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REVIEW ARTICLE

A critical review of energy storage technologies for microgrids

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Abstract

Energy storage plays an essential role in modern power systems. The increasing penetration of renewables in power systems raises several challenges about coping with power imbalances and ensuring standards are maintained. Backup supply and resilience are also current concerns. Energy storage systems also provide ancillary services to the grid, like frequency regulation, peak shaving, and energy arbitrage. There are several technologies for storing energy at different development stages, but there are both benefits and drawbacks in how each one is suited to determining particular situations. Thus, the most suitable solution depends on each case. This paper provides a critical review of the existing energy storage technologies, focusing mainly on mature technologies. Their feasibility for microgrids is investigated in terms of cost, technical benefits, cycle life, ease of deployment, energy and power density, cycle life, and operational constraints.

Keywords Energy storage · Electrochemical batteries · Microgrids

1 Introduction

Energy Storage Systems play an essential role in modern grids by considering the need for the power systems modernization and energy transition to a decarbonized grid that involves more renewable sources. Renewable energy intermittency requires flexibility ancillary services to smooth the variability in power production, both on a large and small-scale, e.g., interconnected bulk power systems and microgrids. Energy storage systems may be able to cater to these needs. They also provide peak-shaving, backup power, and energy arbitrage services, improve reliability and power quality.

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The promising technologies are concerned with the response time (power density) and autonomy period (energy density). These two requirements may or may not be simultaneously present, depending on the circumstances. In long-term storage (for example, seasonal storage), the required technologies do not need high cycling rates. However, a reasonable design of high energy density and low self-discharge rates are desirable prerequisites. These requirements are different for primary reserve, where a faster response for a short time is essential.

There are several ways to store energy. The challenge is to find a solution that combines the operational and technical requirements with economic feasibility in an appropriate way by taking advantage of the strengths and overcoming the weaknesses. It is possible to store energy in mechanical, electrical, and chemical forms for later use [1].

By 2017, the total storage capacity in operation worldwide was 176 GW, mainly found in China (32.1 GW), Japan (24.2 GW), and the United States (24.2 GW). These proportions represented almost 48% of the total share. Regarding storage technologies, 96% is from Pumped-Hydro Storage. However, the fast transition to a decarbonized grid and an increase in the penetration of renewables require other technologies' participation. A 2018 World Energy Council report showed that energy storage capacity doubled between 2017 and 2018, reaching 8 GWh. The current projection is that there will be 230 GW of energy storage plants installed by 2030 [2–5].

Microgrids are a means of deploying a decentralized and decarbonized grid. One of their key features is the extensive presence of renewable-based generation, which is intermittent by nature. Because of this kind of variability, the application of appropriate energy storage systems is mandatory. Although there are many available technologies, some fit better for microgrids application, especially electrochemical technologies.

This paper reviews some of the available energy storage technologies for microgrids and discusses the features that make a candidate technology best suited to these applications. Several alternative systems are examined and analyzed concerning their advantages, weaknesses, costs, maturity, lifespan, safety, Levelized Cost of Storage (LCOS), and Technology Readiness Level (TRL). The LCOS quantifies the unitary cost of discharged energy by a given storage device. This index covers all the technical and financial parameters affected by the storage plant lifespan and compares the costs of different technologies [6]. The TRL assesses the developmental stage of a given technology and is a tool designed to compare their maturity [7].

2 Microgrids and energy storage

Microgrids are small-scale energy systems with distributed energy resources, such as generators and storage systems, and controllable loads forming an electrical entity within defined electrical limits. These systems can be deployed in either low voltage or high voltage and can operate independently of the main grid if necessary [8].

Since microgrids are an environmental-friendly and sustainable solution, they can employ renewable-based generation to supply power extensively. Renewables are intermittent sources by nature, and usually, their availability does not correspond to the load demand. Reductions in power are expected since passing clouds may shadow over photovoltaic panels, and the wind speed is not constant during the whole day. Energy storage systems must be able to handle these short-term variations in power. Thus, one requirement that the energy storage systems must meet is to ensure power balance all the time [9–11]. The energy storage system must react quickly to power imbalance by supplying the lack of power for load or absorbing the exceeding renewable energy. It requires fast devices that can respond on a microsecond-scale, perform large numbers of shallow cycles, and have an appropriate power density.

A large amount of renewable generation also creates other needs for microgrids. Generally, the peak of generation is not coupled with the peak load. Storing this exceeding energy for later use is also an essential task for storage systems. The energy storage capacity needs to be appropriately assessed to ensure a balance between the storage of clean energy and its costs. The storage technology must have high energy conversion efficiency, a low self-discharge rate, and appropriate energy density to carry out this task.

The connected operation also gives an opportunity to provide other ancillary services to the main grid, like peak-shaving and energy arbitrage. Peak shaving entails providing power to the grid during peak load times and avoiding installing generation assets that stay idle for a long time. Peak shaving is a means of earning an extra income during peak times owing to the higher electricity tariffs of the power utilities [12–14]. This service is usually provided by dispatchable units connected in parallel with the load to supply power during peak times and is owned by the customers. Storage systems can also provide a peak shaving service when connected to the grid and result in microgrid revenue that can be used to write off initial investments and O&M costs. However, this is subject to many requirements, such as large power density, deep cycle capacity, low self-discharge rates, and a longer discharge time resulting in a more extended period of self-supply. Energy arbitrage involves absorbing exceeding power in off-peak hours when the tariff is lower and injecting this stored energy in peak hours when the tariff is higher. The difference between the two tariffs is revenue to the microgrid, which requires a storage system with deep cycling capacity, a longer lifespan with more cycles, high efficiency, and low self-discharge losses [15, 16].

With regard to the off-grid operation, the energy storage system has considerable importance in the microgrid. The ESS mainly provides frequency regulation, backup power and resilience features. Resilience refers to the capacity to operate the microgrid in off-grid mode during longer intervals due to unforeseen disasters, like cascading events, hurricanes, floods, and other natural hazards [17]. These island infrastructures must have other survival systems to provide heat, drinking water, and fuel for basic human needs. Longer discharge times, greater efficiency, safety, and good discharging ability are required to meet the needs of the resilience service.

In light of this, designing a microgrid requires a proper energy storage system to be suitably planned to handle the objectives and support grid operations appropriately. Although there are various technologies available, choosing the best candidate to suit off-grid and on-grid operations requirements must take account of factors such as an operational reserve, especially when operating in off-grid mode, system stability reliability, energy quality, and resilience.

Several criteria must be considered in the energy storage technologies when choosing the suitable alternative from the candidate solutions. The final choice concerns its possible role in power grids, off-grid or grid-connected operations, achieving flexibility, intermittence smoothing, backup energy, peak shaving, and other applications. These criteria include the following [18, 19]:

- Energy density and power density;
- Installation and maintenance costs;
- Response time and discharge time;
- Technology maturity;
- Time of life;
- Efficiency.

It is not the goal to investigate all available technologies, but only those mature enough to apply to real microgrids. Thus, only technologies with a TRL equal to or higher than 8 are investigated in this paper. A Grade 8 in TRL indicates that technology is mature and qualified to application in real systems [7]. Table 1 shows the TRL for some technologies.

3 Mechanical storage for microgrids

There are some energy storage options based on mechanical technologies, like flywheels, Compressed Air Energy Storage (CAES), and small-scale Pumped-Hydro [4, 22–24]. These storage systems are more suitable for large-scale applications in bulk power systems since there is a need to deploy large plants to obtain feasible

Table 1 TRL for different energy storage technologies. Source [7, 20, 21]

TRL	Technologies
> 9	Lead-acid Lithium-ion Flow Sodium Beta Ni-Cd Flywheels Micro-pumped Hydro
9 > 8	Hydrogen fuel cells Micro CAES
8 >	Phase Change Materials (PCM) Thermochemical Materials (TCM) Solar fuels Metal-air

cost-effectiveness in the project. The time to build the storage plant is a limiting factor in some cases. Small-scale solutions have been deployed to overcome such drawbacks in microgrids environments.

3.1 Flywheels

Flywheels consist of a spinning mass installed in a vacuum chamber for storing energy in a kinetic form and are connected to the same shaft with a generator. When the energy is stored, the rotating mass speeds up. When discharging, the flywheel loses speed and delivers power to the grid. The complete flywheel system includes the flywheel rotor, a vacuum pump, magnetic bearings, a generator, and a power converter. A comprehensive description of flywheel physical principles and parts is given in [25, 26]. They have high power density, a long life cycle (over one million cycles), long calendar life, a low environmental impact due to zero emissions, fast response, high round-trip efficiency (90% to 95%), high charge and discharge rates, and the use of recyclable materials.

Concerning applications, it is suitable for frequency regulation purposes or short-term backup, which require high power and fast discharge rates. MW scale flywheels can also be applied to reactive support and spinning reserve for fast time ranges (while the backup source starts). Permanent magnet machines are preferred due to their high efficiency, fewer rotor losses, and significant power density. Magnetic bearings may be used to decrease frictional losses, but such an option increases costs and complexity due to the required control system [4, 20, 24–27].

Safety is the most limiting factor in flywheels because of their hazardous potential failure modes. Mechanical stress in the shaft, excessive heating, and failures in subsystems are potential causes of accidents. They also have high self-discharge rates and incur high O&M costs. When used for microgrid applications, flywheels do not match the needs of energy autonomy in terms of cost-effectiveness owing to the lower energy density, which is 5 Wh/kg for low-speed models [28, 29].

The installation costs of low-speed flywheels range from 600 $/kW to 2,400 $/kW [30]. High-speed models have higher costs because of the composite materials used to build the spinning mass and accessory systems. The energy density of such models reaches 200 Wh/kg, but high costs limits their application [20]. In addition, there are the costs of the underground buildings needed to install the flywheel, which requires a reserved area for the storage system for safety reasons.

3.2 Compressed-air energy storage

The Compressed-Air Energy Storage (CAES) is assembled with five major components: a motor/generator, a compressor to pressurize air into a reservoir, a turbine train, a container to store compressed air, and control systems and heat exchanger units. Generally, CAES plants have medium and large-scale to reach cost-effectiveness. The exceeding power is stored in underground/above-ground reservoirs in the form of potential energy. When necessary, the pressurized air is reheated in a diabatic process and injected into conventional gas turbines. An adiabatic process is also possible, increasing the global efficiency [4, 20, 27, 28, 31]. References [32, 33] present a comprehensive review on CAES physics, parts, and types..

These systems are subject to severe restrictions concerning pressurized air reservoirs. It is not easy to find large underground reservoirs, e.g., caves, abandoned mines, and tunnels. Above-ground reservoirs are expensive to construct and have a lower capacity than underground alternatives harming project cost-effectiveness. Other concerns include the consumption of fossil fuels to heat compressed air and heat dissipation in diabatic systems, where an association with gas turbines is mandatory. Adiabatic CAES can eliminate such problems but needs thermal storage systems increasing costs and complexity. Cogeneration and tri-generation arrangements are more environmentally friendly and may help to reach financial feasibility [27, 32].

Underground CAES have power densities of between 30 and 60 W/kg, energy densities up to 0.6 Wh/kg, a response time in a minute-scale, and a discharge time of up to 24 hours. The cycle life ranges between 8000 and 13,000 cycles for a power range from 5 to 300 MW. Round-trip efficiency ranges from 41 to 75% with a lifespan up to 40 years. Above-ground CAES have power densities from 140 to 300 W/kg, a response time from seconds to minutes, and a discharge time from two to four hours. The efficiency rate ranges from 70 to 90%, the cycle life of 20 years ranging from 500 to 1800 cycles, and installed capacity up to 15 MW. In the case of both options, the self-discharge rates are zero [20, 34, 35].

The costs for underground CAES range from 500 to 1800 \$/kW and 50 to 400 \$/kWh, while for above-ground CAES ranges from 1000 to 1550 \$/kW and 200 to 250 \$/kWh [20]. Medium and small-scale CAES are more flexible options for above-ground projects with an installed capacity of up to 10 MW. However, the scaling problem arises again since small reservoirs lead to higher unitary power and energy costs and longer payback intervals. References [27, 33, 36] enumerate some commercial and pilot CAES plants in the USA, UK, China, Germany, Ireland, Canada and Australia. The potential deployment of micro-CAES is investigated in [37].

3.3 Pumped hydro storage

Pumped Hydro Storage (PHS) is a mature and widely employed way to store energy for large-scale applications to peak shaving and backup power services. It consists of two reservoirs at different elevations with an associated turbine/generator to pump water at off-peak hours and generate power during peak periods. PHS has a round-trip efficiency of 75%, power ratings ranging from 100 to 5000 MW, minimal discharge losses, and a lifetime of up to 40 years. Approximately 300 PHS plants are operating in the world. [27, 38]. Reference [38] gives a detailed review of PHS technology, historical development, and future trends.

The main drawbacks of PHS are related to geographical restrictions, building costs and time, and environmental concerns. Finding proper sites to build reservoirs is difficult while flooding extensive areas is not a good option. Some innovations have been investigated to overcome such drawbacks, as sub-surface reservoirs and small-scale PHS [38–43]. Using the sea as a reservoir is also a solution used in one real storage plant in Japan. Other projects in Ireland (Glinsk), Indonesia (East Java), and the USA (Hawaii) are under different deployment stages.

However, small-scale pumped hydro storage is also subject to restrictions in the use of reservoirs. It does not offer the necessary speed response to its application in highly variable grids such as microgrids. Space and volume are common factors that restrict their use in microgrids, and environmental questions also arise when looking for an area that is prone to flooding [20].

Table 2 shows some real mechanical storage systems in power systems.

Mechanical storage options seem less suitable for microgrids because of scaling problems, geographical requirements, and longer deployment periods than other solutions. Concerning technical requirements, mechanical storage options do not match all needs simultaneously. While flywheels have an appropriate response for frequency regulation, backup power and resilience goals are deficient and require a considerable investment in high-speed units. PHS and CAES have a slower response but are appropriate for long-range needs. The presence of conventional generators is also favorable for stability and transient issues.

Some references point that mechanical storage can be handled on a long-duration storage scale, like seasonal storage and spatial-temporal intermittence of bulk power systems [20, 30].

Table 2 Data on real mechanical storage systems. Source [33, 36, 38, 44, 45]

Project	Local	Technology	System Specifications		Application
			MW	MWh	
Coral Bay	Australia	Flywheel	0.5	N/A	Renewable integration and frequency regulation
Marsabit Wind Farm	Kenya	Flywheel	0.5	N/A	Renewable integration and frequency regulation
Stephentown	USA	Flywheel	20	N/A	Frequency regulation
Hazle Township	USA	Flywheel	20	N/A	Frequency regulation
Huntorf plant	Germany	Underground CAES	290	N/A	Load following and peak demand
McIntosh	USA	Underground CAES	110	2700	Load following and peak demand
Birmingham	UK	Above-ground CAES	0.35	2.5	Distributed generation (pilot plant)
RWE Power	Germany	Underground CAES	200	1000	Adiabatic CAES demonstration plant
TICC500	China	Above-ground CAES	0.5	N/A	N/A
Macaoenergy	China	Above-ground CAES	10	N/A	N/A
Okinawa	Japan	Sea PHS	30	N/A	N/A

4 Electrical and electromagnetic storage for microgrids

Supercapacitors and superconducting magnets are used to store energy electrostatically and in magnetic fields and are characterized by high power capacity and fast response time. [20, 46]. These energy storage technologies match microgrid needs for frequency regulation and power quality, but other long-range requirements need to deploy hybrid solutions, as investigated in [47, 48].

4.1 Supercapacitors

A supercapacitor (SC), also known as an ultracapacitor, operates similarly to conventional capacitors. As it is known, the capacitor is a passive device that stores electrical energy in an electric field between two electrodes that are equally charged but with opposite signals.

The difference between conventional capacitors and SC's is in the charging mode. In the SC, the electrical charge accumulates at the interface between the conductor's surface and the electrolyte solution, while in the conventional capacitor, the charge accumulates in two armatures [49]. The capacitors used in power systems can offer several services, such as power factor correction, reactive support, harmonic protection, and voltage support [50, 51].

SCs have excellent characteristics when compared to other devices. Long service life, high efficiency, high cycling, high power density, and very low response time. In addition, no toxic substances are released during the discharge process. They have a high tolerance for deep discharges and very low internal resistance. However, they have a low energy density, short discharge time, and high cost [20, 46, 50].

4.2 Superconducting magnetic energy storage

The Superconducting Magnetic Energy Storage System (SMES) is a technologically advanced and relatively new method of storing energy in a magnetic field, formed when a current flows around a coil. The coil must be made of superconducting material that has no electrical resistance to avoid losses to store energy [52].

The materials needed to create the coil are expensive and the best available today must be cryogenically cooled. The temperature must be close to absolute zero before they become superconducting. There are higher temperature conductors, but they tend to be less efficient. SMESs are attractive due to their reliability, flexibility, and quick response. This mechanism contributes to the improvement of transitory stability and renewable power smoothing [53, 54].

Compared to other storage systems, a SMES has a high energy conversion efficiency (above 90%) and a very low response time (in the order of milliseconds). The biggest disadvantage of this type of storage is the high cost of installation and the need for pumps and compressors to keep the coolant at a low temperature [55].

5 Chemical storage for microgrids

Chemical energy storage systems apply reversible chemical reactions with high energy consumption to store energy. This category includes, among others, the storage of energy in the form of hydrogen and its use through fuel cells [56, 57]. However, it is necessary to consider the various processes responsible for hydrogen generation, as they present thermodynamic inefficiencies, consume a significant amount of energy, and emit polluting substances. The most mature technologies to produce hydrogen are alkaline electrolysis and polymeric membrane electrolyzers (Proton Exchange Membrane - PEM). A technology considered emerging is high-temperature electrolysis, where electricity and heat can be used to produce hydrogen, with an efficiency of up to 90% [58, 59]. Other ways to produce hydrogen are described in [24, 57, 60].

Alkaline electrolysis uses an alkaline solution, typically potassium hydroxide (KOH) with mass concentrations of 25 to 30%. The operating temperatures range from 65°C to 100°C with pressure around 25 bar to 30 bar. The current density of industrial alkaline electrolyzers is in the range of 1,000 A/m^2 to 3,000 A/m^2, with ohmic losses increasing with the current density, thus reducing the efficiency of electrolysis [61].

Proton Exchange Membrane (PEM) electrolyzers, also called Solid Polymer Electrolyte (SPE), are characterized by having solid electrolyte. This electrolyte consists of a polymeric membrane less than 0.2 mm thick. The most common membrane is made of Nafion, which is a sulfonated polymer similar to polytetrafluoroethylene. In contrast, the most common electrodes are made of noble metals such as platinum and iridium [61].

In comparative terms, PEM electrolyzers have some advantages over other technologies, where it is possible to highlight higher energy efficiency and higher production rates, in addition to being less bulky. However, PEM electrolyzers have higher costs, mainly due to the types of membrane and electrodes. Additionally, the service life is comparatively shorter [62].

After hydrogen production, it is necessary to extract electricity from it, and this can be done in two ways: By directly applying hydrogen for burning in turbines and by using fuel cells, which is dominant due to efficiency issues and pollutant emissions.

The fuel cell is composed of an anode (negatively charged electrode and conducts electrons released from hydrogen molecules to be used in the external circuit), a cathode (positively charged electrode and directs electrons from the external catalyst circuit to be recombined with the ions of hydrogen and oxygen to form water) and electrolytic membrane (composed of special material and transports the protons from the anode to the cathode), as illustrated in the figure 1.

The operating principle of a fuel cell is simple. The hydrogen comes into contact with the anode and, from there, the gas separates into two ions: H^+ and e^-. Positive ions cross the electrolytic membrane. The negative ions move towards the charge in a continuous electric current. At the cathode, negative and positive

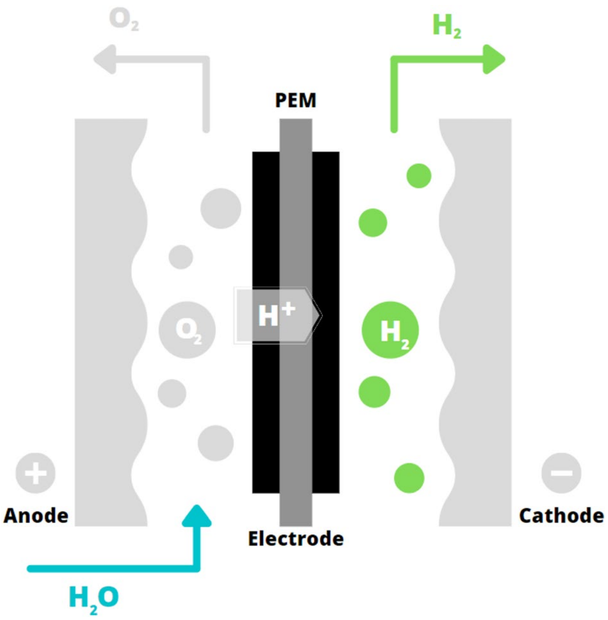

Fig. 1 Polymeric membrane electrolyzers

ions find oxygen in the air and turn into water. Table 3 summarizes some different fuel cell technologies and features.

Hydrogen-based storage has relatively low efficiency compared to other storage technologies, both in small systems (batteries) and in larger systems (CAES). However, due to the high scale of storage, interest in this option is gradually increasing. The storage capacity of 100 GWh indicated in the table 4 corresponds to the amount of electricity that can be produced from hydrogen stored in a salt cave of 500,000 m^3 at 200 bar [27].

While short-term variations are adequately addressed by “fast” technologies, such as electrochemical batteries, annual fluctuations require different measures due to long storage periods and the limited number of cycles per year. The use of exceeding electricity to generate hydrogen can be an important niche for this storage option in the power industry.

6 Electrochemical storage for microgrids

Concerning the storage needs of microgrids, electrochemical technologies seem more adapted to this kind of application. They are competitive and available in the market, as well as having an acceptable degree of cost-effectiveness, good power, and energy densities, and maturity. The modularity of electrochemical technologies is another advantage. Many modules with small individual volumes can be purchased separately, which means they are flexible enough to build systems with

Table 3 Groups of the main types of cells classified according to operating temperature. Source: [19]

	Low and medium temperature fuel cells (< 250 °C)	High temperature fuel cells (> 600 °C)
Applicable Technologies	- Alkaline (AFC) - Phosphoric acid (PAFC) - Proton Exchange Membrane (PEMFC)	- Molten carbonates (MCFC) - Solid oxides (SOFC)
Typical Dimension	- Products available on the market and in development with powers up to 250 kW	- Most of the equipment in development has power in order of 2 MW, but also units with less than 1 MW are being developed
Advantages	- High efficiency - Low emissions - Quick start (Especially PEMFC) - Potential for significant reduction of the resulting cost of large-scale production if success is achieved in the transport area	- Very high efficiency - Low emissions - Simpler fuel processing - There is no need to use catalysts of precious metals - Not damaged by *CO* - Higher powers
Disadvantages	- Limited cogeneration potential - Fuel processing relatively complex - More sensitive to *CO* - Require precious metal catalysts - High costs (PAFC)	- Limited market initially for the production of electricity (which reduces the potential to reduce costs) - Complexity of hybrid systems

different nominal energy and power capacities, which are more appropriate for diverse needs.

The time required to deploy an electrochemical storage system is a positive factor too. A smaller financial investment is needed for civil infrastructure, and less time is required to ensure the system is fully operational. Transporting the storage devices and connecting them are the only measures necessary in such cases. In the next section, the electrochemical technologies are described further.

Although there are several electrochemical battery technologies in different developmental stages, only devices with TRL higher than eight are discussed in the next sections.

6.1 Lead-acid batteries

Lead-acid batteries were first developed in the 19th century. They are widely used in vehicles and grid services, such as spinning reserve and demand shift [34]. Their main advantages include ease of installation, low maintenance costs, maturity,

Table 4 Summary of hydrogen storage technical data. Source: [63]

Storage capacity (MWh)	Electrical Efficiency (%)	Heat Efficiency (%)	Estimated lifetime (Years)	Cost ($/kWh)	Initial investment ($/kW)
< 100.00	30 a 50	< 60	30	2 a 20	500 a 750

recyclability, a large lifespan in power fluctuation operations, and low self-discharge rates [64, 65].

The lead-acid battery cell consists of spongy lead as a negative active material and lead dioxide (PbO_2) as a positive active material, immersed in a sulfuric acid ($H_2SO_4^+$) electrolyte, with lead as a natural collector [66]. During the discharge, (HSO_4^-) ions pass through the anode and react with Pb to produce lead sulfate ($PbSO_4$) and H^+ ions. In the charging process, $PbSO_4$ is converted to Pb and PbO_2 [67]. The greater the current flow, the more hydrogen is generated at the anode and oxygen at the cathode.

However, in the last century, there was no significant improvement in lead-acid technology. Different plate and cell designs were suggested to improve the charging and discharging features, but the lead-acid batteries still have a number of drawbacks [64, 65]:

- Lower energy density compared with modern technologies;
- Limited complete charging/discharging cycles;
- Hazardous gas emissions;
- Potential risks to the environment if not correctly managed;
- The fact that they are generally affected by ambient temperature; and,
- They lead to demands for a strict control of charge and discharge rates.

In microgrids, the intermittent nature of sources may have a negative impact on the life cycle of the lead-acid batteries because they involve stricter operational modes, and require deeper and irregular cycles, as well as different temperature spans. In view of this, lower useful cycles must be expected in practical applications. Further investigations concerning lead-acid batteries stress and degradation factors have been done in [68–71] and different lifetime models have been proposed in [72, 73].

Lead-acid batteries can be classified in accordance with their anode composition, plate design, and electrolyte confinement. With regard to anode composition, conventional batteries have a positive plate of lead dioxide and a negative plate made up of lead. During the operation, the plates form deposits on the negative electrodes during the charge cycles because sulfation reduces their useful life and impairs their performance. This phenomenon is intensified in situations of high load and deep discharges [66]. To overcome this weakness, improved battery models have carbon added to the negative plates and, in some cases, capacitors; in addition, hybrid devices are created with an improved performance, faster response, greater charging capacity, deeper discharging, longer life cycle, less sulfation, and less frequent equalization charges [34, 74, 75].

Regarding the different plate designs, plane plates are the standard model, and these are mainly used in automotive applications. They have discharging restrictions up to 40% and lower life cycles when operated in deep discharge cycles. Tubular plates, in turn, have a longer lifespan, and manufacturers recommend Depth of Discharge (DoD) up to 60%. However, they have the disadvantage of being more expensive than plane-plate models [76, 77]. The most well-known are the OPzS and OPzV models. While the former is a flooded model, the latter has a jellified electrolyte. A third model includes spiral wound plates, which have a higher resistance to material loss because they are subjected to a compression process when they are manufactured. These techniques reduce internal resistance and allow a better distribution of current flow in the battery's plates because there is a higher contact area between the current collectors and active material [78].

With regard to the electrolyte confinement, there are vented models and valve-regulated models. Vented models are characterized by their ability to check the water and acid levels and fill them if necessary, during the maintenance schedules. This model has two terminals, positive and negative, at the upper part of the device and ventilation caps at the top. This allows the gases (hydrogen) to escape from the battery [79].

The valve regulated lead-acid (VRLA) is a sealed model with a valve to control gas leakage and avoid high battery pressure. There are two types of VRLA batteries, depending on the electrolyte used. In the gel type, the jellified electrolyte can be formed by SiO_2 and Al_2O_3, which allows VRLA models to operate at higher temperatures and in vibrating environments. Plane and tubular plates are common in these models, which have to be charged slowly to avoid gasification beyond the capacity of the valve [77]. Absorbent Glass Mat types have a microfiber separator consisting of glass, boron, silicate, and polymers, which absorb the electrolyte. The models have a number of benefits like freezing resistance, higher efficiency in the recombination of hydrogen and oxygen, and a lower self-discharge rate resulting from the low internal resistance [77, 80].

Table 5 compares some features of modern lead-acid batteries that have an advanced performance with standard models such as the life cycle and depth of discharge.

Some references in the literature report the application of lead-acid batteries in different storage systems. Standard models used in commercial and industrial off-grid applications with a nominal/ installed capacity below 1MW/ 2MWh have an installation cost of between 1,278 and 1,483 US$/kW and LCOS between 1,076 and 1,225 US$/MWh. With the use of advanced models in the same application, the costs range from 1,436 to 1,763 US$/kW for installation and LCOS from 1,005 to 1,204 US$/MWh. Generally, the same range is found in other applications since advanced models are more expensive and result in higher installation costs.

Table 5 Different models of lead-acid batteries. Sources: [1, 34, 75, 81, 82]

	OPzV	OPzS	Ultrabattery®
Operation temperature (°C)	15-35	10-30	0-40
Life Cycle (cycles)	3,100(DoD 50%)	3,000(DoD 50%)	4,000-4,500(DoD 70%)
LCOS (US$/kWh)	377	322	300-400
Application	-Hydraulic systems -Microgrids -Off-grid systems -Peak shaving -Residential energy storage -Telecommunications		- Peak shifting - Load leveling -Renewable integration - High-cycle applications

However, they have a lower LCOS owing to their improved operational performance where there is a deeper DoD, and extended life cycle [81, 83].

6.2 Lithium batteries

Lithium batteries are the most widely used energy storage devices in mobile and computing applications. The development of new materials has led to an increased energy density reaching 200 Wh/kg and a longer lifespan with 10,000 cycles. They also have an insignificant memory effect and low self-discharge rates. These features make the lithium batteries suitable for applications - from those with a low capacity range, like residential storage systems, to megawatt applications, such as the spinning reserve for bulk power systems. The use of lithium batteries is preferred for electronic devices and electric vehicles because of their operational features, such as a deep discharge capability and a longer life cycle. However, they are also a competitive choice in power grid services, including renewable intermittence smoothing, frequency regulation, demand shift, and peak shaving [11, 27, 84–86].

Despite including better features than those found in other technologies, lithium batteries give rise to serious safety concerns because some of the materials used in their assembly can decompose in high temperatures and cause explosions or fires. This means that temperature is a critical issue regarding safety and the life cycle. Extreme temperatures can damage the materials in the battery, leading to increased degradation and creating potentially hazardous conditions. Commercial lithium battery packages operate in an interval between 15°C and 35°C and are provided with battery monitoring systems that can control charging/discharging and thus minimize these risks [87]. Reference [88] gives a comprehensive review on lithium batteries and future perspectives. Investigations on degradation and ageing factors and lifetime models for Li-ion batteries have been presented in [89–94].

Lithium batteries are assembled from four key components. The cathode is the positive pole and consists of metallic oxide and lithium, and the anode is made up of graphite. Lithium salt and organic solutions allow the movement of ions from the cathode to the anode. A porous membrane is used to prevent a short-circuit between the poles since it only permits lithium ions to pass through it [85].

Although we refer to lithium batteries in general, there is not just a single commercial model available. There are several families of different lithium batteries which vary according to their chemical compositions. In general, all of them have a mature level of development. Further details are provided in Table 6.

Lithium batteries have different LCOS depending on the application. Large-scale storage systems, with nominal power up to 100 MW and nominal capacity up to 400 MWh, have an LCOS between 204 and 298 US$/MWh. Hybrid plants with PV and storage may have an LCOS between 108 - 140 US$/MWh. Small storage systems and isolated plants have the largest LCOS, reaching 735 US$/MWh and 1,152 US$/MWh, respectively [83].

Table 6 The range of lithium battery models. Sources: [28, 85, 95, 96]

Battery Model	Costs (US$/kWh)	Advantages	Disadvantages
Lithium-titanate Oxide (LTO)	500-850	+ Longest cycle life + Good performance in low temperatures + Reasonable safety	- Low power and energy density - Prohibitive costs.
Lithium Cobalt Oxide (LCO)	250-500	+ High specific energy and energy density + Standard in smartphones, tablets, notebooks, and cameras	- High cost due Cobalt - Short cycle life - Limited current - Demands overheating protection - Toxic materials
Lithium Manganese Oxide (LMO)	450-700	+ Carries high currents + High power density + High thermal stability + High safety level	- Lower energy density than LCO - Short cycle life - Highly toxic materials
Lithium Iron Phosphate (LFP)	350-525	+ Stable operation in overcharge and high-temperature conditions + High safety level + Low internal resistance + Longer cycle life + Low toxicity materials	- Low power and energy densities
Lithium Nickel Manganese Cobalt Oxide (NMC)	325-450	+ High power and energy densities + Long cycle life + Low self-heating rate + High demand for applications in electric vehicles	- High cost due to Cobalt - Less safe than LFP
Lithium Nickel Cobalt Aluminum Oxide (NCA)	180-520	+ Reasonable safety + Long cycle life + High efficiency	- Low energy and power densities - Needs more development

6.3 Flow batteries

Flow batteries store energy in aqueous electrolytes and act in a similar way to fuel cells. These batteries convert chemical energy into electrical energy by directing the flow of ions through a membrane caused by an oxidation-reduction reaction of two different liquids from separate tanks. Although these systems are referred to as batteries, flow batteries are complex units made up of hydraulic pumps and vessels controlled by a dedicated management system and require more physical space than other electrochemical technologies [1, 97, 98].

The application of this kind of technology is suitable for power systems because of their longer life cycles, acceptable operation and maintenance costs, total discharge capacity, and a high degree of reliability. Flow batteries may also be faster since they can be recharged by merely changing the electrolytic tanks [1, 99].

Their main advantage is the physical structure since the parameters that define the nominal power and storage capacity are separated. The energy capacity is related to the size of the storage tanks, while the nominal power is related to the number of cells. Other advantages include fast response, zero emissions, and the ability to operate in ambient temperature [67, 100]. However, they have a drawback which is that when compared with lithium batteries, flow batteries have lower power and energy densities and high initial costs, which restricts their commercial applications [101, 102].

Flow batteries can be classified into Redox Flow Batteries (RFB) and Hybrid Flow Batteries (HFB). RFBs have two liquid electrolytes that are separated by a membrane which allows the ions to flow but without becoming mixed. HFBs have active matter stored internally in a cell, while the other electrolyte is liquid and stored in an external tank [84, 103].

The most prominent of the different flow battery models are Vanadium Redox (VRB) and Zinc-Bromine (ZnBr), which have a good performance with regard to the life cycle and response time. The VRB model has a larger energy capacity ($\leq 6MWh$), nominal power up to 3 MW, round-trip efficiency of 85%, a power density of 800 W/m^2, and a lifespan of 10,000 cycles. It is suited to intermittence smoothing, no-break systems, and stationary applications [104]. Other advantages include the following: the ability to replace the electrolyte at the end-of-life of the application, modularity with different energy and power capacities, a long discharge time, and a high efficiency rate. As for the disadvantages, the VRBs have a low energy density, decreased performance, and are less reliable in temperatures over 40°C, as well as the high costs of the vanadium and membranes. A greater electrolyte flow also reduces the energy efficiency caused by the need for higher pumping. The ZnBr models can be used with an energy capacity up to 3 MWh, power capacity lower than 500 kW, round-trip efficiency of 75%, a power density of 1,000 W/m^2, and a lifespan of 3,000 cycles. Their benefits include low self-discharge rates, 100% depth of discharge, and relatively cheap electrolytes. On the other hand, Bromine is a toxic and highly corrosive material. ZnBr batteries are not completely scalable and need auxiliary temperature control subsystems [2, 27, 39, 105].

The installation costs of flow batteries ranged from US$315 to US$ 1,680/kWh by 2016. Estimates for 2030 predict the costs will decrease to US$ 108-576/

kWh [2]. Table 7 summarizes some specifications of the previous three battery models. Concerning flow batteries, since they have aqueous electrolytes, it is more common to refer to theirs energy and power density in Wh/L and W/L, respectively.

6.4 Nickel-Cadmium batteries

Nickel-Cadmium batteries have been used since 1915 and represent a mature technology. They are rechargeable and have a positive electrode made from Nickel Oxide Hydroxide (NiO(OH)) and a metallic nickel negative electrode, as well as an aqueous electrolyte of Potassium hydroxide (KOH). During discharge, the NiO(OH) is combined with water and produces Nickel Hydroxide and an ion hydroxide. In the charging stage, this process is reversed, and oxygen and hydrogen are produced [19].

Their advantages include low O&M costs, a good performance in low temperatures (up to -40°C), and high energy density with large discharge rates. As for its drawbacks, it has a low cycle life (2,000 to 2,500 cycles), memory effect, and high self-discharge rates. However, owing to cadmium toxicity, these types of batteries tend to be replaced by other cleaner models [39, 106–108].

Nickel batteries also have sealed and vented models and are suitable for portable and industrial applications. The reported efficiency rate in real plants reaches 78% [109]. As well as the environmental constraints, the initial costs are high, ranging from 500 to 1500 US$/kWh [20, 39, 106]. The energy density ranges from 5 to 75 Wh/kg, power density from 150 to 300 W/kg, and there is a 100% depth of discharge. The response time is measured on a millisecond scale, and applications can reach the MW-scale [39].

Table 7 Technical data on lead-acid, lithium, and flow batteries. Sources: [18–20, 35, 105]

	Lead-acid	Lithium	Flow batteries
Energy density (Wh/kg)	30-50	120-230	-
Power density (W/kg)	200-400	150-2,000	-
Energy efficiency (%)	70-90	85-95	65 - 85 (VRB) 65 - 75 (ZnBr)
Response time-scale	ms	ms	min
Discharging time	Seconds-5h	1min-60min	< 8h
Temperature range (°C)	-30 - 50	10-60	< 40°C
Self-discharge range (%)	0.1 - 0.4	0.15-0.3	< 1
Life span (years)	5 - 15	20-25	10
Cycle life (cycles)	500 - 2000	1,000-10,000	10,000 (VRB) 3,000 (ZnBr)
Power range (MW)	< 20	0,5 - 100	< 3 (VRB) < 0,5 (ZnBr)

6.5 Sodium Beta batteries

Sodium Beta batteries are a family of devices that use liquid sodium as the active material in the anode and other materials in the electrolyte. These batteries are competitive in their use for large-scale energy storage, and the most prominent models are Sodium-sulfur (NaS), and Sodium-Nickel Chloride, also known as the ZEBRA battery [34].

Sodium-sulfur batteries have aqueous sulfur as a cathode, while aqueous sodium is used as an anode. A beta-alumina ceramic membrane separates both liquids. At the anode side, sodium ions ($Na+$) are formed as a result of sodium oxidation. These ions pass through the membrane and react with sulfur at the cathode, forming Na_2S_5. In the charging cycle, the reversal of this reaction occurs [20].

Sodium-sulfur batteries have a high energy density, long cycle life, and lower costs because the raw material is abundant. However, the temperature operation is between 300-350° C, which is a drawback because it requires an extra temperature control subsystem [34]. It has an energy density ranging from 150-240 Wh/kg, power density from 150 to 230 W/kg, efficiency rate ranging 70-90%, response time in a millisecond-scale, longer discharging times, and a cycle life ranging from 2,500 to 4,000 cycles. The self-discharge rate is relatively high, reaching 20%. It is suitable for applications on a MW scale, and the installation costs range from 500 to 1,000 US$/MWh [20, 28]. American Electric Power (AEP) and Tokyo Electric Power Company (TEPCO) are successful examples in the deployment of large-scale energy storage systems using NaS batteries [110, 111].

ZEBRA batteries use chloride salts as the main active material. Metallic chloride salts are applied at the cathode, e.g., $NiCl_2$, $FeCl_2$, or $NiFeCl_2$. This allows a decrease in the operating temperature, which can improve the power capacity. ZEBRA batteries have a greater voltage, wider temperature operation range from 230° to 345°C, fewer corrosion problems, more robustness, and safety [34]. The energy density ranges from 86-140 Wh/kg and power density 180-245 W/kg. The cycle life is shorter (up to 1,200 cycles) than NaS batteries, and the self-discharge rate is lower (15%). ZEBRA is not suitable for MW-scale applications, and the installation costs vary from 750 to 1000 US$/MWh [20, 28].

According to [81], the LCOS of Sodium Beta batteries varies depending on the application. Residential systems are the most expensive, with an LCOS ranging from 1,476-1,668 US$/MWh. Large scale plants used in bulk power systems have LCOS from 301 to 803 US$/MWh. Energy storage plants connected at distribution level at substations and directly connected to feeders have LCOS ranging from 385 to 1,455 US$/MWh.

6.6 Nickel metal hydride batteries

Nickel Metal Hydride (NiMH) batteries have a huge nominal capacity, as large as NiCd and Lead-acid batteries. The cathode is made from nickel oxide hydroxide (NiOOH), while the anode is formed of a hydrogen-absorbing alloy and potassium hydroxide as electrolyte. The devices are deployed in a valve-regulated package to allow the gases to be released in overcharging and short-circuit situations.

They have a wide operating temperature range, from -20°C to 45°C, less memory effect, and an insignificant environmental impact. Their energy and power density reaches 80 Wh/kg and 460 W/kg, respectively. The cycle life ranges from 800 to 3,000 cycles, with a lifespan of 10 years. They are well-suited for applications in the kW-scale. However, they are subject to several limitations, such as sensitivity to high charging and discharging rates, a significant self-discharge rate, and an energy efficiency rate lower than 85% [20, 112].

7 Comparing electrochemical batteries

Some metrics need to be established to compare different electrochemical devices with regard to their suitability for microgrids. As discussed in the earlier sections, some features are preferred when deploying energy storage systems in microgrids. These include energy density, power density, lifespan, safety, commercial availability, and financial/ technical feasibility.

Lead-acid batteries have lower energy and power densities than other electrochemical devices. They also have a lower lifespan and a limited performance in systems with a high penetration of renewables. Concerning safety, although there is sulfuric acid inside the device, its leakage is not dangerous to the environment. All the material from the battery is recyclable. Nevertheless, there are risks to the maintenance staff, although oxygen and hydrogen produced in regular battery operations are converted into water, which reduces their flammability in the environment.

Furthermore, if there is an increase in the battery's internal pressure, the safety valve helps to lower the gases' pressure. Lead-acid technology is available in different commercial configurations at a low cost and with a high degree of maturity. Maintenance and storage costs are also lower than those of other technologies.

Lithium batteries have higher energy and power densities than those of competing technologies. The cycling features can reach 10,000 complete cycles, with a high Depth of Discharge capacity. Shallow discharging cycles do not damage these batteries. They are a mature technology that is available in the market and formally standardized. There are not any pollutants in the battery. Research has been conducted to provide a range of alternative devices with updated features by testing different materials in anodes. As for their disadvantages, lithium batteries include scarce materials, like lithium and cobalt, which leads to higher costs than other devices. Since it is a highly inflammable material, research has been conducted to deploy safety devices. Lithium batteries are supplied with a dedicated battery management system to control the operating temperature and battery state of charge to avoid overcharging. NMC, LFP, and NCA configurations provide a higher degree of safety than other lithium batteries.

Flow batteries have relatively lower power and energy densities than competing electrochemical devices. However, the nominal capacities are easily scalable depending on the application. They have a longer lifespan (beyond 10,000 cycles) with a high depth of discharge without substantial degradation. Vanadium flow batteries have a good performance in ambient temperature, but ZnBr models need additional temperature control to prevent bromine corrosion. Since it is a highly modular technology, large-scale applications require large reservoirs and, as a result, a larger area. There is an increase in initial costs because vanadium and other subsystems, such as membranes, control systems, and hydraulic pumps, are expensive. In contrast, the O&M costs are low since zinc and bromine are abundant materials.

Nickel Cadmium batteries have a high energy density as well as a high self-discharge rate. However, there are many disadvantages to their use. Although they include safety devices for a broadly operating temperature interval, they have a limited performance and life cycle due to the memory effect and low voltage cells, high initial costs, and cadmium toxicity.

Nickel-metal Hydride batteries have reasonable power and energy densities that are only lower than lithium technology and are very cost-effective. However, the life cycle is their most serious problem since their power is reduced by fast charging and discharging cycles in renewable-based systems. Deep discharges below 80% also affect the battery lifespan, and the memory effect and low efficiency are other drawbacks. Despite this, since the NiMH batteries do not have problems with low temperatures, they are suitable for specific applications in cold regions of the world.

Beta sodium batteries are a mature technology and commercially available. They usually have low power and energy densities despite the power density of the NaS battery. The battery lifespan and cycling features are appropriate for applications in renewable-based systems. However, although these batteries operate in high temperatures, they require fire protection and temperature control systems, making their use expensive for small systems operations.

To summarize the above comparison, Table 8 displays scores from 1 to 5 for different devices, based on the respective metrics. Score 1 represents the worst performance, while 5 represents the best.

However, the mean value is not a good indicator for choosing one kind of battery rather than another. It conceals some critical properties that are attractive for a specific application. Flow batteries, for instance, have modules with large volumes that are inappropriate for applications with spatial restrictions. In outdoor systems, however, this feature is not essential.

Lithium batteries seem to be suitable for hybrid applications that involve numerous and deep cycles, such as primary regulation and peak shaving services. The LFP model is the safest one, although it incurs higher costs than the other lithium batteries.

The advanced lead-acid batteries also have good indicators of the life cycle and depth of discharge. If future research can improve these features, it will be possible to regard them as competitive technology because of their maturity, safety, and robustness.

Energy storage is having a strategic effect on the growth of many economic sectors. Initially, the costs were affected by the need to develop research and the availability of raw material. Now, with costs falling to stable values, storage valuation will be a critical growth factor. Following this trend, many government entities, private automobile manufacturers, and oil companies in Europe and the USA have invested billions in deploying low-carbon technologies, including energy storage.

Table 8 Comparison between different battery devices. Source: [113]

Type	Energy density	Power density	Lifespan	Safety	Financial feasibility	Overall score
Lead-acid	Low (Score: 1)	Low (Score: 2)	Low (Score: 1)	High (Score: 5)	High (Score:5)	2.8
Advanced Lead-Acid	Low (Score:1,5)	Moderate (Score:3)	Moderate (Score: 3)	High (Score: 5)	Moderate (Score: 3.5)	3.2
NaS	High (Score: 5)	Low (Score: 2)	Moderate (Score: 3.5)	Moderate (Score:3.5)	High (Score: 4)	3.6
LTO	Moderate (Score: 3)	Moderate (Score: 3)	High (Score: 5)	High (Score: 4)	Low (Score: 1)	3.2
LCO	High (Score:5)	Low (Score: 1)	Low (Score: 1)	Moderate (Score: 3)	Moderate (Score: 3.5)	2.7
LMO	Moderate (Score: 3.5)	Moderate (Score: 2.5)	Low (Score: 1.5)	High (Score: 4)	High (Score: 4.5)	3.2
LFP	Moderate (Score: 3.5)	High (Score: 5)	Moderate (Score: 3)	High (Score: 4)	Moderate (Score: 3.5)	3.8
NMC	High (Score: 4.5)	Moderate (Score: 3)	Moderate (Score: 3)	Moderate (Score: 3)	High (Score: 4.5)	3.5
NCA	High (Score: 4.5)	Low (Score: 1.5)	Low (Score: 1.5)	Moderate (Score: 3)	High (Score: 4.5)	3
Flow Batteries	Low (Score: 1)	High (Score: 5)	High (Score: 5)	High (Score: 5)	Moderate (Score:2)	3
Ni-MH	Moderate (Score: 2.5)	Moderate (Score: 3)	Low (Score: 2)	High (Score: 5)	Moderate (Score: 3.5)	3.2

Owing to the manufacturers' constant improvements and innovations, there is a need for a constant review of evolving products and an updating of the technological storage systems, with agents changing positions in terms of rankings and others entering the competitive market. The energy storage market can be regarded as a thermometer for measuring the intensity of the energy transition process.

Table 9 provides a summary of storage system applications based on their technologies.

8 Conclusion and future trends

This paper has provided an overview of electrochemical energy storage technologies that are suitable for application in microgrids. Although there is a range of alternatives, electrochemical batteries seem best suited to microgrids due to their maturity, technical requirements, cost-effectiveness, fast deployment, limited spatial requirements, and modularity.

The general features of the leading electrochemical technologies have been investigated, such as technical characteristics, operating principles, costs, and key applications. The main characteristics have been examined and compared based on classic metrics: maturity level, unit costs, useful life, and degree of safety.

Table 9 Data on Real Electrochemical Energy Storage Systems. Source: [19, 44, 109, 114, 115]

Project	Local	Battery model	System specifications		Application
			MW	MWh	
Ilha Grande	Brazil	Lead-acid	0.03	0.3	Backup power and frequency regulation in an isolated microgrid
Lençóis Island	Brazil	Lead-acid	0.036	0.216	Backup power and frequency regulation in an isolated microgrid
Laurel Mountain	West Virginia, USA	Lithium	32	8	Frequency regulation and power smoothing
Zhangbei	China	Lithium	20	36	Frequency regulation, reliability, and power smoothing
AES Generation Los Andes substation	Chile	Lithium	12	N/A	Frequency regulation, spinning reserve, and power smoothing
Southern California at Tehachapi	California, USA	Lithium	N/A	32	Frequency regulation, power transmission losses, and congestion relief, reliability, and power smoothing
Edison ESS facility	Italy	VRB	0.005	0.025	Power backup for telecommunication systems
Wind Power ESS Facility King Island	Australia	VRB	0.2	0.8	Wind power integration
Wind Farm ESS Project	Ireland	VRB	2	12	Wind power intermittence smoothing
SEI test facility 1	Japan	VRB	1.5	3	Power quality
PacifiCorp facility	USA	VRB	0.25	2	Load shifting and voltage support
SEI facility	Japan	VRB	0.5	5	Peak shaving and voltage support
Kazakhstan Flow Batteries Primus Power	Kazakhstan	ZnBr	25	100	Load shifting and resilience
PSE Bellevue Project	USA	ZnBr	0.5	1	Power quality
Tetiaroa Brando Resort	French Polynesia	ZnBr	0.5	2	Wind power integration
San Nicolas Naval Facility	USA	ZnBr	0.5	1	Demand leveling, power quality, and grid stability
Fort Sill Microgrid	USA	ZnBr	0.25	0.5	Renewable integration
Golden Valley Electric Association	USA	Ni-Cd	27	6.75	Backup Energy
Amplex Group	United Arab Emirates	NaS	350	N/A	Grid stabilization, frequency regulation, voltage support, and power quality
Tokyo Electric Power Company	Japan	NaS	200	N/A	Power quality and peak shaving
Abu Dhabi Water and Electricity Authority	United Arab Emirates	NaS	48	N/A	N/A

Table 9 (continued)

Project	Local	Battery model	System specifications		Application
			MW	MWh	
Japan Wind Development Co.	Japan	NaS	34	238	Wind power integration
American Electric Power	USA	NaS	11	N/A	Power quality and peak shaving
Long Island, New York Bus Terminal Energy	USA	NaS	1,2	6.5	Demand shifting
Younicos	Germany	NaS	1	N/A	N/A

There is a dynamic evolving pattern in creating new products brought about by the constant improvements and innovations of the manufacturers. Three factors (not unique, but the most important) are driving the development of competitive and reliable storage technologies with varying degrees of intensity: electric vehicles, energy transition, and resilience in modern grid management. These factors are not independent of each other, but they converge with explicit couplings in the needs in a way that can meet the specific demands for storage devices in each sector.

The availability of raw material is also a constraining factor in electrochemical storage technologies. The reserves of lithium are concentrated in a small number of countries. In addition, there is the question of vanadium. Seeking substitute materials is essential for industrial development and can prevent demand from being stifled in the next few years.

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Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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