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Review

Review on Energy Storage Systems in Microgrids

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Abstract: Energy storage systems (ESSs) are gaining a lot of interest due to the trend of increasing the use of renewable energies. This paper reviews the different ESSs in power systems, especially microgrids showing their essential role in enhancing the performance of electrical systems. Therefore, The ESSs classified into various technologies as a function of the energy storage form and the main relevant technical parameters. In this review paper, the most common classifications are presented, summarized, and compared according to their characteristics. A specific interest in electrochemical ESSs, especially battery energy storage systems, focusing on their classifications due to their importance in the residential sector. Besides that, the benefits and drawbacks of Lithium-Ion (Li-Ion) batteries are discussed due to their significance. Finally, the environmental impact of these ESSs is discussed.

Keywords: energy storage system; electrochemical energy storage; thermal energy storage; mechanical energy storage; batteries; microgrids

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1. Introduction

At the beginning of the 2000s, scientific research in the field of energy storage systems (ESSs) has been developed and increased significantly. Figure 1 shows the publications per year according to the Scopus analysis on ESSs. Analyzing the papers that were published recently, it has been found that many of the review research papers in ESSs are focusing only on the classification of ESS. Sometimes, the classification is varied from one paper to another. Other papers are summarizing the applications of ESSs, and another includes the environmental impact of ESSs. For instance, in [1], ESSs are classified into mechanical, chemical, electromagnetic, and thermal storage. However, in [2] ESSs are divided into six categories: mechanical, thermal, chemical, electrochemical, electrical, and hybrid systems. ESSs are divided into electrochemical, electromagnetic, thermodynamic, and mechanical in [3]. Reference [4] focus on the environmental impacts of ESSs. Therefore, it is vital to make this review include different groups of ESSs commonly used in microgrids during this period classifying them according to their physical form and technical characteristics. Also, including their applications and environmental impact in the review paper. Energy storage is the formation of different styles of energy at one time, which can be used for some useful operations at different times. Generally speaking, electric energy needs to be transformed into another form of energy that can be stored. Energy can be stored in various forms, such as chemical, electrochemical, electrical, mechanical, and thermal systems. A better way to store energy is essential to improve energy storage efficiency. One of the keys to the progress of energy storage is to find new materials and understand the functions of current and new materials.

A microgrid is a small-scale power grid that can operate independently (Isolated mode) or collaboratively with the power grid (Grid-connected mode), enabling net power flows with the distribution network. The essential elements within a microgrid are the loads, the generation systems, either dispatchable generators or renewable energy sources, power electronic converters, and protection devices. The most significant share of renewable energy sources in microgrids is based on solar photovoltaic or wind turbine generation. Both sources rely on natural phenomena such as solar irradiance or wind speed. With the increasing penetration of renewable energy sources, the stability and the reliability of the microgrid are affected as those energy sources are intermittents [5,6].

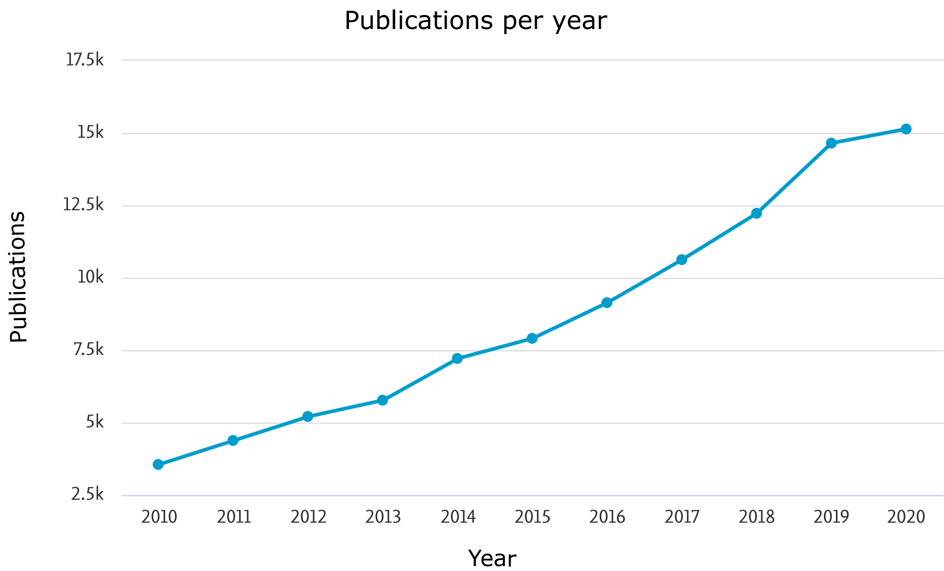

Figure 1. Scopus analysis on energy storage systems researches in the last 20 years.

However, the continuous development of ESS [7,8] balances the stochastic behaviour of both the renewable energy sources and the power demanded at the microgrid, ensuring an uninterrupted and stable power flow to the loads [9–11].

The benefits of integrating ESSs in electrical power systems have been widely increased. This is due to the fact that renewable energy is intermittent and not always reliable in power systems, which is influenced by natural factors. ESSs are solving the intermittent drawback of renewable energy and increase the reliability of the power system. Also, ESSs provide more advantages, for instance, peak shaving, valley filling, etc. This discussion aims to demonstrate how these ESSs play a key supporting role in the performance of electric systems. Even though these benefits are valid from large-scale generation down to the end-user applications, in particular, the benefits of ESS in microgrids are targeted here [12–14]:

- From the point of view of the generation, ESSs allow for:
  - Maintaining uninterrupted and stable power flow to the loads [9–11,15]: Due to the penetration of renewable generation sources, ESS is needed to provide power when the renewable sources are not able to supply energy to the system.
  - Providing peak shaving/load levelling [5,14,16–19]: The ESS enables the system to store the surplus energy during the light load and low price of energy periods and to provide the required energy at heavy load intervals and high price periods.
  - Giving support for black-start and reduce the risk of blackouts [5,6,14]: The black-start occurs when the system needs to be restarted after a blackout (collapse of failure or large power outage). It has been reported how some specific technologies (e.g., electrochemical batteries and supercapacitors) have the capability of achieving such restoring features [20].
  - Enabling the use of mobile/remote applications [20]: It provides power for remote areas or stand-alone systems such as electric vehicles and portable devices.
- At the transmission level, ESS provides for:

  - Postponement of infrastructure upgrades and congestion relief [12]: The usage of ESS reduces the need for new investments in order to have a suitable transmission capacity.
  - Voltage Regulation [13]: ESS allows for stabilizing the voltage levels between each end of the power lines in the system.
- Finally, at the distribution level and end-user services, the implementation of ESS yields to:
  - Improving the power quality [5,12,15–17,21–23]: In order to effectively minimize the effects of power quality issues (instantaneous voltage drop, transients and flicker, sag, swell, and harmonics), it required a fast response of the ESS. Supercapacitors, superconducting magnetic storage systems, and flywheels have a very fast response, within the range of milliseconds. These dynamics are followed by the performance of batteries, with characteristic responses in the order of seconds [20].
  - Increasing reliability [12,16,17]: ESSs support customer loads in the case of the loss of total power.
  - Providing voltage support [17]: Maintain the voltage within an acceptable range.
  - Postponement of the infrastructure upgrades [12]: Utilizing ESS reduces the need for new investments to have suitable distribution capacity to meet the increasing load demands. ESSs can mitigate the congestion and thus help utilities to postpone or suspend the reinforcement of the distribution network. This can be done using peak shaving.
  - Ride-through support [17]: ESS can provide energy to ride-through operation after disconnection due to a fault in the system and fault clearance.

In order to determine the optimal ESS technology for a given application, the requirements in terms of minimum response time and minimum discharge time need to be characterized. Table 1 shows the minimum response time needed and the minimum discharge duration of the key applications of the ESSs [12,21].

Table 1. The minimum response time and discharge time of the applications of the ESS.

Applications of ESS	Minimum Response Time	Minimum Discharge Duration
	Generation	
Uninterrupted and stable power flow	s	10 min–2 h
Peak shaving	min–h	s–10 h
Black-start	s–min	1 h–6 h
Mobile applications	ms–s	s–h
	Transmission	
Postponement of infrastructure upgrades	min	1 h–6 h
Voltage regulation	ms–s	6 min–1 h
	Distribution and end-user services	
Power quality	<5 ms	ms–1.2 min
Reliability	5 ms–s	5 min–5 h
Voltage support	<5 ms	15 min
Postponement of infrastructure upgrades	min	2 h–8 h
Ride-through support	<5 ms	10 s–15 min
Transportation applications	ms–s	s–h

The structure of this paper is organized as follows: Section 2 explains the different ESSs depending on how the energy is stored. Then, classification based on characteristic time is discussed in Section 3. After that, Section 4 focuses on batteries electrochemical ESSs as it is one of the most ESSs widely used in several applications. Sequentially, Section 5 shows the environmental effect of different ESSs. Finally, Section 6 summarises the conclusions and illustrates the future trends in this topic.

2. Energy Storage Systems Technologies

In this section, a summarized review of the different ESS technologies suitable for electrical system applications is carried out. Depending on the physical form and mechanism in which the energy is stored, the energy stored could be mechanical, electrical, chemical, electrochemical, and thermal form. A first classification established as follows [12,21,24–29]:

1. Mechanical Energy Storage System: The energy is stored in the form of kinetic or potential energy.
    (a) Kinetic Energy Storage System:
        i. Flywheel energy storage system (FESS) [5,6,22,23,30–34]:

        The flywheel relocates kinetic energy through an electric machine. The rotating mass of this machine is received the charging power to be stored and used later as electric energy when discharging on demand [35–37].
    (b) Potential Energy Storage System:
        i. Compressed air energy storage system (CAESS) [5,6,22,23,30–34]: The air is compressed into a defined pressure using a piston, then using natural gas to combust it for turbines using as mechanical energy storage generating electricity when needed. It stores a large amount of energy without needs a specific location installation [38–40].
        ii. Pumped hydro energy storage system (PHESS) [5,6,22,23,30,32–34]: The pump stores energy in the form of the gravitational potential energy of water. The structure of the PHES integrated storage facility consists of three items; Water resource, pump, and two dedicated reservoirs with different height levels linked by a pipeline. Recently, adding power electronics enables PHES units to work at mutable speeds in both pump and turbine modes [41–44].
        iii. Gravitational energy storage system (GESS) [45,46]: It is a device stores renewable energy or pumped hydropower in the form of gravitational potential energy. The gravity power is based on a huge underground piston, which is lifted hydraulically to store energy and then released to push water through a turbine. Its feature over electrochemical batteries is that their capacity does not decay each cycle, and their power capacity is decoupled from their energy capacity.
2. Electrical Energy Storage System: The energy is stored in the form of electrostatic or magnetic fields.
    (a) Electrostatic Energy Storage System:
        i. Conventional capacitors [6,30]: A capacitor stores energy in the electrical field between their plates; so capacitors connecting to the grid can retain voltage stability by releasing their stored energy. As energy cannot be stored mechanically; the electrostatic charge can be stored in capacitors [47,48].
    (b) Magnetic Energy Storage System:
        i. Superconducting magnetic energy storage system (SMESS) [5,6,22,23,31–33]: SMESS is a method to store energy electrically, and it considers a high-power pulsed source. It consists of a superconducting coil kept at temperatures low enough to save coil conductivity, and this coil is made with those materials to keep the current and the magnetic flux can be stored. The SMESS strategy to maintain energy is called the dual nature of electromagnetism as it absorbs electrical energy directly and after that delivers it as electrical energy [49–51].

3. Chemical Energy Storage System: Energy can be stored and recovered when some chemical substances are subjected to a transformation through a chemical reaction. The main chemical technologies for energy storage are:
   (a) Hydrogen energy storage system (H_2ESS) [5,22,34]: Hydrogen energy is an immaculate energy source s based on water electrolysis. There are two methods used to store it, physical storage and solid-state storage methods. Compressed gas and liquid hydrogen (physical storage)is the most method used to store hydrogen [52–54].
   (b) Synthetic natural gas (SNG) [5,33,55]: synthetic or substitute natural gas is a fuel gas (methane, CH_4) extracted from fossil fuels that are used in generating electricity. The technology of convert coal to product SNG (Power-to-Gas technology) provides flexibility to meet energy demand, supports domestic employment, and also decreases greenhouse gas emissions through carbon holdover [56,57]. SNG also may be produced from renewable energy by combining pressurized reversible solid oxide cells and catalytic reactors, which have a lot of CO_2 gas through electricity production. During electricity storage and in solid oxide cells, CO_2 and H_2O is turned into CO and H_2, and then in high pressure, the CO and H_2 can be converted to CH_4 into the cell [58].
4. Electrochemical Energy Storage System: This can be defined as a particular case of chemical energy storage, in which reversible chemical reactions in a combination of cells are used to store electrical energy. In electrochemical energy storage systems, the chemical energy contained inactive materials are converted into electrical energy during an electrochemical oxidation-reduction reaction [59].
   (a) Conventional rechargeable batteries [5,6,22,30,31,34].
   (b) Liquid-metal and molten-salt batteries [1,60,61].
   (c) Metal-air batteries [1,62–65].
   (d) Flow batteries [6,22,33,34].
   (e) Supercapacitors [5,6,22,23,32–34]: A supercapacitor is a high-capacity capacitor but with lower voltage limits across electrodes. Based on the voltage difference between charges of electrolytes, supercapacitors rapidly charge/discharge ions from the electrolyte plate. This system has a high cycle life and fast response time [48,66]. The electrochemical energy converts the chemical energy stored into electrical energy, which will be then as electric current at a specific voltage and time [67].
   (f) Fuel Cells (FCs) [15,31,33]: FCs are used to convert the chemical energy of reactant into electricity as a long-term storage system and then supply power in short periods; so, it improves power quality export, flexibility, and reliability. It presents a relatively slow transient dynamic due to the time response of the gas supply system. Because the FCs are limited to compensate for an imbalance in power, FC must be connecting with other energy storage systems such as batteries [68], hydrogen [69], and supercapacitors [70]. There are different types of fuel cells based on the type of electrolyte, such as proton exchange membrane fuel cell (PEMFC), solid oxide fuel cell (SOFC), phosphoric acid fuel cell (PAFC), molten carbonate fuel cell (MCFC), alkaline fuel cell (AFC). Proton exchange membrane fuel cells (PEMFCs) that contain a hydrogen-storable polymer (HSP) are considered the most successful and commercialized in residential and automobile [71,72].
5. Thermal Energy Storage System (TESS) [5,6,22]: Heat is also a form of energy that can be used for electrical systems storage applications. Depending on the range of temperatures involved, two different sets of technologies can be identified:
   (a) Low/temperature thermal energy storage system [23,73,74]:
      i. Aquiferous low-temperature thermal energy storage system (ALTTESS) [12,13,21]: Aquifer thermal energy storage is a convenient tech-

nology for enabling substantial storage capacities compared with other ground energy systems which stores cooled and heated groundwater in the ground from respective cooling and heating mood cycles [75,76].
    ii. Cryogenic energy storage system (CESS) [12,13,21]: Cryogenic energy storage stores energy using low-temperature liquids (cryogenic) such as liquid air or liquid nitrogen as a storage medium. The CESS converts heat to power efficaciously in energy extraction using cryogen itself as the working fluid [77,78].
(b) High-temperature thermal energy storage system (HTTESS) [23]:
    i. Molten salt storage (MSS) and room temperature ionic liquids (RTIL) [12,13]: Molten salts can retain thermal energy so that they can use as a thermal energy storage method. Molten salts and room temperature ionic liquids are a beneficial milieu for several inorganic materials synthesis in various temperature reactions, so the energy is stored at a high temperature through the heated molten salt [79,80].
    ii. Concrete storage [13,81]: Because of the suitable cost of Concrete material and availability to handle and being castable into a building component, using concrete is very convenient as a solid storage material. To store energy in concrete material at a high temperature requires special installation and some definite measures for long-dated stable storage material. Concrete storage is designed dependent on system parameters such as temperature, pressure, required storage capacity, and heat rate [82].
    iii. Phase change material (PCM) [13,21]: PCMs are materials that have unique characteristics that are different from conventional ones. PCMs are excellent heat storage materials as they have a superior efficiency in energy conversion and energy density, and also they store repetitively and releasing a lot of heat at an almost stationary temperature through the phase change. [83,84].
(c) Hybrid thermal energy storage system (HTESS) [85]: A hybrid thermal energy storage system aims to administer the storage of heat from solar and electric energy together, as the energy is stored on sunny days in solar cells and at the off-peak time in thermal electric energy to restore them in on peak times. There are different designs for designs of HTESS; such as Packed-bed thermal energy storage, two-tank thermal energy storage [86], metal hybrid thermal energy storage system for the concentrating solar power (CSP) plant [87].

3. Diversified Classification of Energy Storage System

Notice how some of these technologies are classified into different forms of energy depending on the technical literature references. The criterion followed in this classification aims to simplify the definitions of the technologies involved.

On the other hand, these technologies can also be classified based on their storage characteristic duration into short-term ESS used for power quality and voltage support, medium-term ESS used for grid congestion management, reliability, ride through support, peak shaving and frequency response, and long-term ESS used for supply and demand matching, and postponement of infrastructure upgrades [5,6,12–14,16,21,32,55,88]. This classification provides an initial guide to choose the proper ESS depending on the application.

The following classification is thus carried out as a function of this characteristic time:

1. Short-term Energy Storage System (from seconds to minutes): The energy to power ratio is less than 1 (e.g., a capacity of less than 1 kWh with a power of 1 kW system).
    (a) FESS.
    (b) Conventional capacitors.

   (c) Supercapacitors.
   (d) SMESS.
2. Medium-term Energy Storage System (from minutes to hours): The energy to power ratio is between 1 and 10 (e.g., a capacity between 1 kWh and 10 kWh for a 1 kW system).
   (a) Conventional Rechargeable batteries.
   (b) Liquid-Metal and Molten-Salt Batteries.
   (c) ALTESS.
   (d) CESS.
   (e) SNG.
3. Long-term Energy Storage System (from hours to days to months): The energy to power ratio is greater than 10 (e.g., a capacity of greater than 10 kWh for a 1 kW system).
   (a) CAESS.
   (b) PHESS.
   (c) GESS.
   (d) Metal-air batteries.
   (e) Flow batteries.
   (f) Fuel cells.
   (g) H_2ESS.
   (h) MSS and RTIL.
   (i) Concrete storage.
   (j) PCMs.
   (k) HTESS.

Figure 2 shows the rated energy capacity versus duration of storage of the different technologies of ESS [14,16,21,32]. Again, this division into short, medium, and large term scales depends mainly on the specific application, on the power and energy ratings involved, and also on the given criteria followed in the analysis carried out at the specific technical literature references. The categorization shown here aims to match the most general classifications studied.

Table 2 shows the key characteristics of the main ESSs, regarding energy density, power density, specific energy, specific power, rated power, rated energy capacity, response time, discharge time, suitable storage duration, lifetime, and environmental impact [5,12–14,21,55] in order to easily select the proper technology of ESS for the suitable application. Discharge time is the maximum power discharge duration. It depends on the depth of charge and operating conditions [33].

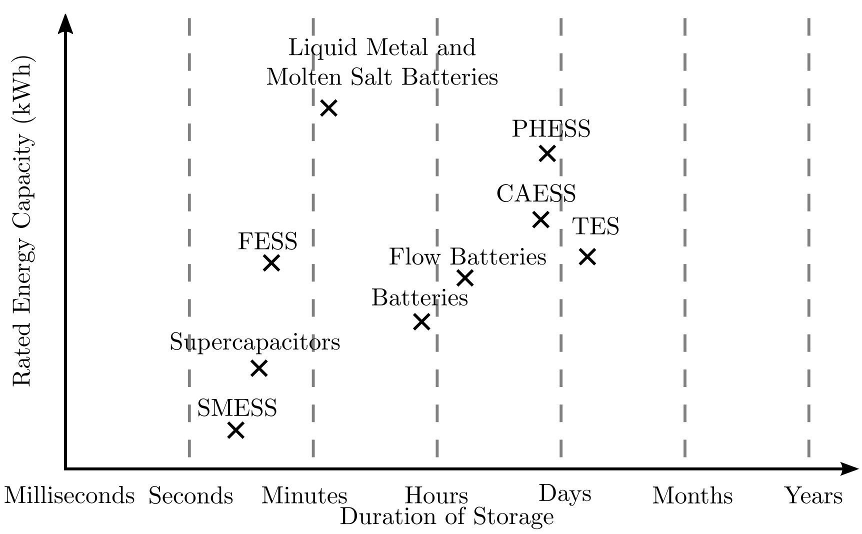

Figure 2. Rated energy capacity versus duration of storage of ESSs.

Table 2. Key Technical characteristics of the main ESSs.

ESS	Energy Density (Wh/L)	Power Density (W/L)	Specific Energy (Wh/kg)	Specific Power (W/kg)	Rated Power (MW)	Rated Energy Capacity (MWh)	Response Time	Discharge Time	Suitable Storage Duration	Lifetime Cycles	Lifetime Impact Years	Environmental
Mechanical Energy Storage System												
FESS	20–80	5000	5–130	400–1600	<20	0.01–5	<4 ms–min	ms–15 min	s–min (short-term)	> 100,000	>20	Very Low
CAESS	12	0.2–0.6	30–60	-	100–300	200–5000	1 min–15 min	30 s–days	h–months (long-term)	>13,000	25–40	Medium
PHESS	0.2–2	0.1–0.2	0.30–1.33	0.5–1.5	100–5000	200–5000	s–min	1 h–days	h–months (long-term)	>100,000	50–100	High
Electrical Energy Storage System												
Conv. cap.	0.05–10	100,000	0.05–5	3000–100,000	0.05	-	<5 ms	ms–1 h	s–h (short-term)	>50,000	1–10	Low
SMESS	6	2600	0.5–10	500–2000	0.01–10	0.00001–0.1	<5 ms	1 ms–1 h	min–h (short-term)	>100,000	>20	Low
Chemical Energy Storage System												
Hydrogen	600	0.2–20	33,330	>500	<50	>100	ms–min	s–days	h–months (long-term)	>1000	5–15	Low
SNG	-	-	-	-	-	-	min.	h–days	Medium-term	-	-	Medium
Electrochemical Energy Storage System												
Supercap.	10–30	40,000–120,000	0.1–15	0.1–5000	0.01–1	0.00001–0.001	<5 ms	1ms–1.2 h	s–h (short-term)	>100,000	>20	Medium
FC	500–3000	>500	800–10,000	>500	50	-	ms–s	s–days	h–months (long-term)	>1000	5–15	Medium
Thermal Energy Storage System												
ALTESS	120–500	-	80–120	-	5	-	min	1 h–8 h	min–days (medium-term)	-	10–20	Low
CESS	120–200	-	150–250	10–30	0.1–300	-	s	1 h–8 h	min–days (medium-term)	-	20–40	Medium
HTTESS	120–500	-	80–200	10–30	60	-	s	1 h–days	min–months (long-term)	13,000	5–15	Low

4. Batteries Energy Storage System

Electrochemical batteries stand out as one of the most commonly used storage technologies both in industrial and residential applications of power systems, microgrids, and nanogrids [13,21]. The energy and the power ratings of the electrochemical battery need to be sized to fulfill the peak power demands, as well as any backup requirements under the islanding mode operation of the target application.

Using Batteries in different parts of the power system (power generation, transmission, distribution system) support system with batteries high power and energy density and the resilient configuration, also battery energy storage systems (BESSs) are used in many fixed and moveable applications; as electric vehicles, submarine missions, aerospace operation. According to these merits batteries are widely used in the generation, transmission, distribution, and also power consumption [89–91].

Batteries consist of two electrodes, during an electrochemical reaction, the chemical energy in batteries turned into electrical energy, as this reaction includes carrying electrons from one material to another through an electrical circuit. Firstly, the operating for a single cell is flooding two electrodes (anode and cathode) into an electrolyte component, which provides the medium for the transfer of charge. Then, the anode is oxidized while it is let down electrons to the external circuit, and the cathode accepts electrons from the external circuit during the electrochemical reaction [59,89].

Given the inherent modular approach of the battery system, which indeed is formed by an assembly of cells and modules, the only limitation for finding a device with enough power ratings comes from the cost or size/weight sides. In fact, increasing the size of the battery pack will solve the power rating requirements, apparently raising the cost as well.

The fundamental characteristic parameters used to define a battery are summarized ahead [92]:

- Nominal Voltage: Reference voltage of the battery pack, as per the conditions specified by the manufacturer. It is measured in Volts.
- Nominal Capacity: Coulometric capacity, measured in Amperes-hour, available when the device is discharged at a given discharge current (generally specified as C-rate), from 100% state-of-charge to the cut-off voltage. The capacity generally decreases with increasing discharge currents.
- State of Charge (SoC): It is a measure of the amount of electrical energy stored in the battery pack [93]. The units of SoC are percentage points (0% = empty; 100% = full). An alternate form of the same measure is the Depth of Discharge (DoD), the inverse of SoC (100% = empty; 0% = full). SoC is normally used when discussing the current state of a Battery pack in use, while DoD is most often seen when discussing the lifetime of the battery pack after repeated use.
- Discharge Current: A measure of the rate at which a battery pack is discharged, relative to its maximum capacity. A C-rate of 1C means that the discharge current will discharge the entire battery in 1 h.
- State of Health (SoH): It is a figure of merit of the condition of a battery or a cell, compared to its ideal conditions. Typically, a battery's SoH will be 100% at the time of manufacture and will decrease over time and use [94].
- Cycle Life: The number of discharge-charge cycles that the battery pack can suffer, before failing to meet specific performance criteria. This number of cycles is affected by the charge/discharge conditions, temperature, humidity, etc. Generally speaking, the higher the DoD, the lower the cycle life.
- Maximum Continuous Charge (Discharge) Current: Maximum current at which the battery pack can be charged (discharged) continuously. It is given by the manufacturer to limit dangerous charging/discharging rates.
- Maximum Voltage: Also known as charge voltage, it is the voltage at which the device is charged to the full capacity.
- Float Voltage: The voltage at which the battery pack must be kept once charged to 100% SoC to compensate for self-discharge.

- Internal Impedance: The impedance of the battery, generally different for charge and discharge, that accounts for internal losses and dynamic performance. This impedance is a function of parameters that state the battery pack condition, such as the SoH and the SoC.
- Specific Power and Specific Energy: The specific power, measured in W/kg, is the maximum available power per unit mass of the device. In turn, the specific energy (Wh/kg) is the nominal energy stored in the battery, at 100% SoC, per unit mass of the device.
- Power Density and Energy Density: The power density, measured in W/m^3, states the maximum available power per unit volume of the device, whereas the energy density defines the amount of energy stored per unit volume, in Wh/m^3.

The main limitation in the lifetime of the battery comes from the voltage mismatch at cell level within a given battery module. Passive or active cell balancing techniques are required for ensuring an even distribution of the voltages that maximizes the battery lifetime and SoH [95]. These devices are suffering from frequent charge and discharge cycles, in order to supply the instantaneous power requirements [96,97]. Also, if the charge/discharge levels are greater than the rated ones, the lifetime of the battery is significantly jeopardized [98].

The thermal management of the batteries is a significant challenge to operate safely in high power demands. In fact, the batteries need to be adequately refrigerated in high-temperature environments, but in turn, they require warming-up in low-temperature environments, in order to provide the desired power in optimal conditions [99]. Generally speaking, the batteries have a limitation in the transient response (di/dt) [100] as large transient fluctuations might affect the device's performance.

4.1. Classification of Electrochemical Battery Technologies

The batteries are widely used in power systems applications, being quite mature, well-known technology ESS [1,15]. The different implementations of such a battery can be classified attending to their general structure and operation principle.

1. Conventional Rechargeable Batteries: These batteries consist of: positive cathode, negative cathode, electrolyte, and the separator. They are a mature technology and are widely used in many applications.
    (a) Lithium-Ion (Li-Ion) Battery [5,6,22,23,31,99,101–103].
    (b) Lithium-Polymer (Li-Poly) Battery [99].
    (c) Lithium-Iron Phosphate ($LiFePO_4$) Battery [99].
    (d) Lead-Acid (Ph-Acid) Battery [5,6,23,31,99,101–103].
    (e) Nickel-Cadmium (NiCd) Battery Battery [5,6,22,23,31,102].
    (f) Nickel-Metal Hydride (NiMH) Battery [5,6,22,31,99,101,102].
    (g) Nickel–Zinc (NiZn) Battery [102].
    (h) Nickel-Hydrogen (NiH_2) Battery.
    (i) Nickel-Iron (NiFe) Battery [1].
    (j) Zinc Silver Oxide (ZnAg) Battery [1].
    (k) Alkaline Zinc-Manganese Dioxide (ZnMn) Battery [1].
2. Liquid-Metal and Molten-Salt Batteries: These batteries utilize liquid metal/molten salts as electrolytes which plays the part of electrodes. The electrodes are separated by a solid membrane separator. They are still not widely implemented in commercial applications.
    (a) Sodium-Sulfur (NaS) Battery [5,6,22,23,31].
    (b) Sodium Nickel Chloride (NaNiCl) also is known as (ZEBRA) Battery [5,6,13,22,23].
3. Metal-Air Batteries: These batteries replace the second electrode with an air electrode. At present, the technology is not mature enough for practical implementation in grid applications.
    (a) Zinc-air (Zn-Air) [1,13,62,63].

   (b) Iron-Air (Fe-Air) [1,64,65].
4. Flow Batteries: The electrolytes in the battery contain dissolved active materials, that flow through the cell to generate electricity.
   (a) Vanadium Redox Flow Battery (VRFB) [5,6,22,23].
   (b) Polysulfide-Bromide (PSB) Battery [5,6,12,22,23].
   (c) Zinc-based Flow Battery e.g., Zinc-Bromine (ZnBr), Zinc-Cerium (ZnCe) and Zinc-Iodide/Iodine Flow Battery [1,5,6,22,23].
   (d) Iron-based flow batteries [104]. e.g., Iron-chromium (Fe-Cr), Iron-vanadium (Fe-V) [105], Iron-lead (Fe-Pb) [104] and Iron Cadmium (Fe-Cd) [104] .

4.2. Characteristic Parameters of Batteries

The characteristics of the main battery technologies, regarding energy density, power density, specific energy, specific power, rated power, rated energy capacity, response time, discharge time, suitable storage duration, lifetime, and environmental impact are presented in Table 3 [1,12,13,21,23–25,31,67,99,106].

It can be seen from Table 3 that the Li-Ion battery has better characteristics compared to other technologies of batteries [21]. Li-Ion batteries are increasing in the market due to they have a long cycle life, a high cell voltage, good low-temperature performance, good charge retention, high depth of charge [1].

4.3. Applications of the Lithium-Ion Battery

From the technical literature and Table 3, it can be said that the Li-Ion technology presents a great potential for many applications:

- At generation level:
  - Renewable energy smoothing and stable power flow to the loads[14].
  - Provide peak shaving [55].
  - Emergency supply [55].
  - Used in mobile applications such as electric vehicles [55].
- At transmission level:
  - Voltage regulation [14]
- At distribution level and end-user services and end-user:
  - Improving the power quality [14,55].
  - Increasing the service reliability (Customer backup) [14].
  - Distribution upgrade deferral [14].

From the above, the Li-Ion battery has several applications and advantages; however, it has some drawbacks. In large-scale applications, the high cost of batteries is considered the main issue. Li-Ion batteries cannot tolerate excessive charge and discharge, aging, and overheating can also be problematic. Therefore, it is required internal protection circuits. Transportation became a problem in recent years as many airlines limit loading the number of Li-Ion batteries [89,107,108]. Once misused, life will be shortened, the electrolyte is flammable, and may even be prone to catastrophic failure [12]. However, Flow batteries are preferred in large-scale applications as they are not flammable, and deep charge-discharge is not harmful to such technique.

In order to match the application with the suitable ESS; data in Tables 1–3 is used to propose the suitable ESSs for each application. The proposed ESS is decided according to the minimum required response time and minimum discharge time, and it can be seen as follows in Table 4.

Table 3. Technical Characteristics of batteries.

Technology	Energy Density	Power Density	Specific Energy	Specific Power	Rated Power	Rated Energy Capacity	Response Time	Discharge Time	Suitable Storage Duration	Lifetime	Lifetime	Enviromental Impact
	(Wh/L)	(W/L)	(Wh/Kg)	(W/Kg)	(MW)	(MWh)				(Cycle)	(Years)	
Li-Ion	94–500	1300–10,000	30–300	8–2000	1–100	0.0004–25	ms	15 min–8 h	min–days (medium-term)	4500	8–15	Very Low
Li-Poly	200	250–1000	130–200	1000–2800	-	-	-	-	-	-	-	-
Pb-Acid	25–90	10–700	10–50	25–415	0–50	0.001–48	<5 ms	s–10 h	min–days (medium-term)	2000	3–15	Medium
Ni-Cd	15–150	75–700	10–80	50–300	0–50	6.75	ms	s–8 h	min– days (medium-term)	3000	15–20	Very Low
Ni-MH	38.9–350	7.8–588	30–120	6.02–1200	0.01–0.2	3	ms	18 min–8 h	min–days (medium-term)	300–500	5–10	Medium
Ni-Zn	80–400	121.38	15–110	50–900	0.001–0.05	-	ms	18 min–8 h	min–days (medium-term)	-	-	Low
Ni-Fe	25–80	12.68–35.18	27–60	20.57–110	0–0.05	-	-	-	-	-	-	Low
Zn-Ag	4.2–957	3.6–610	81–276	0.09–330	0.25	-	-	-	-	-	-	-
Zn-Mn	360–400	12.35–101.7	80–175	4.35–35	0–0.001	-	-	-	-	-	-	-
NaS	150–345	50–180	100–250	14.29–260	0.01–80	0.4–244.8	ms	s–7 h	s–h (medium-term)	2500–6000	12–20	Very Low
NaNiCl	108–200	54.2–300	85–140	10–260	0–53	0.12–5	ms	min–4 h	s–h (medium-term)	1000–2500	12–20	-
Zn-Air	22–1673	10–208	10–470	60–225	0–1	5.4	ms	s–days	h–months (long-term)	-	-	Very Low
Fe-Air	100–1000	250	8–109	18.86–146	0–0.01	-	-	-	-	-	-	Very Low
VRB	10–70	0.5–33.42	10–75	31.3–166	0.03–50	2–60	<1 ms	s–d	h–months (long-term)	12,000	10–20	Low
PSB	10.8–60	1–4.16	10–50	-	0.001–100	0.06–120	20 ms	s–10 h	h–months (long-term)	-	10 - 15	-
ZnBr	5.17–70	1–25	11–90	5.5–150	0.001–20	0.05–50	<1 ms	s–10 h	h–months (long-term)	2000	5–10	Low

Table 4. Proposed ESSs for various applications.

Applications of ESSs	Proposed ESS
Generation	
Uninterrupted and stable power flow	FESS, CAESS, SMESS, BESS, Flow batteries, Supercapacitors and FCs.
Peak shaving	PHESS, CAESS and BESS, flow batteries, FCs and TESS
Black-start	CAESS, BESS, Flow batteries, FCs and TESS
Mobile applications	FESS, BESS, supercapacitors and FCs.
Transmission	
Postponement of infrastructure upgrades	PHESS, CAESS, BESS, Flow batteries, FCs and TESS
Voltage regulation	FESS, SMESS, BESS, Flow batteries and supercapacitors
Distribution and end-user services	
Power quality	FESS, capacitors, SMESS, BESS, flow batteries and supercapacitors
Reliability	FESS, SMESS, BESS, flow batteries and supercapacitors
Voltage support	FESS, BESS, SMESS, flow batteries and supercapacitors
Energy management	FESS, CAESS, Li-Ion, ph-Acid, Ni-Cd, Flow batteries, FC and TESS
Ride-through support	FESS, BESS, Flow batteries. FC and supercapacitors
Transportation applications	FESS, Li-Ion, Ph- Acid, Ni-Cd, Metal Air Batteries, Supercapacitors and FC

5. Environmental Impact

ESSs have some impacts on the environment, and these impacts are varying from one ESS to other. The environmental impact of the ESS is gaining a lot of interest in the last few years. The environmental impact of pumped-hydro and compressed air is the most severe. Some technologies of ESSs contain toxic materials and cause potential risks, e.g., lead, bromine and, cadmium in batteries. However, flywheels generally have a very low environmental impact during normal operation [12,28,37]. The environmental impact of ESSs is classified into high, medium, low, and very low according to the effect of ESS on the environment as shown in Table 2.

1. Mechanical Energy Storage Systems
    (a) FESS: It is considered the least environmental impact among the technologies of Mechanical ESSs. These systems couldn't cause issues to their zones; because of safety protection applied to the operation of heavy, rapidly rotating objects [2–4].
    (b) CAESS: It is better than PHESS in terms of high reliability, flexibility, long life, comparatively low operation, maintenance costs, and low self-discharge rates. Due to no combust of fossil fuel, and a critical selection of construction and operation of a CAESS facility, the CAESS has a low environmental impact [2–4].
    (c) PHESS & GESS: The environmental impact of PHESS is affected by the construction of roads, pipes, or tunnels for water conveyance, a powerhouse and switchyard, and high voltage transmission lines. To minimizes the environmental impact in PHES, selecting a location far from rivers is very important. PHESS and GESS are considered a high environmental impact compared with FESS as it depends on location [1,109,110].
2. Electrical Energy Storage Systems
    (a) SMES: It requires extremely low temperature for its operation. This could be a safety issue. Protection is needed to deal with magnetic radiation issues [111].
3. Chemical Energy Storage Systems
    (a) H_2ESS: The hydrogen production includes natural gas to Steam, transform coal into gas, electrolysis using renewable power, and also convert biomass

and nuclear power to gas. These processes happen for remote consumers, so H_2ESS is considered a clean technology [4].

(b) SNG: As natural gas has a lower sulphur and nitrogen content than coal and hydrocarbons, thus synthetic natural gas is a lower environmental impact than fuel because of the energy involved in the gas's creation [112].

4. Electrochemical Energy Storage Systems

   (a) Batteries: They are the most appropriate method to store energy because of their effectiveness with low maintenance. However, environmental impacts of large-scale battery use such as global warming, weather change, the soil, water, air pollution, and its effect on health remain one of the most important of batteries' limitations. Raw materials of batteries and public health issues are environmental impacts affecting batteries during manufacturing, processing, recycling, and utilization. [113]. Table 3 shows the environmental impact of these batteries.

      i. Lithium batteries have very low environmental impacts due to their materials being capable of being recycled, like the salts and the lithium oxides [114]
      ii. The lead used in Pb-Acid batteries is toxic and should be recycled. Also, the sulphuric acid in these batteries generates hydrogen when the battery is overcharged which could be an explosion risk [2,4].
      iii. The main issue in Ni-Cd is the highly toxic cadmium. Most nickel is recovered from end-of-life batteries. However, in Ni-MH batteries, both the nickel and the electrolyte are semi-toxic [2,4].
      iv. The environmental impact of NaS batteries is low. This is due to the materials used in the construction of these batteries are environmentally inert [2,4].
      v. Metal-air batteries are relatively environmentally inert since no toxic materials are involved in their construction. Metals such as zinc, iron, or aluminum used in battery construction should be recycled [2,4].
      vi. The size of flow batteries could be an issue as significant space is required. These batteries can discharge infinitely so that no significant waste is produced [115].

      In order to reduce the environmental impact of battery systems, the battery management system (BMS) is the approach that affects batteries' operation and performance to achieve this aim. BMS is achieved by making an interface between the management system and user to control and examine battery systems' performance through six functions. Monitoring, protection, charging and discharging management, communication, diagnosis, and data management are the BMS functionalities used to enhance the battery performance with suitable safety measures in a system [116].

   (b) Supercapacitors: The environmental impact is considered low, but it increases in supercapacitors depending on the materials and their construction and operation at vehicles as supercapcitors used to improve vehicles' performance [4].
   (c) FCs: The environmental impacts of FC depend on the hydrogen-rich fuel used. So, if the hydrogen is pure, FCs will be an environmentally friendly alternative to conventional fossil fuels. [2,4].

5. Thermal Energy Storage: They have a low environmental impact as they reduce greenhouse gases. The collection of photovoltaic panels along with solar heating panels, make it an appreciated system with low environmental impact for small-scale heat storage [4].

6. Conclusions and Future Trends

A review of energy storage systems is exhibited, giving an initial guide to select the appropriate technology. In this paper, a short brief for prospective energy storage systems is demonstrated, and various classifications for these technologies are defined according to the form that the energy is stored and their characteristic time. The ESSs are increasing steadily in many countries and the residential sector is mainly utilizing electrochemical Batteries. Therefore, a detailed review of electrochemical battery technologies is discussed due to their importance in microgrids. Recently, the environmental impact of ESSs is gaining a lot of interest due to the worldwide challenges to protect the environment.

Future research should cover the optimal size of ESSs depending on the application, and define the constraints and limits of ESSs. Also, an analysis on combing more than ESSs to form a hybrid ESS and a study on their effect on the efficiency and performance of the overall system. In addition, the diverse typologies used to connect these ESSs to the electrical grid should be Explored. Finally, the cost of ESSs should be taken into account., considering low-cost energy with high efficiency.

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Abbreviations

The following abbreviations are used in this manuscript:

AFC	Alkaline Fuel cell
ALTTESS	Aquiferous low temperature thermal energy storage system
BESS	Battery energy storage systems
BMS	Battery management system
CAESS	Compressed air energy storage system
CESS	Cryogenic energy storage system
CSP	Concentrating solar power
DoD	Depth of Discharge
ESS	Energy Storage System
FC	Fuel cell
Fe-Air	Iron-Air
FESS	Flywheel energy storage system
GESS	Gravitational energy storage system
H_2ESS	Hydrogen energy storage system
HTESS	Hybrid thermal energy storage system
HTTESS	High temperature thermal energy storage system
HSP	Hydrogen-storable polymer
$LiFePO_4$	Lithium-Iron Phosphate
Li-Ion	Lithium-Ion
Li-Poly	Lithium-Polymer

MCFC	Molten carbonate fuel cell
MSS	Molten salt storage
NaNiCl	Sodium Nickel Chloride
NaS	Sodium-Sulfur
NiCd	Nickel-Cadmium
NiFe	Nickel-Iron
NiH_2	Nickel-Hydrogen
NiMH	Nickel-Metal Hydride
NiZn	Nickel–Zinc
PAFC	Phosphoric acid fuel cell
PCM	Phase change material
Ph-Acid	Lead-Acid
PEMFC	proton exchange membrane fuel cell
PHESS	Pumped hydro energy storage system
PSB	Polysulfide-Bromide
RTIL	Room temperature ionic liquids
SMESS	Superconducting magnetic energy storage system
SOFC	Solid oxide fuel cell
SNG	Synthetic natural gas
SoC	State of Charge
SoH	State of Health
TESS	Thermal Energy Storage System
VRFB	Vanadium Redox Flow
ZnAg	Zinc Silver Oxide
Zn-Air	Zinc-air
ZnBr	Zinc-Bromine
ZnCe	Zinc-Cerium
ZnMn	Alkaline Zinc-Manganese Dioxide

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