous study. This renders our contribution significant and original. In Table 1, a summary of the main contributions and limitations of the analysed surveys, which have been published during the last three years, is presented.

Table 1. Summary of the main results and limitations of some relevant surveys.

Year	Ref.	Contributions	Limitations
2022	[38]	This review critically examines energy storage systems' evolution, classification, operating principles, and comparison from 1850 to 2022.	The article is quite long (51 pages and 566 references).
2022	[39]	This study focuses on the integration of energy storage systems for microgrid applications, providing an analysis of issues, control techniques, challenges, solutions, applications, etc.	In this research, the authors focused solely on the integration of energy storage systems for use in microgrids.
2022	[40]	This study reviews thermal energy storage applications such as heat recovery from waste and the cooling of heavy electronic equipment. The study demonstrates that thermal energy can be used for heating and cooling and has enormous potential with respect to new technologies and strategies.	This paper is limited to the study of thermal energy storage applications.
2021	[41]	Battery-based energy storage systems are thoroughly reviewed in this study with regard to their optimal sizing goals, system constraints, different optimization models, and methodologies.	This paper is limited to the study of battery-based energy storage systems.
2021	[42]	In this work, the authors conduct a literature assessment and propose an organizational plan for utility-scale hybrid systems that generate electricity solely from commercially accessible renewable energy technology.	The scope of this research is restricted to the study of renewable-energy-based hybrid systems.
2020	[43]	This paper may help decision-makers and practitioners choose the latest and most innovative energy storage technologies and systems for grids, machinery, and portable devices.	Some issues and objectives raised by numerous stakeholders are not covered.
2020	[44]	This study examines the current advancements in the exploitation of mechanical energy storage devices linked with wind and solar energies.	This paper is limited to the study of mechanical energy storage systems.
2020	[45]	This paper provides a thorough examination of the key elements required to comprehend the use of quick response storage technology for frequency regulation services. Additionally, it addresses the shortcomings and restrictions in the state-of-the-art techniques based on real-world experiences.	This research focuses solely on the analysis of quick response energy storage technologies for frequency regulation in contemporary power systems.
2020	[46]	In this review, natural carbon sources used to synthesize graphene and carbon products/derivatives for supercapacitors with good electrochemical performance are discussed. The review also covers the latest synthetic methods applied to such materials and their use as electrodes in supercapacitors.	This article focuses exclusively on supercapacitors as energy storage devices and how they use natural carbon resources as their electrode materials.
2020	[47]	This study reviews some recent advancements in railway energy storage systems (ESSs) and presents a thorough comparison of several ESSs. The main functions of the railway ESSs are discussed together with potential solutions from the academic community and current railway industry practices.	The objective of this review paper is restricted to the study of energy storage devices that are used in electrified railway systems.
2020	[48]	In this work, a comprehensive evaluation of the existing literature on electric vehicle (EV) power conversion topologies and energy storage systems is presented, along with problems, possibilities, and prospects based on a systematic classification of EVs and energy storage.	The scope of this review paper is limited to the investigation of several power conversion topologies and energy storage systems for electric vehicles.

The remainder of this article is structured as follows. Section 2 lists the key concerns and goals for the study of energy storage and the key participants in the process. We focus on the many known strategies for storing power in Section 3 and the criteria to apply in order to select the best option. Then, the development of the rechargeable battery industry and environmental concerns associated with battery use are covered in Section 4. We explore the shortcomings and unresolved issues regarding current storage systems in Section 5. The paper is finally concluded in Section 6, which also identifies potential future research directions.

2. Issues and Objectives

The capacity to store electrical energy to ensure the balance between production and consumption at the various levels of a given network and under acceptable technical, economic, and media conditions is an essential prerequisite for the massive and sustainable development of intermittent renewable energies. The amount of power consumed and the amount of electricity produced and imported to the electricity network must always be equal. This process has become considerably more difficult as a result of the rise in the production of renewables, which fluctuates depending on the weather. Conventional power plants must now compensate for these changes. Otherwise, the operating frequency of electricity network can fluctuate. The typical operating frequencies for the European and North American networks are 50 Hz and 60 Hz, respectively. However, the electrical frequency rises if the network is supplied with more electricity than is required. On other hand, the frequency declines if the injection capacity is insufficient to match the demand. Such scenarios increase the chance that power plants will eventually disconnect from the grid because they are built to operate within a specific frequency range. Generally, this problem arises due to a lack of supply. To mitigate such scenarios, the automatic load-shedding strategy can be employed—after certain operating frequency variations occur—to prevent a blackout, because if the frequency drops to too low of a level, power plants start to shut down successively until the network completely collapses, causing a blackout.

These issues concern all stakeholders, and the solutions implemented should facilitate the addressal of the various issues and objectives targeted by each [35–37].

- Network Managers:
 - I. The existing infrastructure should be maximally harnessed, and the investments needed to strengthen the networks should be postponed until the latest possible verification: A network of electrical distribution has many sources and recipients. An ideal network must adhere to a number of requirements, including minimizing ohmic losses, lowering building costs, and providing recipients the power they require even in the case of a partial anomaly in the network. The optimization of existing infrastructures to develop their networks, increase their lifespan, lower their costs, and limit their environmental impacts are the main priorities in this regard.
 - II. Intermittent energy production must be incorporated while ensuring that users are receiving a stable supply of electricity: The states of intermittent energy sources can vary greatly and rapidly; in a few minutes, the production of a wind or solar farm can be transformed from operating at maximal levels to producing almost no power. Note that on this level, wind power is more erratic than solar power. Critics of renewables blame intermittency for energy wastage, wearing out grids more rapidly (which increases maintenance costs), and, overall, being too complex to manage. It is in this context that the question of storage in the modern day generates new interest as an additional tool given to operators to manage production.
 - III. The balance between supply and demand must be secured by optimizing peak and demand response capacities: Electricity, for the moment, is characterized by the particularity of being unable to be stored in large quantities economically; thus, the quantity of electricity produced and injected into the

network must be equal at all times to the quantity of electricity consumed. Otherwise, local imbalances can be created and spread to an entire electrical grid, resulting in widespread blackouts that would be extremely disruptive and costly for a country's economy.

- For Producers with Intermittent Installations:
 - I. Optimize the sizing of installations by coupling intermittent production and energy storage: An increase in energy storage capacity is required to accommodate the growth of renewable energies (solar and wind), whose production is unpredictable and decentralized. However, there are still several economic, legal, and technical barriers preventing the widespread use of novel storage systems. This is why considerable research efforts are being undertaken globally.
 - II. Use storage as an arbitrage tool in the energy markets and hedge against medium and long-term economic risks: A severe economic catastrophe is being brought about by the scarcity of gas and electricity and their astronomical costs. Businesses are struggling to pay their bills, and worldwide power outages pose a threat to everyone's health and safety. In the affected neighbourhoods, power outages also mean that traffic lights at intersections, elevators in buildings, heating, computers, and telephones will not operate. Trains are also stopped, as are schools and companies that depend on electricity to run their machines. In other words, this situation constitutes a large, unpredictable mess.
- Industrial Consumers:
 - I. Electricity supply should be conserved in quantitative and qualitative terms: The foundation of the economy is the manufacturing sector. It consumes raw materials and energy to change them into compounds and goods. In addition to the indirect advantages of producing goods for human comfort, companies use a great deal of energy. Thus, the trends in energy consumption in the industry also significantly influence trends in overall energy consumption. Manufacturers are aware of the installations' inefficiency, but they are unsure of how to start and what steps to take to improve their overall situation.
 - II. Electrical energy storage must be integrated into activities and processes to generate load-shedding revenues: Solutions conducive to the achievement of energy intelligence are required to improve the energy characteristics of businesses. The contextualization of these data with organizational and production models is possible. For judgments to be made regarding energy use, these data are more valuable and more pertinent. To increase productivity and profitability, businesses need to determine the expenses associated with producing each product and alter their production accordingly.
- Territories:
 - I. Integrate energy storage as a component of a renewable energy development strategy: One of the essential elements of the integration of intermittent renewable energy sources such as solar and wind is energy storage. With the help of a reserve that fills up during periods of high output and empties during periods of low production, these renewables' fluctuations can be compensated. Globalizing energy storage also increases the prevalence of self-consumption scenarios, in which a home or community directly stores and uses the energy it generates.
 - II. Secure a territory's energy supply and reduce its dependence: The energy independence of a country or territory refers to its ability to meet all its energy needs without relying on imports in the form of primary sources or final energy. For many nations, renewable energy sources and their storage are the only options that are likely to progressively wean such nations off their reliance on foreign energy sources.

3. Why and How Should Energy Be Stored?

Globally, the primary energy production of 13,800 million tonnes of oil equivalent (Mtoe) is mainly attained via the consumption of fossil resources. Almost 80% of the 13,800 Mtoe is secured via fossil resources [49]. The percentage of contribution to the global level of energy generation by various energy sources is depicted in Figure 1. The figure displays that a significant portion of the energy is generated by the use of fossil fuels. However, this practice of energy generation is harmful to the environment. Therefore, the fight against global warming has become a major strategic issue. In 2015, the Paris Conference of the Parties (COP21) marked a turning point in this direction, wherein, among other things, historic decisions were made with respect to the objectives of reducing greenhouse gas emissions (GHGs) and carbon dioxide (CO₂) in the foreground. Reducing the emission of GHGs involves, on the one hand, reducing the consumption of fossil fuels, particularly in the field of transport (replacement of thermal vehicles), and, on the other hand, finding alternatives to thermal power plants (using fossil fuels) and nuclear fuels (for reasons linked to the problems of waste and safety) for the production of electrical energy [50,51].

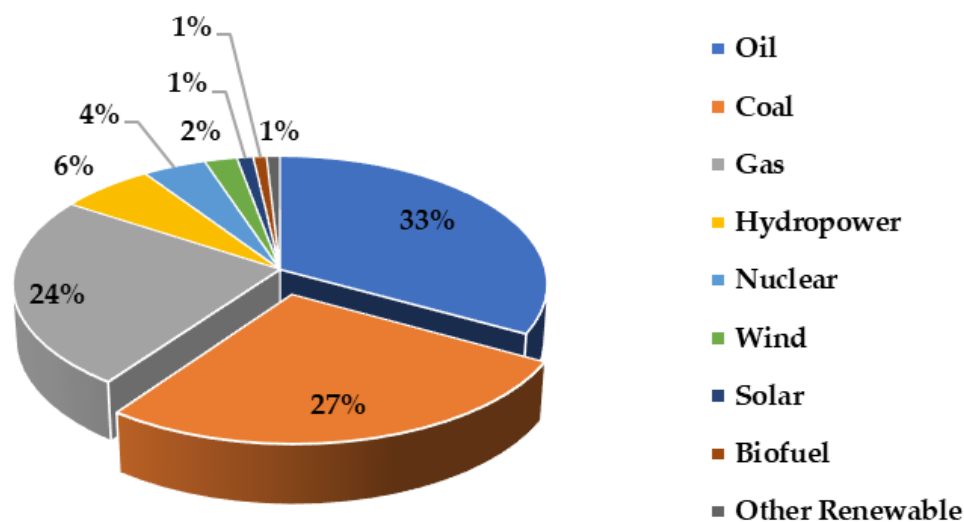


Figure 1. The percentages of global energy generation contribution by various energy sources.

Consequently, global concentration switches to renewable energies, mainly wind and solar, which are available in almost unlimited quantities. Their contribution to our energy supply is, therefore, set to progress rapidly. However, these two renewable energy sources suffer from a significant defect in that they are by nature intermittent; that is to say, they offer variable and discontinuous production over time, depending on the weather conditions or the day cycle. Therefore, we cannot rely purely on such sources to meet electricity demands [52]. Thus, it is illusory to consider lighting areas at night using electricity directly from photovoltaic panels since they can only produce light during the day. The electricity production by wind turbines is subject to the vagaries of the wind and cannot directly and continuously supply homes and industries with energy [53]. Therefore, alongside the development and improvement of renewable energy collection technologies, it is essential to develop suitable storage solutions to manage this gap between the production and use of electricity [54].

Another strategy to reduce the emission of pollutants into the atmosphere and the consumption of fossil fuels is to gradually replace internal-combustion-engine-powered vehicles with hybrid or fully electric motor vehicles. Since the energy storage unit is on board the vehicle, energy storage solutions are also essential [55,56].

Therefore, it is necessary to distinguish on-board storage systems and stationary systems. Depending on their uses, the specifications relating to the storage methods can thus be very different in terms of energy and specific power (compared to mass or volume),

cost, safety, and lifespan. To power a mobile (vehicle) or portable (computer, telephone, etc.) object, the weight and volume of the on-board storage system are essential parameters, to which must be added the lifespan and the level of security [57,58]. With regard to the static mode, the requirements in terms of mass and volume are much less restrictive. Still, given the large quantity of electricity to be stored, which can reach a few thousand-megawatt hours (MWh), the cost of the system (construction, instalment, and maintenance) and its lifespan are essential parameters. These considerations justify the extensive work conducted to assess these storage systems' costs and returns on investment [59].

The United States' energy storage requirements, for a period of six weeks, amount to 3.4 million Gigawatt hours [60]. This alarming percentage provides an idea of the challenge of establishing very-large-scale storage infrastructures (so-called massive storage), which is a condition essential for developing renewable sources of electricity for our energy consumption [60].

The studies in [61,62] have shown that large-scale, long-duration energy storage is necessary for the substantial decarbonization of electricity systems to support more prolonged periods of lower generation capacity or seasonal energy supply constraints.

3.1. Selection Criteria for Storage Techniques

The different storage solutions have characteristics that render them more complementary than competitive. Moreover, their degrees of industrial development are not at comparable levels of maturity [63,64].

3.1.1. Technical Criteria

- Available power and energy capacity. Combining these two criteria facilitates the definition of the energy/power ratio corresponding to the possible discharge time, which is often characteristic of a particular application.
- The reaction time is an indicator of the reactivity of the storage medium. Occasionally, it is preferable to define the speed of the rise and fall under load, which characterizes the reactive behaviour of the system more comprehensively.
- Efficiency, which is the ratio between stored and restored energy (expressed as MWh-OUT/MWh-IN).
- Lifespan is sometimes preferable to define in terms of the number of charge/discharge cycles admissible for technologies such as batteries.
- For other uses, other criteria must be considered, such as energy density (in MWh/kg or MWh/m³) for mobility.

3.1.2. Economic and Societal Criteria

- Investment and operating costs.
- Performance and environmental constraints.
- Geographical location and losses induced by transport.

3.1.3. Maturity Level

Finally, it should be noted that the levels of technological maturity of energy storage solutions vary greatly. Several possibilities are currently being evaluated. Significant research and development efforts mobilize both public and private institutes and equipment manufacturers providing solutions and operators of electricity or heat networks.

3.2. Energy Storage Approaches

Figure 2 shows an overview of the energy storage technologies discussed in the study [65]. The selection criteria for the storage techniques were discussed in the previous section, and different energy storage approaches are described in the following subsections. In addition, as per [44], the mechanical storage approaches with respect to electricity are described in Section 3.2.1.

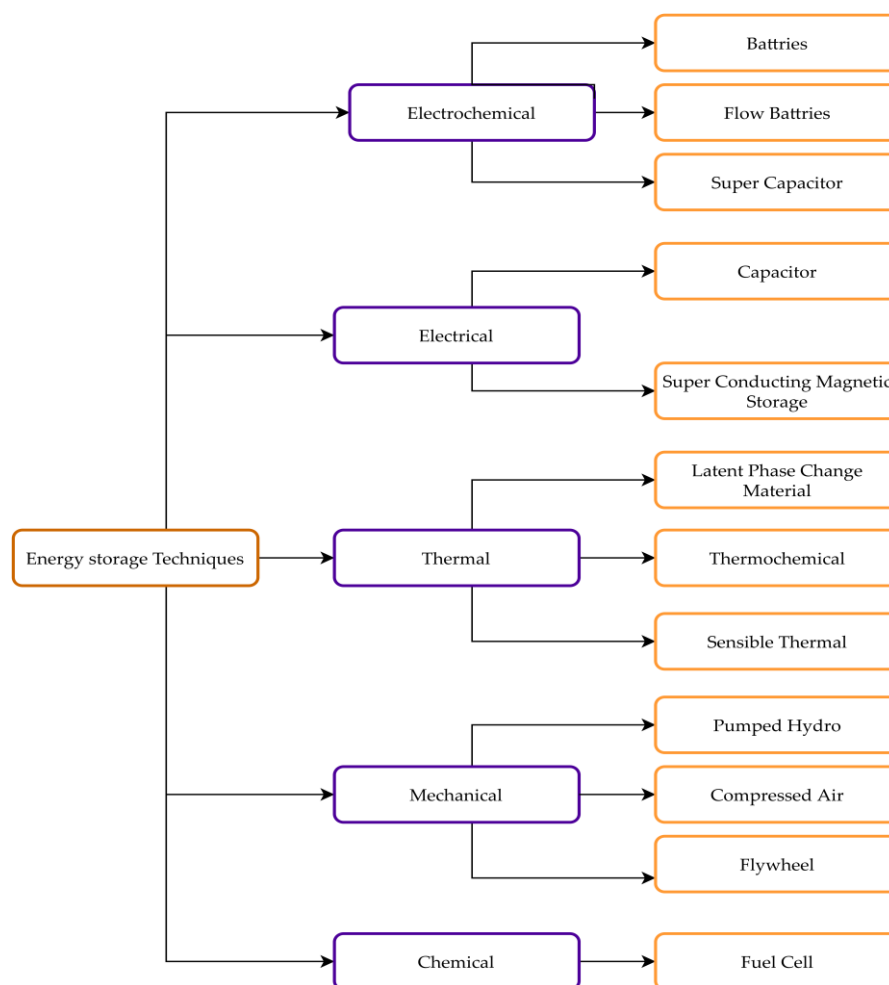


Figure 2. Categories of different energy storage technologies.

3.2.1. Mechanical Storage of Electricity

Today, the mechanical storage of electricity is mainly achieved through three different technologies that use potential energy (hydraulic storage), kinetic energy (flywheels), and compression [44].

Pumped Energy Transfer Stations

An energy transfer station that operates via pumping consists of the circulation of water between two reservoirs, either natural (rivers, sea, or ocean) or artificial (dam lakes), that are close but located at different altitudes [66]. The quantity of energy stored is proportional to the amount of water contained in the highest reservoir and the difference in the level between these two water reserves. It is by far the most widely used solution because it enables the mechanical storage of large quantities of electrical energy in the form of potential energy during periods of overproduction.

These stations are equipped with reversible, so-called “synchronous” hydroelectric groups: in the energy storage phase, they operate as a pump–turbine assembly, consuming electricity to pump water from the lower basin to the upper basin; in the energy release phase, they work in a “turbine-alternator” mode, thus producing electricity when transferring water to the lowest reservoir. The process is depicted in Figure 3.

This type of storage has been used since the end of the 19th century and is known as hydraulic storage. It is based on mature technology with a long lifespan (concrete structures). It is flexible because it responds in almost real-time (with the delay being caused by the opening time of the valves) to high power demands from the power grid. Although the current level of investment to build these large-scale structures is very high, the large

quantity of energy they can accumulate and their lifespan (more than forty years) render them the optimal storage option available today. Additionally, they are less expensive (in EUR per kWh and charge/discharge cycle). However, their development is limited by geographical solid and ecological constraints. Some 250 wastewater treatment plants (WWTPs) distributed worldwide (enabling the storage of more than 160 GW) alongside the number of construction projects that will be undertaken by 2040 represent only around 30 GW of additional power.

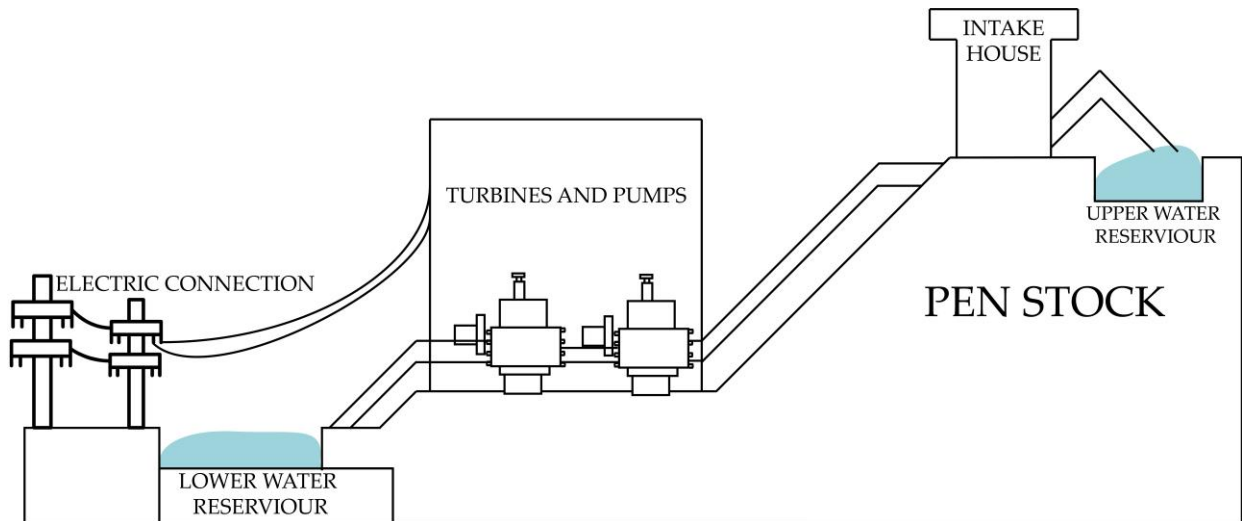


Figure 3. The main components of a pumped energy transfer station.

Flywheels

Flywheels convert excess electrical energy into a kinetic form through a mass (usually a cylinder) that rotates around an axis in a vacuum chamber to limit energy loss by friction [67,68]. The rotational kinetic energy of the cylinder is then converted back into electrical energy. This is an ancient technology that is used in steam engines to smooth their movement. It delivers high power with a brief startup time (a few seconds) and a very long lifespan. The following significant drawbacks of this device explain its low contribution to electrical storage: limited mass-energy density (around 5 to 10 Wh/kg); strong self-discharge by friction, resulting in low energy efficiency, which only allows for short storage times; and a limited amount of stored energy. The process is depicted in Figure 4.

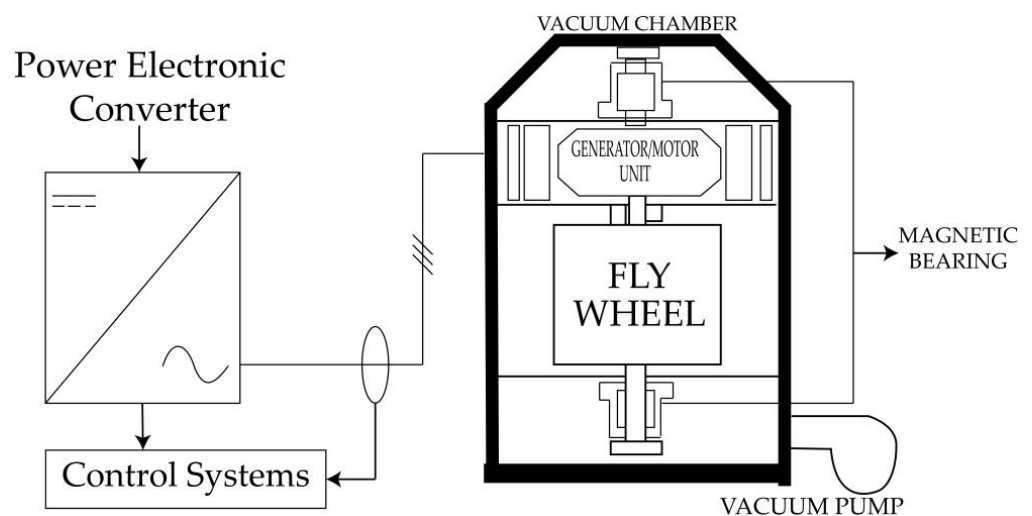


Figure 4. Flywheel-based energy storage principle.

At one point, the use of flywheels was considered in the transport field. Thus, gyro buses, developed by a Swiss company, and having been rolled out in the 1950s, were equipped with an electric motor powered by a large steel flywheel that recharged at the stops of the bus lines. However, security problems considerably limited its use in this area. The flywheel, however, met with some success in Formula 1 with the introduction of the kinetic energy recovery system (SREC or KERS (Kinetic Energy Recovery System) in English), which enables the storage of the energy recovered during braking to provide extra power to cars when overtaking. In the mid-2010s, Volvo proposed the use of a flywheel to power an electric motor in addition to a heat engine (S60 Fly Brid model), but this application did not meet with the expected success.

Compressed Air

Compressed Air Energy Storage (CAES) is developing rapidly [69,70]. These systems' energy efficiency is relatively low. Their operation consists of storing air in underground caverns (former salt mines or natural gas storage caves) using a compressor during intense demand, and then releasing this compressed air during high-consumption periods to power turbines that generate energy. The principal components of the CAES are displayed in Figure 5.

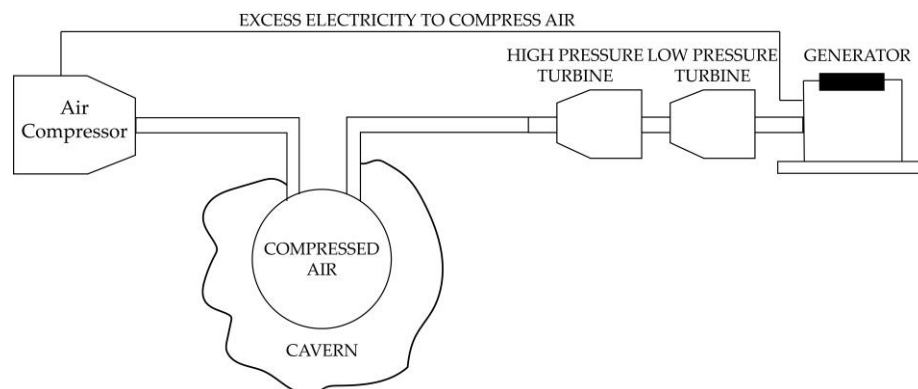


Figure 5. The principal components of a CAES station.

The two problems posed by their development are as follows:

- The heating of gas during compression. Currently, thermal storage systems are being developed to recover heat (adiabatic storage).
- The number of sites (caves, old mines, etc.) for which good sealing performance is necessary versus the existing natural gas storage facilities.

3.2.2. Thermal Solutions

Thermal storage facilities [71,72] (heat and cooled air) mainly concern the industrial and tertiary markets with achievements on the order of 1 to 10 MW, heating networks, and the residential market through domestic hot water tanks. It should be noted that heat storage mainly concerns buildings' heating (or air conditioning), representing nearly 50% of European energy consumption, for example.

There are two critical factors for the materials studied:

- Thermal inertia (sand, concrete, ceramics, etc.);
- The ability to withstand very high temperatures.

These facilities offer significant potential in terms of competitiveness for tertiary and industrial activities and in terms of their impact on peak electricity demand. Indeed, by storing heat or cooled air during periods of low electricity demand, the potential for shifting power calls is significant. Heat storage enables the optimization of the sizing of installations in heating networks, particularly with respect to the extension of existing networks. The main elements of a thermal energy storage system are displayed in Figure 6.

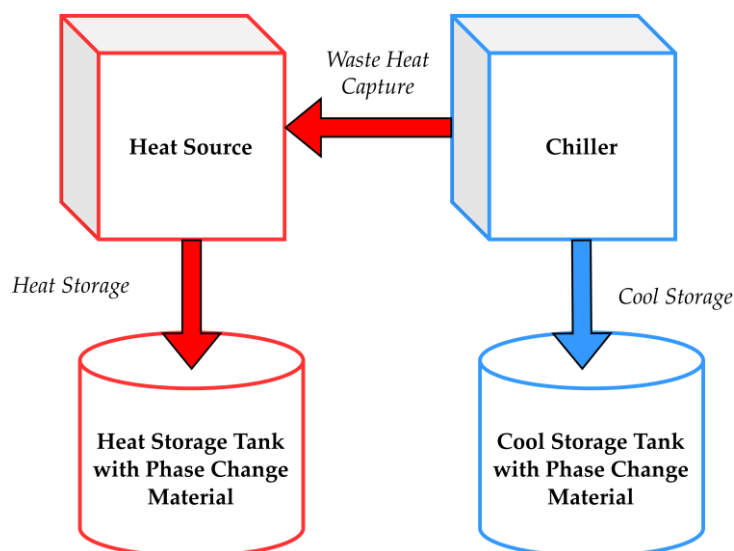


Figure 6. The main elements of a thermal energy storage system.

Today, heat storage in domestic hot water tanks corresponds to a fleet of several million installations, representing a power demand of several gigawatts. This power demand is predictable and controllable, which enables the shifting of this power demand in a programmed manner.

Another solution being studied is heat storage linked to thermodynamic solar power plants, which consists of concentrating solar radiation on a receiver to heat a heat transfer fluid to a high temperature that will thus activate a heat generator directly or after the storage of electricity through a turbine [73]. Different types of heat transfer fluids are studied, but molten salt seems to be the most promising. Thus, in 2008, the Andasol 1 solar power plant was the most potent thermodynamic solar power plant in Europe, producing 50 MWe. Two identical extensions (Andasol 2 and Andasol 3) have been completed and commissioned [74].

The Andasol 1, 2, and 3 solar power plants, located in Andalusia, are each equipped with a thermal storage unit that absorbs part of the heat produced during the day to restore it at night or during cloudy periods, thus practically doubling the number of operational hours in a year. The entire thermal reservoir represents a reserve of 1010 MWh of heat, which is sufficient to operate a turbine for 7.5 h at full load (50 MW per plant) when it rains or after sunset. Each plant's thermal capacity is represented by two tanks of 36 m in diameter and 14 m high, each storing 28,500 tonnes of salts consisting of 60% sodium nitrate and 40% potassium nitrate (melting point 221 °C) and operating between 291 and 384 °C. The tanks work in a push–pull configuration, with one tank in the filling phase (heating) and the other in the emptying phase (cooling). They take or restore energy to the heat transfer fluid via exchangers [75].

3.2.3. Supercapacitor-Based Energy Storage

A supercapacitor (SC) is an electrochemical device with two porous electrodes, an ion-exchange membrane between the two electrodes, and a potassium hydroxide electrolyte. An SC shares many physical principles with a regular capacitor. In other words, the capacitance depends on the effective area of the plates, the distance between the electrodes, and the separating medium's dielectric constant. However, an SC's liquid electrolyte structure and porous electrodes significantly increase its surface area compared to traditional capacitors. Additionally, a high value of specific capacitance is generated in SCs via the development of a double layer that is very thin [76,77].

To meet the high voltage and power demands of applications for renewable generation, hundreds of SCs are often linked in series because of an SC cell's comparatively low voltage

and capacity. The typical structure of an SC-based energy storage device in a generating system is shown in Figure 7.

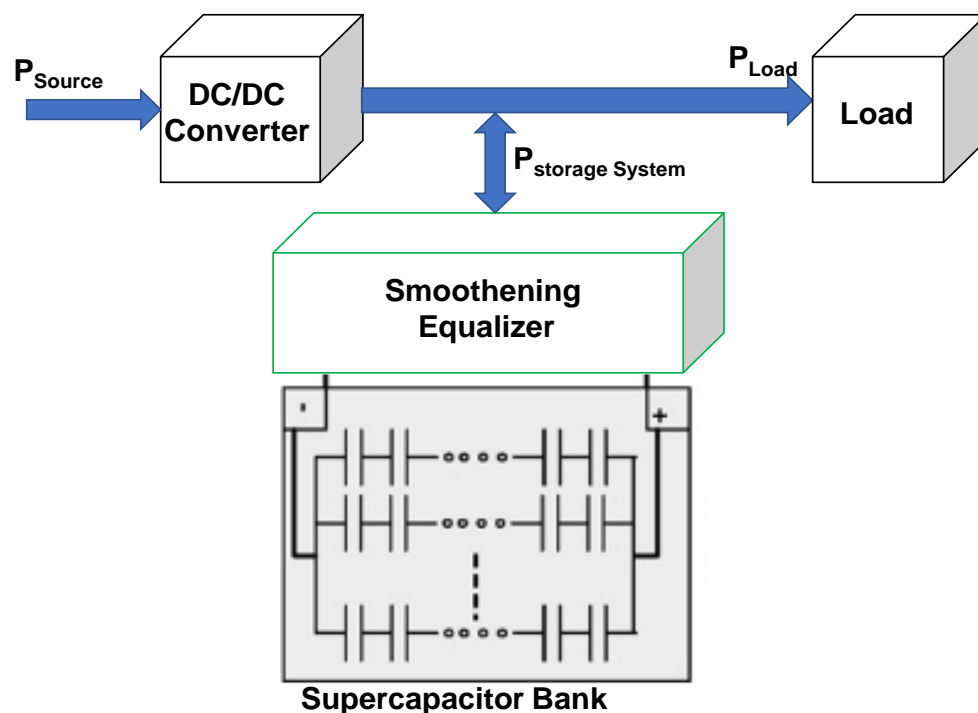


Figure 7. The structure of an SC-based energy storage device.

3.2.4. Hydrogen Storage

The use of hydrogen presents additional difficulties, but it also allows for the transition away from fossil fuels [78]. It is distinguished by its storage capabilities and potential for flexible and effective energy conversion [79,80]. Hydrogen can be employed as a raw material, fuel, energy source, or medium for energy storage [81]. There are no CO₂ emissions produced by its combustion [82] and it causes little air pollution [83]. The use of hydrogen facilitates the decarbonization of industrial processes [84] and processes in those economic sectors where it is challenging to reduce the CO₂ emissions [85].

3.2.5. Electrochemical Energy Storage

As renewable energy sources, solar and wind energy are widely promoted and used worldwide to cost-effectively provide power in accordance with an envisioned environmentally friendly future society [86]. However, their duration and scope are restricted. Therefore, it is necessary to develop adequate electrochemical energy storage (EES) devices that are both environmentally friendly and capable of providing long-term energy [87,88]. Rechargeable batteries and supercapacitors (SCs) stand out among all EES devices due to their superior energy storage performance [89–92]. According to studies [93–96], the electrochemical storage properties of their electrodes can be further optimized to meet the swiftly growing demand for energy, and their energy storage efficiency can be improved by improving their electrode materials. To enhance EES devices, it is essential to investigate new electrode materials that offer superior electrochemical performance at a lower cost and a long cycling life [97–99].

The principle of electrochemical energy storage is depicted in Figure 7. The transformation of chemical energy into electrical energy in electrochemical storage systems is reversible. In a charging process, reduction processes transform and store electrical energy into and as chemical energy, respectively. In contrast, oxidation processes at the electrodes transform chemical energy into electrical power during a discharging process. These gadgets have two electrodes that generate electrochemical

oxidation–reduction processes, which enable the storage of an electric charge and serve as vectors for the electric current density. These devices also consist of an electrolyte medium, which requires a high electric resistance value to ensure the conduction of electrons via the external electric circuit, through which an ionic charge moves from one electrode to the next. Finally, each electrode material’s current collector should have excellent electrical conductivity. In Figure 8, the electrochemical device’s operating principle is schematically illustrated during the discharging phase.

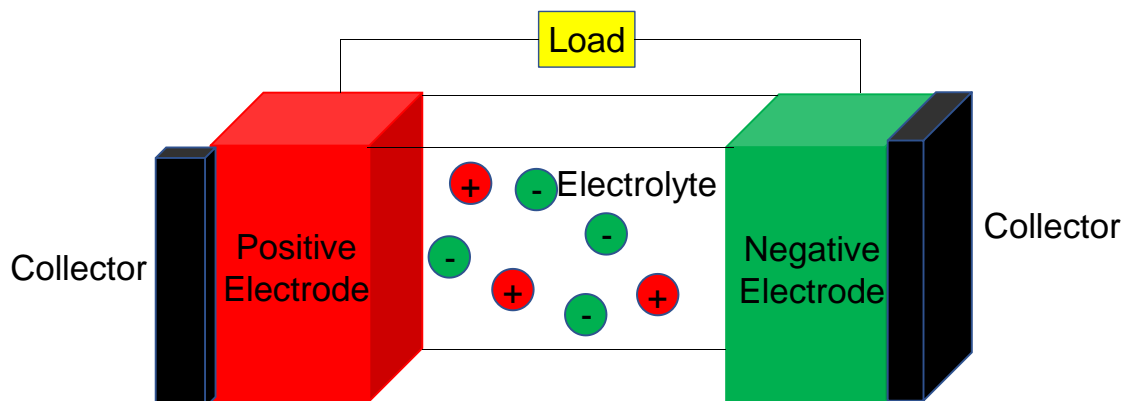


Figure 8. The principle of an electrochemical energy storage system.

The use of lightweight, high-energy-density, and long-cycle-life batteries as EES devices has received a great deal of attention [100,101]. So far, these devices have been extensively utilized in energy-related applications such as portable electronic devices and hybrid electric vehicles. However, these batteries need to be improved in terms of their safety, energy density, service life, and rate performance. Electrodes significantly impact batteries’ electrochemical performance as essential components of rechargeable batteries [102]. It is difficult to find materials with high-performance electrodes that can be used in batteries.

As a result, it is crucial for materials science research to investigate novel materials with improved performance at lower costs that can be used for battery electrodes. Figure 9 shows the number of related publications published from 2010 to 2020 [103]. It confirms that based on the frequent deployment of Lithium-ion batteries in multiple applications, the researchers have undertaken a significant number of studies on this technology.

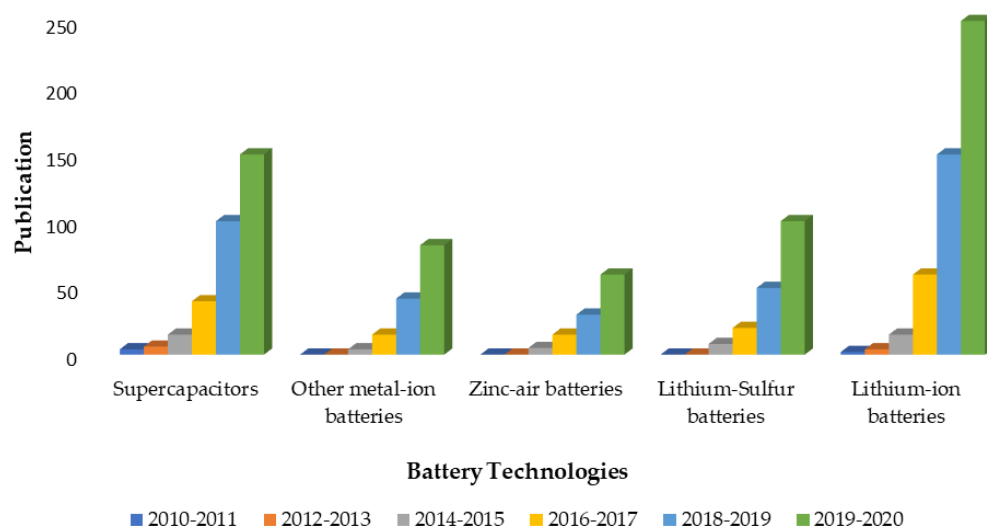


Figure 9. No. of publications on different battery technologies.

4. Batteries

Based on the above literature review, it is evident that the usage of electrochemically based energy storage systems and particularly the deployment of batteries are more frequent and vaster compared to the counter energy storage mechanisms (cf. Figure 9). Therefore, in the following subsections, we focus on the usage of batteries, types of batteries, their environmental impacts, state estimation solutions for battery packs, and battery management systems.

4.1. Uses of Batteries

Batteries are the small but crucial components that enable many devices to function. They have evolved into one of the essential elements of our daily existence. Some batteries can be recharged, and these are utilized in almost every industry. The list below includes several battery applications [104,105].

- **Home Battery Use:** Many household appliances depend on batteries; for instance, disposable batteries power items such as torches and remote controls. Rechargeable batteries, such as alkaline batteries, are used in various devices, including mobile phones, handheld video game consoles, digital cameras, and many more. Modern batteries such as lithium batteries power excessively power-hungry appliances such as computers and other gadgets.
- **Battery Use in Medical Devices:** Batteries are used in various forms of medical equipment. Such battery-operated devices include artificial limbs, insulin pumps, hearing aids, and valve support devices. Electronic gadgets such as real-time appliance clocks and photographic light meters also benefit from the use of mercury batteries.
- **Battery Use in the Medical Industry:** Batteries are utilized extensively in the medical industry. The battery-operated electrocardiogram (ECG) heart monitor may move with the patient and is always on to display the patient's vital signs. Hospitals typically use rechargeable batteries such as lithium-ion and nickel–cadmium batteries.
- **Battery Applications in Construction and Logistics:** Heavy-duty batteries are used to power machinery such as forklifts because combustion, which produces carbon monoxide and exhaust fumes, can be hazardous in small areas. Lead–acid batteries are the type of batteries used in autos.
- **Battery Use in Emergency Response and Firefighting:** Radios that are essential for emergency response require batteries. These radios cannot store oversized charges without hefty batteries. ECGs, lamps, and even metal and fire detectors utilize batteries. These tools save lives daily.
- **The Use of Batteries in Military Operations:** High-energy and power-density-batteries are frequently used in military activities. Radios, which are used for communication, consume batteries. Batteries are used to power various field devices, including infrared goggles. While silver oxide batteries are utilized in missiles and submarines, lithium batteries have a significantly longer lifespan for electronic equipment.
- **Using Batteries in Vehicles:** Electric vehicle batteries (EVs) are extensively utilized in automobiles. This type of battery powers the electric motors in electric vehicles. Batteries for electric cars are frequently rechargeable. Lithium-ion batteries are usually used in electric vehicles.
- **Using Batteries in Renewable Energy Plants:** Given the intermittent nature of renewable resources such as solar and wind, it would be beneficial to have a way in which to store this energy so that it can be used when it is needed. In Figure 3, this concept is presented [106].
- **Using Batteries in Wearable Electronic Devices:** Sensory, communication, and digital entertainment functions can be applied to clothing and accessories. There are various typical examples, including smart watches, smart glasses, smart clothing, heart rate monitors, fitness trackers, and so on [107].

According to batteries' usage and chemistries, the global battery market share in 2019 is projected in [108]. The statistical values are shown in the upper row of Figure 10. Further details on the secondary batteries market share are shown in the lower row of Figure 10.

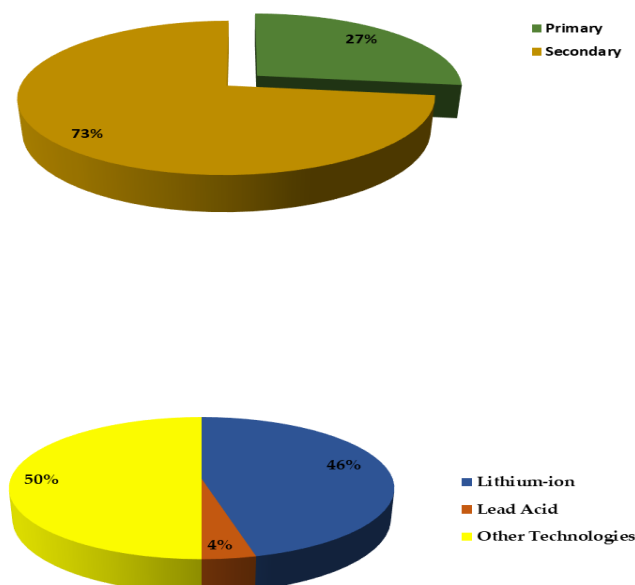


Figure 10. Market share of various types of batteries worldwide.

4.2. Different Types of Batteries

The history of rechargeable batteries [109] began with the development of the lead–acid accumulator (whose unit voltage is 2 volts) by the physicist Gaston Planté in 1859. Originally composed of two sheets of lead immersed in a solution of sulfuric acid and charged using Daniel batteries, this accumulator quickly evolved to be able to serve, from the end of the 19th century, multiple applications (e.g., lighting, the storage of energy produced by a dynamo, etc.), including the production of electric vehicles. Lead–acid batteries quickly reached an energy density of 30 watt-hours per kilo (Wh/kg), which, although modest (due to the high molar mass of lead, which exchanges 2 moles of electrons for 217 g per mole), renders this composite one of the most widely used accumulators due to its low cost. The development of accumulators operating in an alkaline medium with the development of positive electrodes in nickel oxyhydroxide (NiOOH), has facilitated the increase in this energy density to more than 70 Wh/kg by first combining this nickel electrode with a negative electrode of cadmium (Chemistry Ni/Cd), and then with a hydride alloy MH (Chemistry Ni/MH). However, the cell voltage remained modest (around 1.6 V). A significant scientific breakthrough appeared in the early 1970s with the marketing, twenty years later, by Sony of Lithium-ion batteries. This chemistry combining ligated lamellar oxides and a carbon electrode has enabled a technological breakthrough in the race for superior energy density.

It is interesting to study the theoretical energy densities of some electrochemical storage systems based on their thermodynamic and chemical data. For example, lithium is a light element (7 g/mol) that can exchange an electron at a meagre potential of -3.04 V with a Standard Hydrogen Electrode (SHE). Therefore, it is a perfect candidate metal for a negative electrode. Still, its redox potential is so low that water is unstable under these conditions, implying that the electrolyte is based on an organic solvent. The lithium-ion batteries marketed today use intercalating materials. They have a cell voltage of 3.8 V for a specific energy of about 200 Wh/kg. Oxygen (a couple of O_2/H_2O in an aqueous medium) has a high potential of 1.2 V vs. SHE and can exchange two electrons for a modest molar mass (16 g/mol). Therefore, it is an excellent positive electrode material. Its association with a zinc (Zn) negative electrode (2 moles of electrons exchanged for 65 g of Zn, with a potential of -0.76 V) to form a Zn–air system in an aqueous medium seems promising at

the level of theoretical energy density. Still, the performances achieved are more modest, and their recharging is limited to only a few cycles.

There are two different systems used in a non-aqueous medium: lithium–sulphur (LI–S) and lithium–air (Li–air) systems [90,110,111]. A lithium–sulphur system uses metallic lithium as the negative electrode and sulphur (S), which can be reduced by capturing two electrons using a non-aqueous electrolyte. With a modest voltage (2.2 V), a high mass capacity compensates for the potential difference between sulphur and lithium (two relatively light materials), thus rendering this system a promising candidate for the next generation of batteries.

The association of a negative electrode of lithium with a positive electrode where oxygen reduction occurs, called the Li–air association, is the electrochemical storage system that presents the highest theoretical energy densities (where high corresponds to more than 3.5 kWh/kg).

Today, advanced Li-ion batteries [112,113] have a practical energy density of around 200 Wh/kg, which is particularly due to new materials such as silicon placed at the negative electrode. Considering potential improvements in material capacity, electrolytes, and packaging, the energy density should reach 300 Wh/kg. Prototypes of LI–S technology now demonstrate more than 300 Wh/kg, but their cyclability still needs to be improved. Indeed, this is not yet satisfactory, but avenues exist, and solutions have been proposed in recent communications. It is estimated that a LI–S battery should achieve an around 500–600 Wh/kg performance, which would provide a range of over 400 km for an electric vehicle such as the Nissan Leaf.

The most likely choices for the next generation of energy storage devices are solid-state batteries (SSBs). Solid electrolytes (SEs) can be used in place of liquid electrolytes to improve safety by preventing combustion, and energy density can be enhanced by deploying more evolved electrodes [114,115].

The last system, the Li–air system, has the highest energy density, with 500 Wh/kg demonstrated at the prototype level and estimates on the order of 900 Wh/kg achievable. However, unlike the chemistry of LI–S, many scientific locks block their development. Recent results published in the literature do not encourage optimism regarding the chances of the short-term success of this system. It does not seem reasonable to expect commercial products to offer such performance and a lifetime in cycling before, at best, fifteen years.

Figure 11 displays the income contributions made by various battery technologies. It shows that lithium-ion batteries account for 40% of all sales of batteries used in portable electronics and electric vehicles [116]. Currently, no alternative systems exist that might challenge these batteries' hegemony.

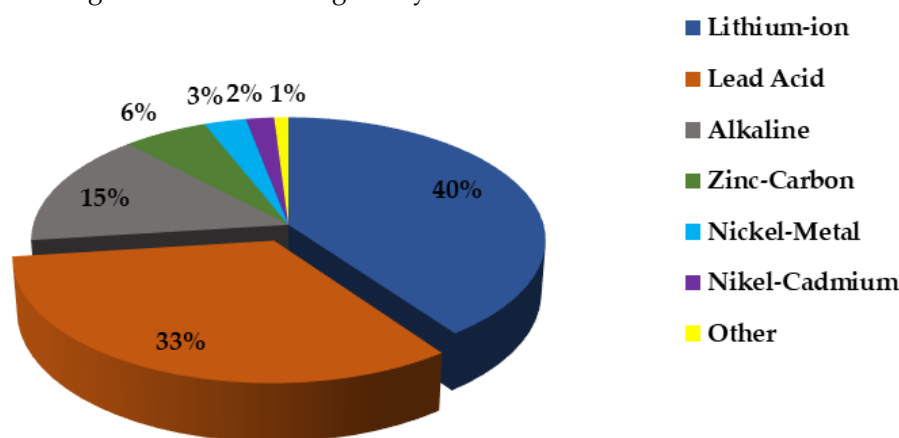


Figure 11. The income contributions made by various battery technologies globally.

Figure 12 represents the life and efficiency of Pumped Hydroelectric Storage (PHS), Compressed Air Energy Storage (CAES), nickel–cadmium (Ni–Cd), lithium-ion (Li-ion),

sodium–sulphur (Na–S), sodium–nickel chloride (Na–NiCl₂), Vanadium Redox Batteries (VRB), and zinc–bromine (Zn–Br₂) batteries [117].

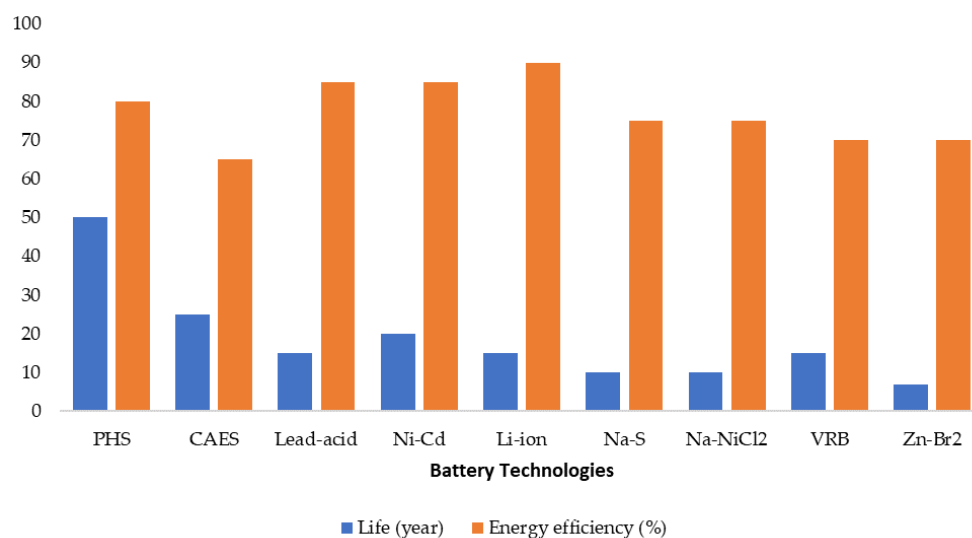


Figure 12. Life and efficiency comparison of different battery technologies.

4.3. Batteries for Electricity Storage

All the just-described systems with the highest energy densities are essential for transportation. In stationary applications, such as the bulk storage of power from renewable energies or the electrification of dwellings, the criteria for selection are entirely different. The absence of mass or volume constraints in these stationary applications renders the concepts of Wh/kg and Wh/L meaningless. In addition to safety, the factors for selection are recyclability (durability) and affordability. Even if cost—like security—is a constraint common to all applications, this criterion is paramount. Historically, the first batteries to be used on a large scale in stationary applications (such as backup batteries) were lead–acid batteries. They are gradually being replaced by sodium–sulphur (Na–S) batteries operating at high temperatures (300 °C). Batteries with a power of several megawatts are currently in operation around the world, mainly in Japan.

Another technology for large-scale energy storage has been studied for several years: flow-through batteries [118,119]. These batteries store energy in electrolytes that contain soluble redox couples; these anodic and cathodic electrolytes are stored in reservoirs that can reach several hundred or several thousand litres. To discharge the battery and thus provide energy on demand, the anodic and cathodic electrolytes are pumped and circulated inside a cell core, in which oxidation–reduction reactions will release the energy. These systems have the significant advantage of allowing for the simple control of the amount of stored energy since it is directly proportional to the size of the reservoirs.

On the other hand, there are still some questions about these systems' durability (corrosion linked to the nature of the electrolytes used, the risk of an undesired mixture of electrolytes, etc.) and their cost [120]. This lack of hindsight is explained by the difficulty of obtaining feedback on these large-scale installations, which are difficult to establish unlike Li-ion technologies, whose development was based on mass applications in small formats, such as in telephones or laptops. Therefore, the result of the circulation batteries remains to be determined. Still, it will be necessary to wait a few more years before being able to draw conclusions regarding the performance of the many examples in use.

The replacement of lithium ions with sodium ions [121], for which the raw material is ten times less expensive, allows for substantial savings on the price per kWh. However, if this approach is promising in theory, the development of the Na-ion battery has long been challenged by the strategy of simply duplicating materials with the intercalation of Li⁺ ions to make materials with the intercalation of Na⁺ ions. However, the recent development of new Na⁺ ion-intercalated materials has shown that despite a 30% decrease in energy

density compared to the Li-ion process, the Na-ion battery could play a role in stationary applications because of its reduced cost.

To complete this overview of electrochemical energy storage, we will discuss supercapacitors [76,77], which are intermediate systems between conventional capacitors and batteries. They can provide very high power densities (>10 kW/kg) with a modest energy density (6 Wh/kg), which corresponds to a time constant ranging from a few seconds to a few tens of seconds. This performance is linked to the mode of storage of the charge. No redox reactions occur in these supercapacitors because the storage is carried out by electrostatics via the adsorption of ions from an electrolyte on the surface of porous carbons with a highly developed character, thus charging the electrochemical double layer.

The capacitance of this electrochemical double layer is on the order of 10 to 20 $\mu\text{F}/\text{cm}^2$ (microfarad per cm^2). By replacing a flat electrode with a porous material with a large specific surface such as activated carbon (1000 to 2000 m^2/g), capacities of more than 100 F/g of carbon are achieved. The maximum voltage of these cells is limited by the decomposition of the electrolyte, namely, 2.7 to 3 V in non-aqueous electrolytes. The storage of charges on the surface explains the incredible power of these systems compared to batteries. The absence of volume variation in the electrodes during the cycles (wherein the charge remains on the cover) means that the cyclability of supercapacitors can reach several million cycles at room temperature. Finally, solvents such as acetonitrile allow for operation between -40 °C and $+70$ °C. Remember, however, that the energy density is about 30 times lower than that of batteries.

Supercapacitors are used to provide power peaks or to recover energy. They are found on a small scale (<100 F) in power electronics (uninterrupted power supply (UPS), power buffers, etc.). Larger structures (>100 F) are used in aeronautics (e.g., the Airbus A380), automotive products (e.g., the recovery of braking energy), transport (tramways, buses, boats, etc.), port cranes, etc. They also enable, in conjunction with the properties of the batteries employed, an increase in the latter's lifetime by providing the most restrictive power peaks for the battery. Today, the main challenge involves increasing the energy density of supercapacitors; current research is directed towards the design of new porous carbons by controlling the size of the pores and the development of new high-potential electrolytes (for example, based on ionic liquids), or even the use of nanostructured two-dimensional redox materials with exacerbated reaction kinetics.

Improving the performance of batteries and supercapacitors requires the synthesis of new high-performance materials, better control of material/electrolyte interfaces, and the development of structural characterization and mathematical modelling tools.

Power-electronics-based converters connect battery storage systems to an AC distribution grid. Power-Conditioning Systems (PCSs) account for a small portion of the total costs in storage systems based on lithium-ion and lead–acid batteries, as shown in Figure 13 [122].

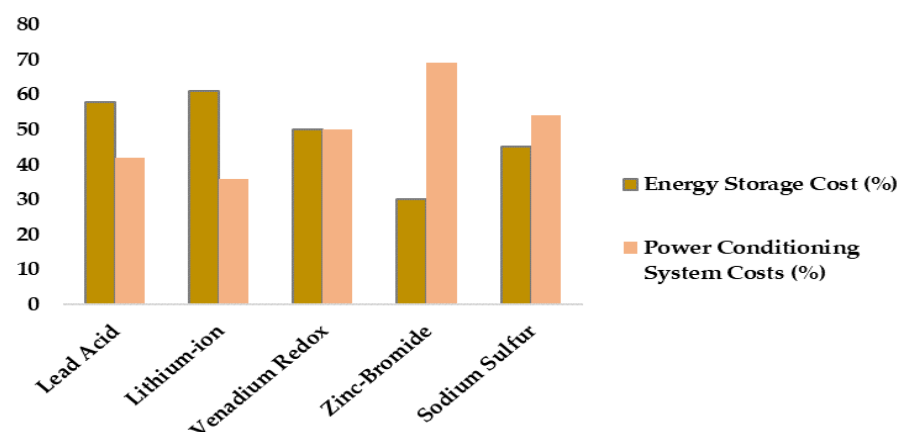


Figure 13. Power-conditioning system costs.

4.4. Environmental Impact of Batteries

Depending on their application and composition, the environmental impact of batteries varies significantly [123–125]. The purer the lead that a lead–acid battery contains, the higher its quality. While countries such as India and China rely on renewable energies such as solar power, the option that appears to be the most environmentally friendly has severe collateral consequences. The reason for this is the lack of distribution networks in these nations, which forces them to store their energy in lead batteries.

In 2011, the solar energy sectors of China and India had already released almost 2.4 million tonnes of lead into the environment, accounting for roughly a third of this element's total global production. Concurrently, China shut down 583 lead–acid battery companies in response to the contamination of adjacent villages, because if lead has a substantial impact on the environment, it also impacts human health [126]. In addition to causing memory loss, lead exposure can also harm the cardiovascular system. It can induce miscarriages and early deliveries in pregnant women.

Globally, lithium batteries are found in many consumer products. The economic stakes are fairly appealing for the countries supplying this metal, particularly Australia, Chile, Argentina, Bolivia, Tibet, and Afghanistan [127,128]. However, the extraction of lithium, which uses a great deal of water, causes other issues, such as soil contamination and the depletion of water sources.

The Swedish Research and Environment Agency sought to determine the carbon footprint of a lithium-ion battery by combining the findings of approximately forty worldwide studies [129]. According to the organization, each kilowatt-hour of energy the batteries created would generate the equivalent of 150 to 200 kg of carbon dioxide (CO₂)—a figure based on a worldwide energy mix dominated by fossil fuels (50 to 70 percent of produced electricity). According to this calculation, constructing a 30-kilowatt-hour battery would generate approximately 5 tons of carbon dioxide, whereas the average Tesla car would exceed 17 tons. Figures that differ from those reported by the agency for environment and energy management (ADEME) in 2013 (9 tons of CO₂ for an electric car and 22 tons for an internal combustion engine) accounted for the complete battery life cycle.

According to Battery Council International, 99 percent of lead–acid batteries, the most used batteries available, are recyclable. After the plastic container of this type of battery has been shredded into small bits, both the lead and the plastic can be recovered. As for the electrolyte, the acid-and-water-based liquid at the battery's bottom can be recovered and reused as such by a portion of the industry, or it can be decomposed by removing the water so that only the acid is ultimately utilized. The delivery of new batteries is paired with the collection of old batteries for recycling, which is more crucial given the significance of the carbon footprint of transportation.

As with all other things we consume with a high carbon footprint (smartphones, etc.), we must endeavour to extend the battery life as feasibly as possible to lower our carbon footprint. Studies indicate that, depending on the country of production of the batteries and their energy mix, an electric vehicle must travel between 25,000 and 150,000 km before it becomes less polluting than a diesel or gasoline vehicle. In addition, the typical lifespan of a car battery is five years. However, its longevity varies based on numerous factors, of which the most prominent is the date of purchase. When utilized immediately after leaving the factory, a battery's performance is at its peak, which is why an original battery always lasts longer than a spare battery or one that has been stored for an extended period.

Therefore, batteries need to be safeguarded by avoiding high temperatures, for instance. The most effective solution is still to minimize the usage of battery-based items, especially by preventing the excessive use of automobiles via regulatory measures. Note, however, that a viable option, sodium-ion batteries, is on the horizon. They consist of no harmful chemicals or heavy metals, have a 10-year lifespan, and are “Cradle to Cradle”-certified.

The use of batteries should also be selected based on their ease of recycling. The collected %age of the weight of different battery types recycled in 2013 is shown in Figure 14 [130].

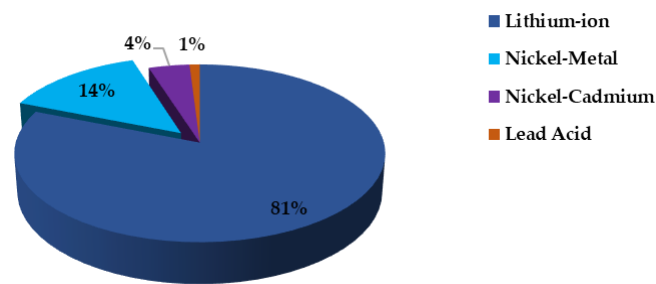


Figure 14. The collected %age of weight of different battery types recycled in 2013.

4.5. Battery Management System (BMS)

Since a battery is a complicated nonlinear system with many state variables, the only way to manage and control such a system is to estimate its states accurately. The theoretical approaches to assessing battery state are systematically summarized in this section from the following four perspectives: the estimation of the remaining capacity and energy, power capability predictions, lifespan, and health predictions, as well as other important BMS indicators.

A battery’s eyes and ears should be in a battery management system (BMS), as shown in Figure 15 [131]. It must act as a watchdog, take precautions, and shield itself from mishaps. Voltage and current control, thermal management solutions, fire protection, and cybersecurity are all standard BMS functions related to battery safety and security. In this section, we will overview the most common threats to a battery and how a BMS can address them.

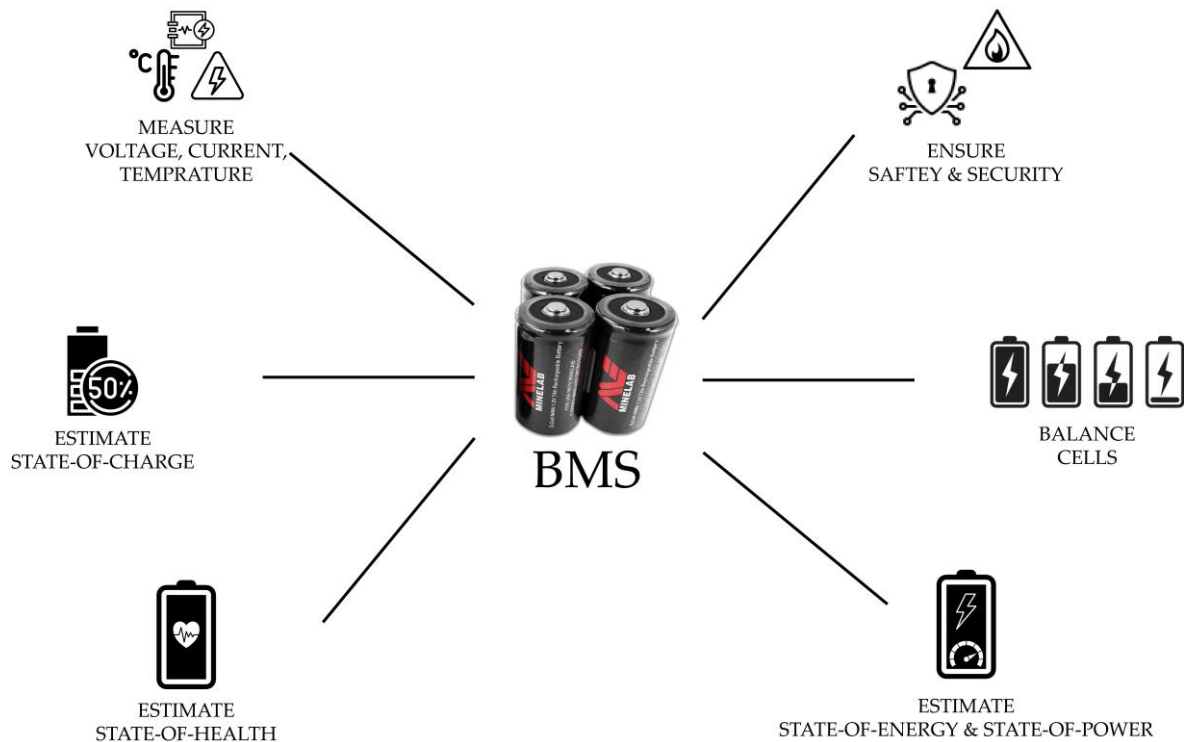


Figure 15. The principle of BMS.

The key modules in Figure 15 are described in the following. The state of charge (SOC) cannot be determined solely by voltage because it depends on average particle concentrations. Thus, it is challenging to obtain and measure a battery’s capacity directly. Figure 16 represents the approaches used for SOC estimation [132,133].

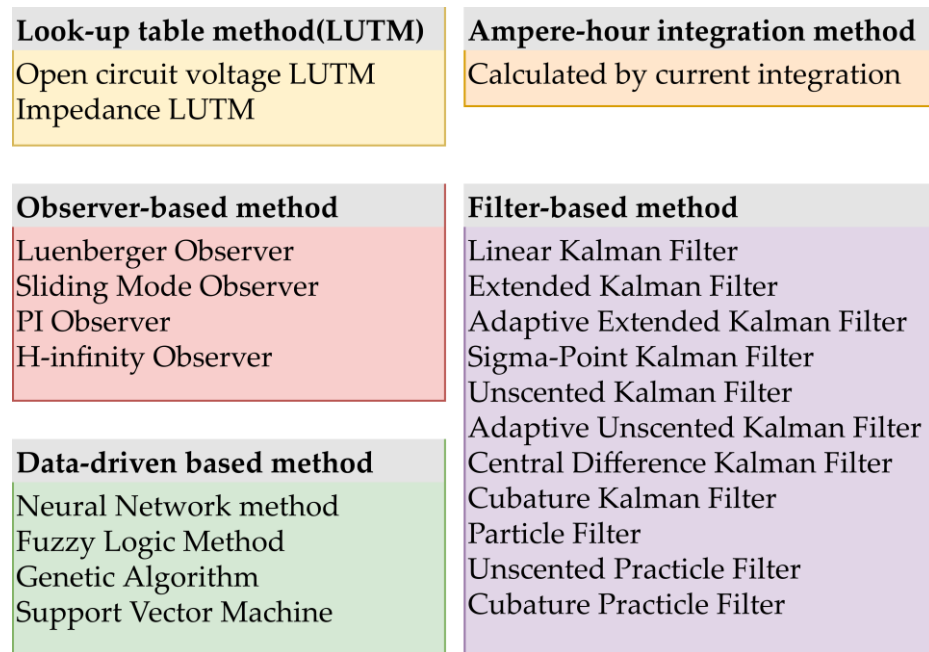


Figure 16. Different SOC estimation approaches.

State of health (SOH) classifications have been presented in various studies, each with their own characteristics. The battery SOH estimation methods in this paper are divided into two categories to track these degradation behaviours for the online management of batteries in a BMS, namely, the estimation methods based on models and experiments. Below each significant type are two branches containing several standard methods, as depicted in Figure 17 [134].

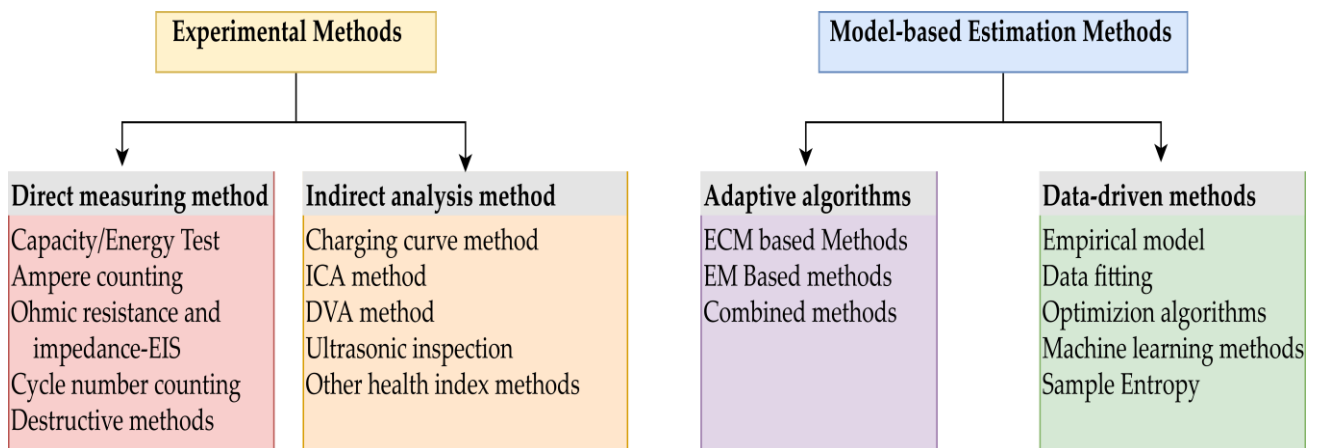


Figure 17. Different SOH estimation approaches.

Regarding battery management, the prediction of power capacity is also important because it shows users how much power is available at a given time. An instantaneous quantity, power capability is the rate at which energy can be transferred from the battery pack to the loads without exceeding the cell’s or electronics’ design limits. The state-of-power (SOP) or state-of-function (SOF) tests are typically used to assess a battery’s power capacity. The percentage of peak power to rated power, i.e., the maximum continuous control over a brief period that does not exceed the thresholds, can be used to define the SOP [135]. There are three types of standard SOP calculation methods according to the available literature: experimental testing, the estimation of multiple constraints, and the data-driven approach, as shown in Figure 18 [136–138].

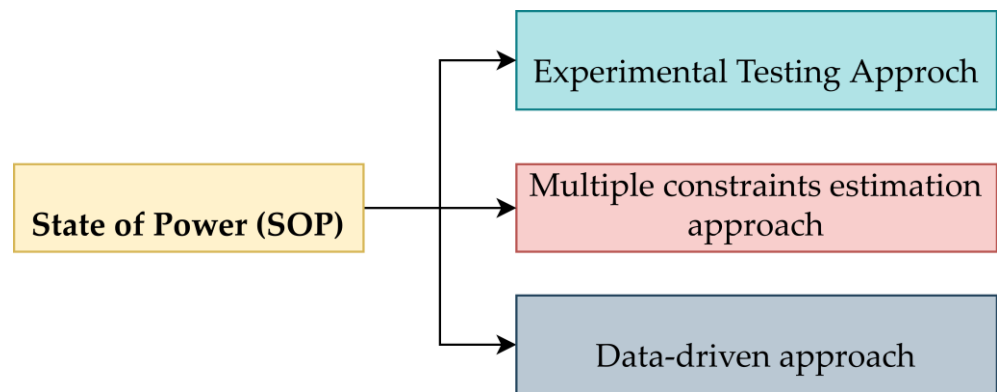


Figure 18. SOP estimation approaches.

Cell balancing is essential for a BMS’s operation to be safe and reliable. When the batteries are fully charged, the voltages and SOC can be balanced using cell balancing. Even cells from the same manufacturer and model are not identical. SOC, voltage, current, impedance, temperature, and other characteristics vary slightly. Without a balanced system, a cell’s voltage will only fluctuate over time, thus reducing pack capacity and causing battery arrangement malfunctions [139]. Figure 19 shows examples of active and passive cell-balancing topologies [140–142].

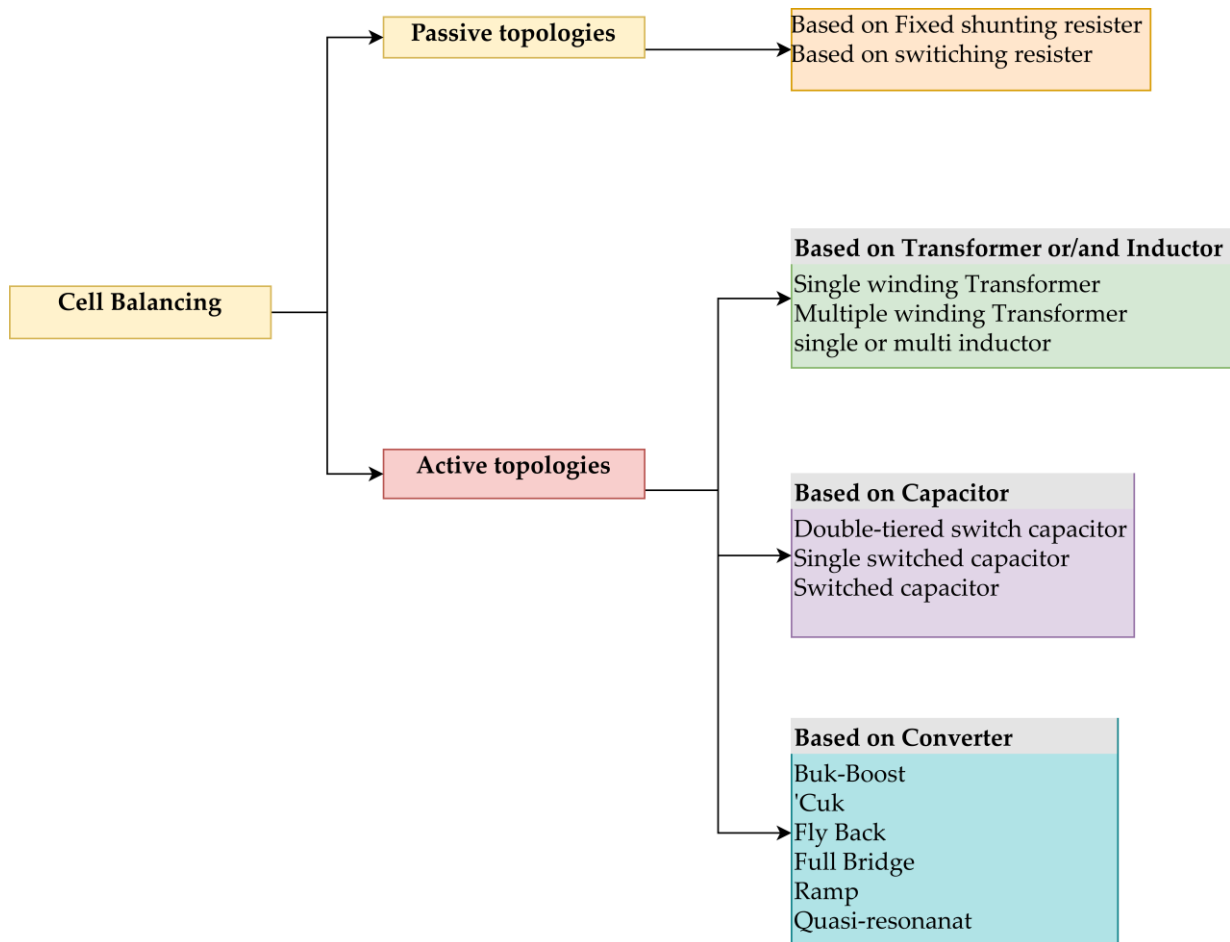


Figure 19. Cell-balancing technologies.

5. Discussion

The electrochemical storage of energy is an essential global strategic concern. Numerous nations are devoting significant research and development resources to creating more efficient batteries, with multiple goals ranging from enhancing the autonomy of portable systems, electric vehicles, and hybrids to providing large-scale storage for the electrical grid. New approaches, such as lithium–sulphur (LI–S), metal–air, and sodium–ion (Na-ion) batteries, are being developed, while conventional Li-ion batteries (because of their energy density) and supercapacitors (due to their power density) still account for most of the electricity storage market.

From a global perspective, the storage of electrical energy will thus contribute significantly to meeting the following three challenges:

1. Environmental gain linked to the possibilities of the large-scale deployment of intermittent energies;
2. The ability to provide and adapt centralized or decentralized responses on a case-by-case basis for local or global constraints;
3. The achievement of economic, political, and environmental Independence from fossil resources.

The development of storage techniques for electricity and their integration into the available networks is a sine qua non for a successful energy transition. Storage solutions will need to be diversified to meet different supply–demand balance needs, such as those relating to duration, the speed of response, the quantity stored, and location. In the short and medium terms, the act of meeting this enormous need for storage appears to be increasingly urgent and important in order to satisfy the objectives regarding global warming, which are intellectually accepted by most citizens. Of course, a review of possible solutions shows no low-cost solution. Significant financial efforts are and will be necessary. However, the stakes are high. For instance, the use of electric or hydrogen cars, although constituting magnificent innovative advances towards the achievement of greater purity in our environments, cannot be practical. Only when “carbon-free” electricity has dethroned current “carbon-based” electricity will significant progress be achieved. Otherwise, we will always drive while consuming oil and coal, and the carbon footprint, although locally improved, will always be treacherously similar globally.

In general, the current technologies all require significant improvements to develop a market at a competitive rate of return. In this regard, the main research topics relate to manufacturing and implementation processes, materials (container and content), overall efficiency, self-discharge and losses, service life and aging, safety, location, and the link with the network (a systemic approach).

These needs mainly relate to the following areas:

1. For WWTPs, the optimization of pump turbines and infrastructures (the limitation of corrosion by salt water, the assessment of sites and environmental impacts, etc.).
2. For the CAES, the improvement of the compression systems under high pressures and high temperatures, as well as the improvement of the mechanical strength and conductivity of the materials used for the exchangers.
3. For chemical processes, more efficient materials and chemical compounds, particularly with respect to thermic and manufacturing-related implementation, and management processes likely to increase the lifespan, autonomy, and recycling of the system.
4. For heat storage, materials that increase service life and improve yields are required. A reduction in bulk volumes is also sought.
5. For hydrogen storage, the development of new concepts and new materials offers maximum safety at an acceptable cost.

6. Conclusions

In this research, we were interested in investigating several aspects of the storage of electrical energy. We overviewed the key concerns and objectives relating to the storage

of electrical energy. In addition, we discussed the many different techniques that are now being utilized for the storage of electrical energy, as well as the criteria that have been used to select the most appropriate methods. Furthermore, we shed some light on the background of the evolution of the technology used in rechargeable batteries. Additionally, we listed some of the unresolved issues and limitations linked with the storage of electrical power. Researchers and scientists interested in electricity storage must address various topics in their future work. Security is one of these factors that must be carefully addressed to prevent potential attacks such as electricity theft and the abuse of smart meters. The use of blockchain technology could improve security measures. The application of artificial intelligence techniques can help power storage in a variety of ways. To maximally exploit these applications and fields, their study and that applied to many other directions is necessary.

Author Contributions: Conceptualization, M.K. and S.M.Q.; methodology, M.K. and S.M.Q.; implementation, M.K. and S.M.Q.; validation, S.M.Q., Y.B. and A.W.; formal analysis, M.K. and S.M.Q.; investigation, Y.B., S.M.Q., A.W. and M.K.; resources, S.M.Q.; writing—original draft preparation, M.K., S.M.Q. and Y.B.; writing—review and editing, M.K., S.M.Q. and A.W.; visualization, M.K., S.M.Q. and Y.B.; supervision, S.M.Q. and A.W.; project administration, S.M.Q. and A.W.; funding acquisition, S.M.Q. and M.K. All authors have read and agreed to the published version of the manuscript.

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