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Review

Recent Advances in Energy Storage Systems for Renewable Source Grid Integration: A Comprehensive Review

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Abstract: The reduction of greenhouse gas emissions and strengthening the security of electric energy have gained enormous momentum recently. Integrating intermittent renewable energy sources (RESs) such as PV and wind into the existing grid has increased significantly in the last decade. However, this integration hampers the reliable and stable operation of the grid by posing many operational and control challenges. Generation uncertainty, voltage and angular stability, power quality issues, reactive power support and fault ride-through capability are some of the various challenges. The power generated from RESs fluctuates due to unpredictable weather conditions such as wind speed and sunshine. Energy storage systems (ESSs) play a vital role in mitigating the fluctuation by storing the excess generated power and then making it accessible on demand. This paper presents a review of energy storage systems covering several aspects including their main applications for grid integration, the type of storage technology and the power converters used to operate some of the energy storage technologies. This comprehensive review of energy storage systems will guide power utilities; the researchers select the best and the most recent energy storage device based on their effectiveness and economic feasibility.

Keywords: renewable energy sources; power fluctuation; energy storage systems; selection criteria

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1. Introduction

Power generation using renewable energy sources has minimized the use of hydrocarbons for power generation and transportations. Power generated from renewable energy sources can be integrated to the grid in grid connected mode or can act as an independent power island (island mode) [1–3]. Renewable energy supplies 14.8% of the total industrial energy demand mainly for low temperature industries. Nevertheless, for heavy industries such as iron and steel, cement and chemicals, renewable energy accounts for just less than 1% of the combined energy demand. Currently, an energy mix of electricity, solar, wind, and nuclear is being used to supply the loads in various countries of the world and the other forms of energy contributed just less than 1% of the total energy demand [4,5].

The intermittent nature of renewable resources hinders the performance of the grid by introducing issues with system stability, reliability, and power quality. The variability and uncertainty of power output are the two fundamental issues that hinder the bulk integration of renewable energy sources with the existing grid. Introducing energy storage systems (ESSs) to the grid can address the variability issue by decoupling the power generation from demand. In addition, the ESSs improve the power quality of the grid by providing ancillary services [6–8]. The demand for energy storage will continue to grow as the penetration of renewable energy into the electric grid increases year by year.

ESSs are enabling technologies for well-established and new applications such as power peak shaving, electric vehicles, the integration of renewable energies, etc. [9]. ESSs make the grid more reliable by acting as a power source or providing different functions such as spinning reserve, load leveling, power quality improvement and power fluctuation minimization from renewable energy sources. Large ESSs are routinely used alongside renewable generation such as wind to stabilize the power output. The authors of [10–12] presented a comprehensive review of different energy storage systems that are used for grid integration of large-scale renewable energy sources. There is a big opportunity to transition to a carbon-free energy future by integrating ESS with renewable power. ESSs with high ratings and a long duration will play a great role in reducing the environmental impact of the conventional power source.

According to estimates, the worldwide revenue from energy storage for renewables integration will exceed $23 billion by 2026 and the requirements for storing energy will become triple the present values by 2030 [13]. Solar energy has reached grid parity in several locations around the globe and no longer requires policy incentives to incentivize deployment in many markets. However, energy storage mechanisms also face many challenges as well [14] as there being no one storage type that has the complete characteristics required by the modern grid. Limitations such as storage capacity, response time, efficiency, cost and implementation requirements are to name a few. Some ESSs such as batteries also have an environmental effect by releasing toxic gas [15].

This review paper provides a comprehensive review of electrical energy storage technologies used to integrate renewable energy sources to the grid. Recent advances and maturity level of the ESSs is also addressed. ESSs are compared based on efficiency, response time and storing capacity and will help researchers and power utilities identify the best storage technology for their system. The rest of the paper is organized as follows. Section 2 presents the global renewable installation while Section 3 describes the necessity of storing electrical energy. Section 4 presents Energy storage systems while Section 5 presents discussion and recommendation and Section 6 concludes the paper.

2. Global Renewable Installation

The total global installed renewable generation capacity at the end of 2020 reached 2799 GW. Hydropower takes the lion share of the global total with an installed capacity of 1211 GW. Wind and solar come second and third with a total installed capacity of 733 GW and 714 GW, respectively. Other renewables installed include bioenergy with an installed capacity of 127 GW, geothermal 14 GW and marine energy 0.5 GW [16].

There was a 10.3% increase in renewable generation capacity in 2020 with installed capacity of 261 GW. Solar energy leads the installed capacity with an increase of 127 GW (+22%) followed by wind with 111 GW (+18%). Hydropower capacity increased by 20 GW (+2%) and bioenergy by 2 GW (+2%). Geothermal energy increased by 164 MW. Along with the renewed growth of hydropower, this exceptional growth in wind and solar led to the highest annual increase in renewable generating capacity ever seen. Figure 1 depicts the share of the renewable generation capacity. Figure 2 shows the total wind installed capacity for the years 2010–2020. Wind power accounted for a substantial share of electricity generation in several countries in 2020. Global capital expenditures committed to offshore wind power in 2020 surpassed investments in offshore oil and gas. Figure 3 represents the total PV installed capacity for the years 2010–2020 and solar PV had another record-breaking year in 2020. Favorable economics have boosted interest in distributed rooftop systems. Competition and price pressures continued to motivate investment to improve efficiencies.

The energy consumption of different countries is variable and depends on economic development, lifestyle, and weather. The top ten highest consuming countries in descending order are China, USA, India, Russia, Japan, Canada, Germany, South Korea, and Brazil [17]. The per capita consumption of electricity is also highly variable in different countries. Table 1 presents region based renewable generation capacity.

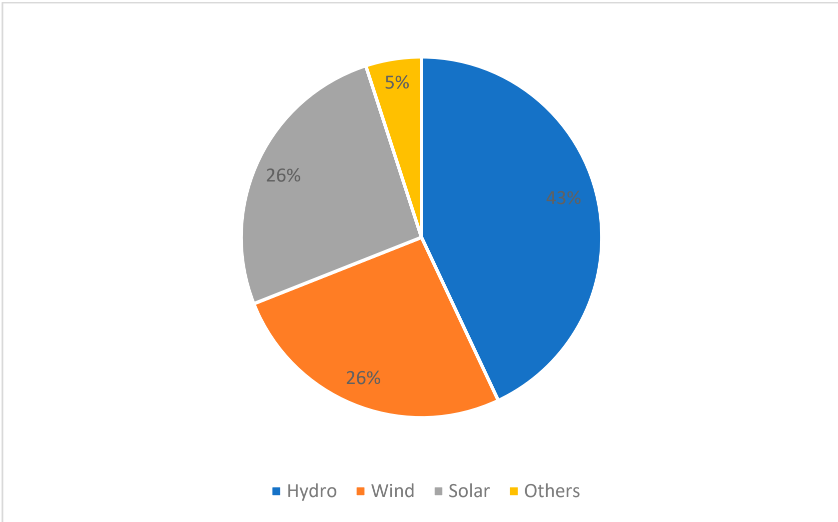

Figure 1. Energy source based renewable generation capacity.

Figure 2. Wind Power Global Capacity and Annual Additions, 2010–2020. Source: [16].

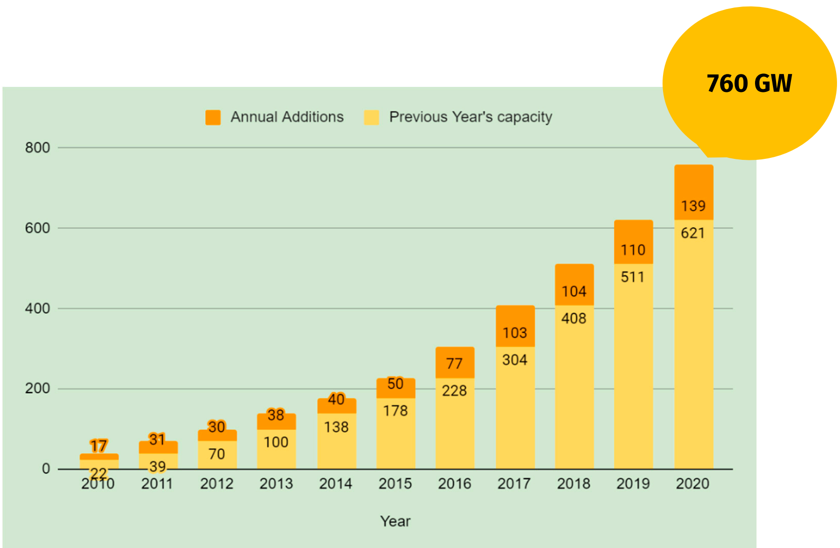

Figure 3. Solar PV Global Capacity and Annual Additions, 2010–2020 [16].

Table 1. Renewable generation capacity by region [17].

Region	Capacity	Global Share	Change	Growth
Asia	1286 GW	46%	+167.6 GW	+15%
Eurasia	116 GW	4%	+6.2 GW	+6%
Europe	609 GW	22%	+34.3 GW	+6%
North America	422 GW	15%	+32.1 GW	+8.2%
South America	233 GW	8%	+9.2 GW	+4.1%
Central America and the Caribbean	16 GW	1%	+0.3 GW	+2.1%
Middle East	24 GW	1%	+1.2 GW	+5.2%
Africa	54 GW	2%	+2.6 GW	+5%
Oceania	44 GW	2%	+6.9 GW	+18.5

Asia's installed capacity reached 1.29 TW in 2020 by increasing its capacity by 167.6 GW. Asia only accounts for 46% of the global total. A huge part of this increase occurred in China. Capacity in Europe and North America expanded by 34 GW (+6.0%) and 32 GW (+8.2%) respectively, with a notably large expansion in the USA. Africa continued to expand steadily with an increase of 2.6 GW (+5.0%), slightly more than in 2019. Although its share of global capacity is small, Oceania remained the fastest growing region (+18.4%).

3. Energy Storage Necessity

The demand for energy fluctuates from peak to off-peak due to individual needs and climatic effects. Storing the excess power during off-peak hours might be an urgent need as generation may surpass the total demand. The power mismatch challenge between generation and demand becomes more relevant because of the intermittency of the RES [18–21]. The conventional grid reliability is affected by the large scale integration of renewable energy sources. It is generally agreed that more than 20% penetration from intermittent renewables can greatly destabilize the grid system. Large scale ESSs can alleviate many of the inherent inefficiencies and deficiencies of the conventional grid and facilitate the full scale integration of renewable energy sources [22–27]. Generally, ESSs can balance supply and demand, reduce power fluctuations, decrease environmental pollution, and increase grid reliability and efficiency.

Recent studies have shown that energy storage facilities, when properly scheduled, are capable of assuring firm power (up to 90% on average of their nameplate capacity) during peak loading conditions. By charging during valleys of net demand and discharging during peak hours, ESSs can make a profit from the differences in energy prices while at the same time enhancing the overall load factor, thereby reducing the need for expensive peak generators, and preventing renewable energy from being spilled. This should be supported by enhanced forecasting and control techniques, and be fully coordinated with demand-side flexibility. Additional markets that could enhance the business case for storage might also emerge in the near future; for example, providing advanced grid functions such as synthetic/virtual inertia/frequency regulation to support system stability.

Small-scale ESS are finding their place in households or small businesses. There might be two main reasons. On the one hand, they can store self-generated energy, typically from PV systems, for later consumption. On the other hand, if connection tariffs are in place, they might be used in order to decrease the network connection sizing, to support consumption at peak times by storing network energy at valley times, regardless of a self-generation system being installed or not. The economics of both applications are dependent on the tariff structure. Electric vehicles (EVs), including transitional technologies such as plug-in hybrids, are expected to play a relevant role.

Large scale energy storage with a capacity of 100 MW is being installed frequently around the world from 2020. According to statistics from the CNESA, the total energy storage installed capacity globally reached 191.1 GW by the end of 2020; an increase of 3.4 % from the previous year [28]. The largest share (around 90%) of the energy storage capacity is covered by pumped hydro with 172.5 GW. The second largest energy storage installed is electrochemical energy storage with an installed capacity of 14.1 GW. Battery energy storage tops the electrochemical storage technologies with an installed capacity of 13.1 GW (Lithium-ion type). In 2020, the scale of electrochemical energy storage projects newly put into operation in the world reached 4.73 GW, and the scale of planned and under construction projects exceed 36 GW; most of them are applied in wind and solar power generation projects. Figure 4 presents the global energy storage installed capacity for the years 2000–2020. Figure 5 shows the electrochemical energy storage types whereas Figure 6 presents the installed electrochemical energy storage capacity for the years 2000–2020. Figure 7 depicts the regional electrochemical energy storage installed capacity for 2020.

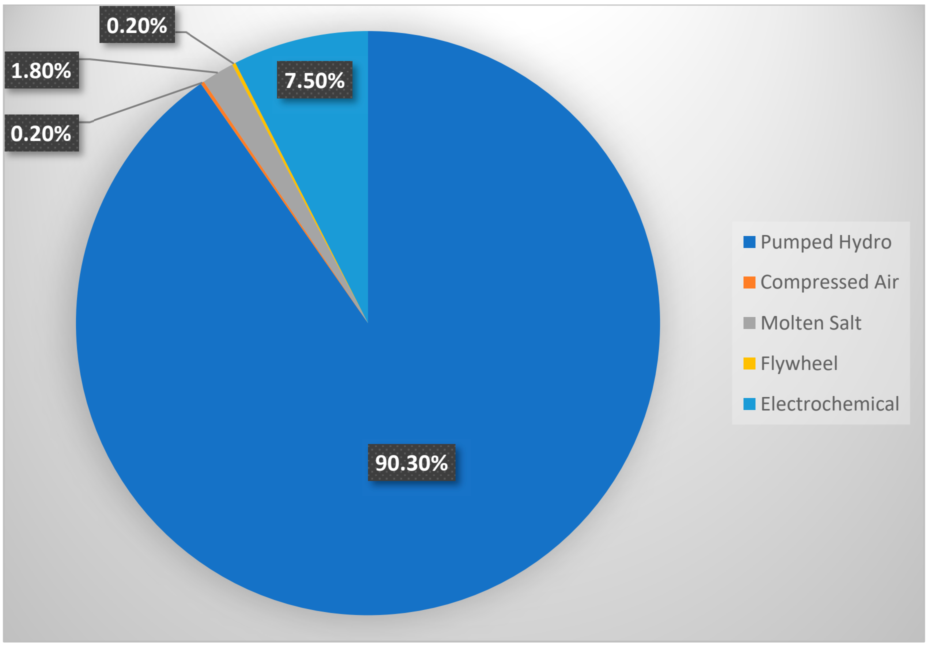

Figure 4. Global energy storage market by total installed capacity (2000–2020).

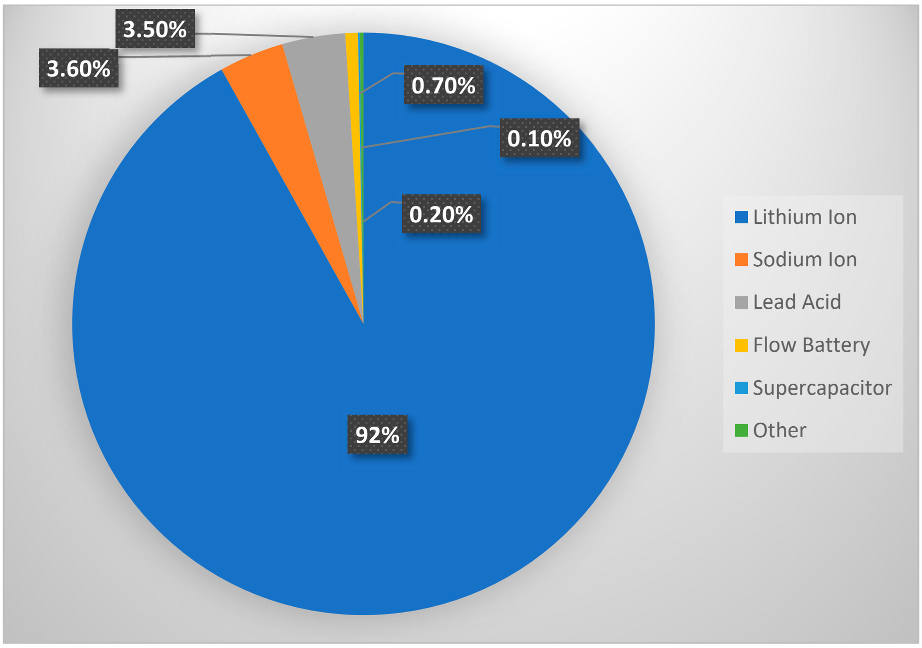

Figure 5. Electrochemical energy storage types.

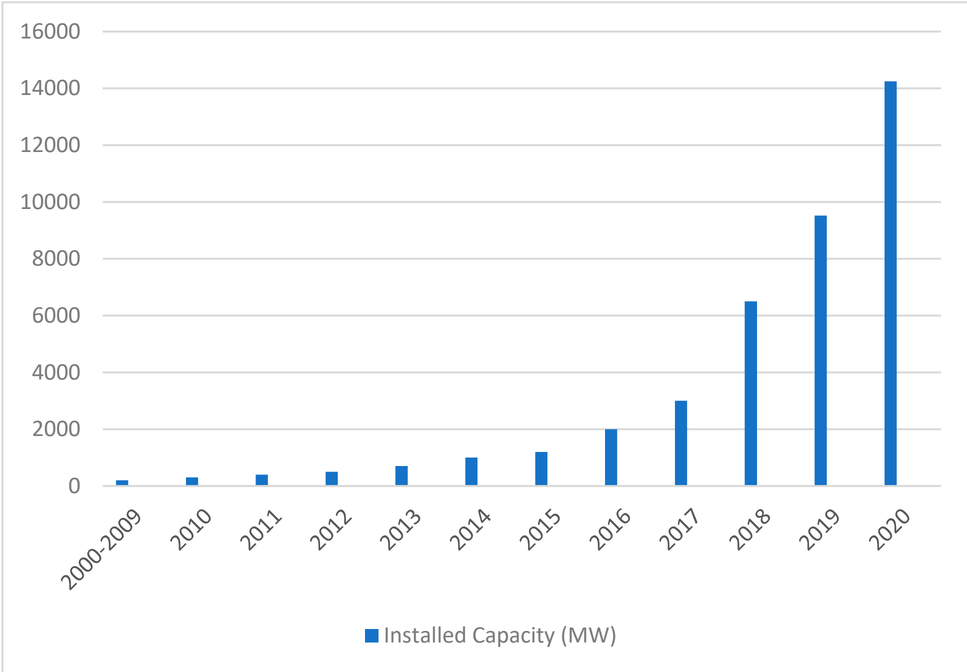

Figure 6. Global electrochemical energy storage market size by cumulative installed capacity (2000–2020) [28].

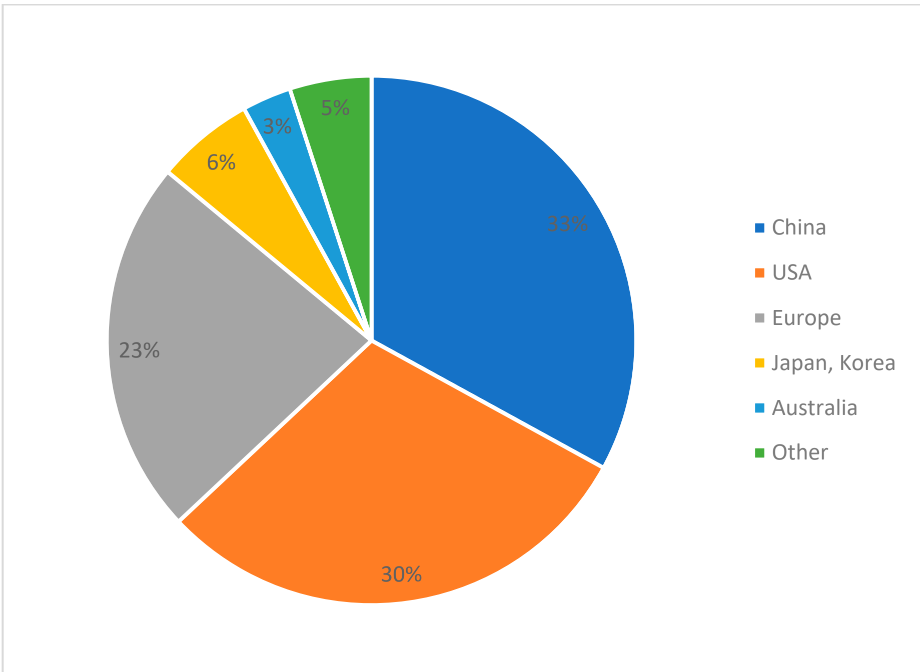

Figure 7. Regional distribution by new installed electrochemical energy storage capacity in 2020 (MW%).

4. Energy Storage Systems

Electrical energy in an AC system cannot be stored electrically. However, energy can be stored by converting the AC electricity and storing it electromagnetically, electrochemically, kinetically, or as potential energy. Each energy storage technology usually includes a power conversion unit to convert the energy from one form to another. Energy storage systems (ESSs) make the power system more reliable and efficient by providing a wide array of solutions including spinning reserves, frequency control, load leveling and shifting, voltage regulation and VAR support, power quality improvement and relief of overloaded transmission lines. The use of artificial intelligence to optimally integrate energy storage systems and renewable energy sources is presented in [29]. The authors of [30] presented a review of machine learning tools for the integration of energy storage systems with renewable sources.

Depending on the method of operation, there are a variety of ESSs such as flywheels, pumped hydro, batteries, supercapacitors, super magnetic energy storage, and compressed air energy storage. Thus, choosing a storage device that can perform the required function efficiently is a preliminary step, as the majority of storage devices are expensive.

Long-term storage may favor chemical fuels as the cost of renewable power generation is decreasing and the curtailment of excess generated power provides an opportunity to convert the renewable power to fuel or chemicals when combining hydrogen with sequestrated or recycled carbon dioxide. Pumped hydro is well established, efficient as well as versatile, and has been around for nearly one hundred years; however, its expansion is limited by geographical, as well as environmental, constraints. Many of the suitable locations for hydro dams are within protected areas, where constructing a dam wall will have an important impact on the eco-system. Underground pumped hydro seems to be a promising alternative in flat regions, but it is still at the design or prototype stage. Compressed air energy storage (CAES) combined with natural gas for incineration in gas turbines appears on all candidate lists, yet only a handful of industrial facilities exist worldwide. Research efforts that are currently underway on the much more efficient adiabatic CAES systems that store the heat generated during compression, to re-inject it during expansion still raise concerns about the technical and economic feasibility of such facilities. Electrochemical batteries are perhaps the most versatile technology (given their outstanding ramping and start-up/shut-down capabilities), but their costs need to be significantly reduced and their life cycle extended. Fast-response AC/DC power converters with sophisticated control strategies are used to integrate ESSs to the electric network. Figure 8 shows the different classification of energy storage systems used in power systems.

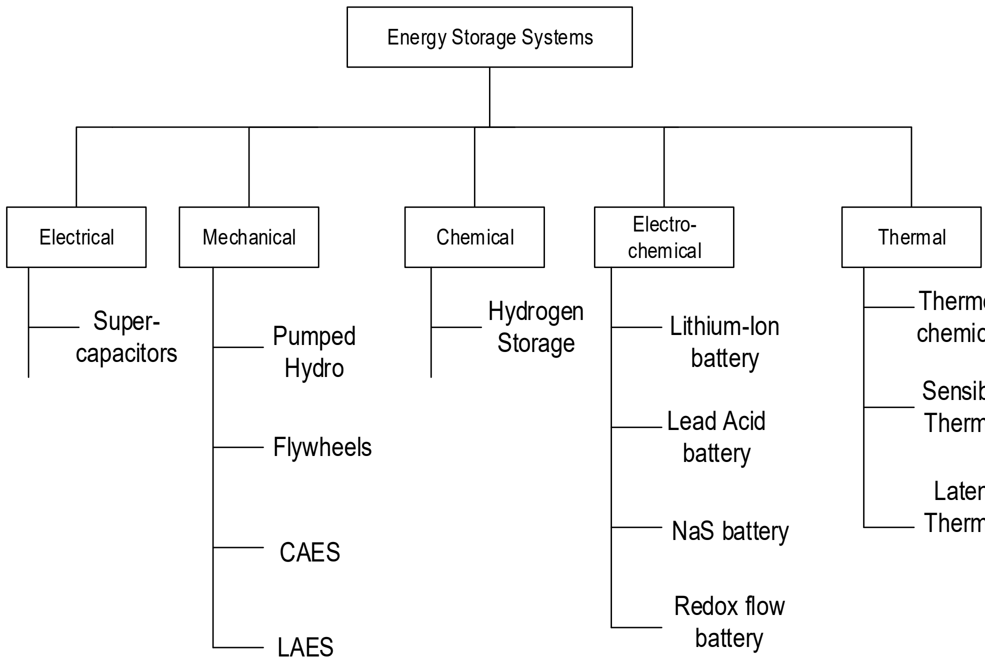

Figure 8. Classification of different energy storage systems.

The amount of energy they can store versus the response speed varies depending on the energy storage selected. A correlation between these two attributes does exist. For instance, supercapacitors are able to store up to about 1 kWh to release in about 1 s, whereas pumping stations can store 10 GWh or more on daily or weekly cycles. Some technologies, such as hydrogen electro-synthesis, would be able to store even greater amounts of energy for even longer periods. Some technologies, such as pumped storage, are quite mature whereas other ones, such as CAES, are still in the research and development (R&D) phase. A review of energy storage systems used in renewable energy resources is presented in [31–33]. Figure 9 shows the technological maturity of the different technologies.

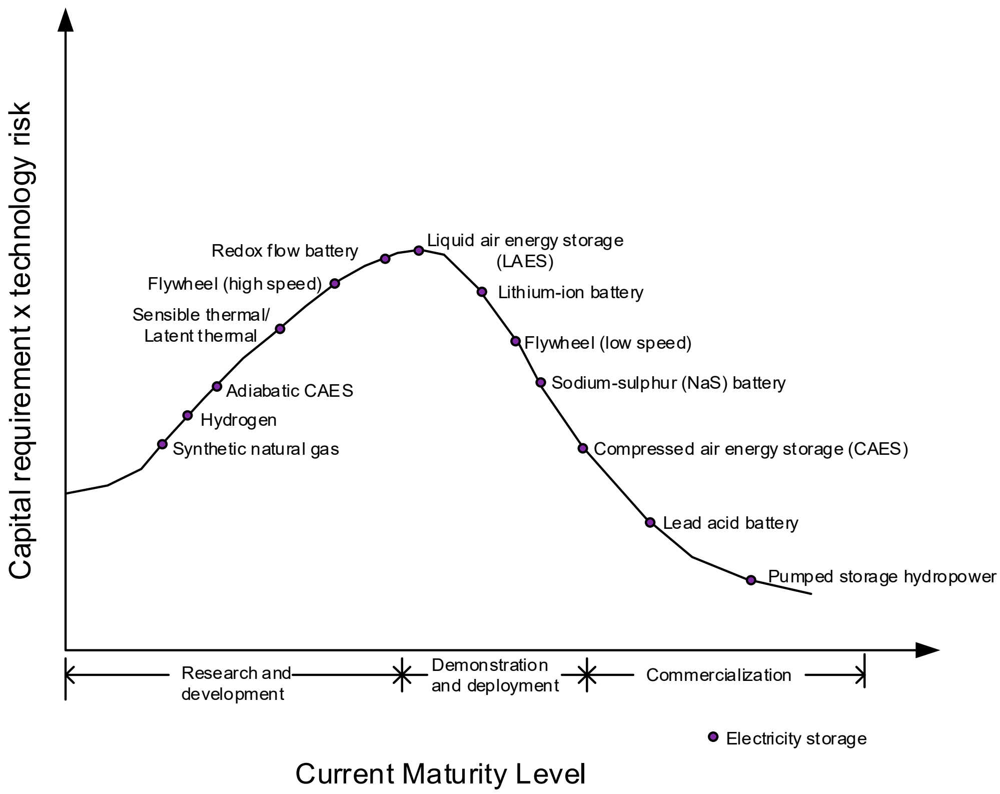

Figure 9. Technology Maturity level of different ESS.

Technological progress is the root to achieving a better energy storage system. In 2020, there were advances in battery technology because of the breakthrough of the cost inflection point of lithium-iron phosphate batteries. In addition, there has been good progress in the development of non-lithium storage systems such as liquid flow batteries, CAES, and sodium ion batteries. CAES is a potential competent of PHS with the advancement of speed reduction technology. Hydrogen storage systems are developing more rapidly and more advanced hydrogen systems will be available in the market. A review of hydrogen energy storage and the impact it will have on the future of renewable source integration is described in [34]. The authors of [35] presented a techno-economic assessment of hydrogen energy storage systems for renewable grid integration. They performed a mixed-integer linear programming formulation to identify key factors that affect cost-effectiveness. To reduce the fluctuation caused by renewable sources, the authors of [36] proposed a nuclear based energy storage system using data-driven stochastic emulators. The role of thermal energy storage integrated with concentrated solar power (CSP) is presented in [37]. The authors concluded that the combination of CSP with thermal energy storage has small role in adding flexibility to the grid. A fuel cell energy storage system integrated with renewable energy sources for reactive scheduling and control is discussed in [38]. A review of artificial intelligence and numerical models for a fuel cell energy storage system integrated with hybrid renewable energy systems are presented in [39]. The authors of [40] studied the economic analysis and optimization of different energy storage systems integrated with renewable energy sources in the island mode. They optimized and compared nine different off-grid renewable energy sources and studied the impact of self-discharge on the energy cost. A review of modeling variable renewable energy and storage in the long-term electric sector is discussed in [41]. A critical overview of energy storage systems, specifically thermal and electrochemical energy storage and their synergies with the development of renewable energy source technologies, is discussed in [42]. A review of hybrid electrochemical energy storage systems for electrified vehicle and smart grid applications is presented in [43]. An effective method for sizing electrical energy storage systems for standalone and grid-connected hybrid systems using energy balance is presented in [44,45]. Some of the energy storage systems used in power systems are explained in detail below.

4.1. Battery Energy Storage Systems (BESS)

Batteries store energy electrochemically and are made of several modules connected in parallel or series to achieve the desired rating. Power electronics converters are required to convert the DC stored energy in batteries to connect it to the AC grid. Batteries have several advantages including high energy density, high efficiency, high life span, and cycling capability [46,47]. Batteries can be designed for bulk energy storage or for rapid charge/discharge [48,49]. The disadvantage of batteries is that they cannot operate at high power levels for a long time due to chemical kinetics. Improving the energy and power density and charging characteristics are active research areas. The other disadvantage of battery energy storage systems is that batteries release toxic gas during battery charge/discharge. The disposal of hazardous materials presents some battery disposal problems [50,51].

Battery energy storage systems are playing a great role in integrating solar photovoltaic power generation to the grid and in reducing the fluctuations. Systems equipped with battery energy storage can deliver both active and reactive power and improve the system voltage and frequency. Beyond these applications focusing on system stability, energy storage control systems can also be integrated with energy markets to make the solar resource more economical [52]. A review of battery energy storage systems with its historical overview and analysis for renewable integration is discussed in [53]. Among the different battery storage systems, the most mature battery technology at this moment is the lead–acid battery [54,55]. A sustainability analysis of a battery energy storage system integrated with a hybrid renewable energy source in the island mode is presented in [56]. Recent advances in non-Vanadium redox chemistries for flow batteries for grid-scale energy storage are discussed in [57]. A case study of a microbrewery under demand response for optimal energy management of a grid-connected photovoltaic system with battery storage is discussed in [58]. A thorough assessment of battery energy storage systems, describing the features and capabilities of each type of battery storage technology including the benefits and drawbacks of each innovation is presented in [59]. A battery energy storage system for the supervisory energy management of a hybrid renewable energy source based on a combined fuzzy logic controller and high order sliding mode methods is discussed in [60]. A case study of the environmental benefit and emissions reductions thresholds of flow battery energy storage systems is presented in [61].

4.2. Flywheel Energy Storage (FES)

Flywheel energy storage stores energy as rotational energy and works by accelerating a cylindrical rotor called a flywheel at high speed. The energy is stored as kinetic energy with the rotating rotor and the storage capacity depends on the mass, shape and the maximum available angular velocity of the rotor. Mechanical inertia is the basis of this storage method and the energy is stored in the rotational mass as kinetic energy. The discharge process begins when an electric generator is connected to the flywheel. Conversely, when a torque is applied to the flywheel, the system is charged. The storage time can be prolonged by keeping the friction as minimum as possible by placing the flywheel in a vacuum [62]. Generally, depending on the speed of operation, FES are divided into two groups. The first group has a maximum speed of 10,000 rpm while the second group has a rotational speed of up to 36,000 rpm [63,64]. FES has a round-trip efficiency of 70–80% with equal discharge and recharge time. FES has approximately 100,000 full charge/discharge cycles and has a power density that is almost ten times greater than that of batteries. Currently, one of the most encountered flywheel applications is the microgrid [65]. The market value of FES is growing fast due to increasing industrial development and population growth causing an increase in power demand [66]. Figure 10 presents the operation principle of a flywheel energy storage system.

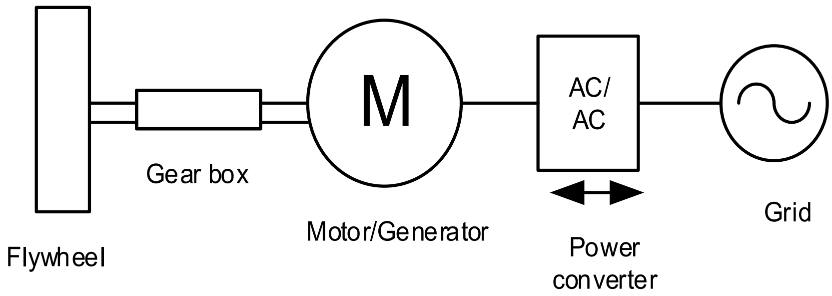

Figure 10. Flywheel Energy storage system.

4.3. Compressed Air Energy Storage (CAES)

The basic working principle of CAES is to drive compressors using motors to compress air and store it in suitable storage vessels. An expander is used to expand the compressed air and release the stored energy. The expander drives a generator to convert the stored energy to produce electricity [67]. A burning natural gas can be used to boost the output power but this will release CO2 emissions and affect the environment [68]. More advanced CAES can store heat during air compression and release it during the expansion phase. CAES are cost effective and promising for bulk grid services as they have a high power rating and storage capacity, a long life time and low self-discharge. However, the start-up time is usually high [69,70]. The economic and reliability impacts of grid-scale storage in a high penetration renewable energy system are presented in [71]. The authors concluded that energy storage systems, specifically CAES, will support the grid inertia if it is synchronously connected for a long duration.

CAES can be used together with renewable energy sources to compress the air using the power generated from renewable energy sources during off-peak hours. During peak-hours the air can be released and converted back to electrical power to make sure that there is no curtailment in the renewable source. Storing fresh air in salt caverns is a proven, reliable and safe method of ensuring that excess energy is not wasted [72–75]. The authors of [76] compared CAES and battery energy storage systems based on a levelized cost of storage. They concluded that the adoption of CAES systems can lead to a better economic performance with respect to battery technologies. The use of combined heat and CAES for wind power peak shaving is presented in [77]. There are only two commissioned CAES worldwide. The first one was commissioned in 1978 in Huntorf, Germany and is 290 MW. The second one is located in Alabama, USA, is 360 MW, and was commissioned in 1991.

4.4. Pumped Hydro Storage (PHS)

PHS is the most mature energy storage technology and has the highest installed generation and storage capacity in the world. It is a type of hydroelectric energy storage which has two water reservoirs (upper and lower) at different elevations that can generate power as water moves down from one to the other (discharge), passing through a turbine.

The lower reservoir is usually a river or lake while the upper reservoir can be an artificial lake [78,79]. The stored water is released during peak demand to hit a turbine and convert it to electrical power similar to a conventional hydropower station. During off peak demand, the upper reservoir is recharged using low cost power or a power generated from renewable energy sources. Similar to CAES, PHS is used for large scale renewable integration and helps the grid in many respects, such as reactive power support, frequency control, and synchronous or virtual inertia and black-start capabilities. The operating cost per energy unit has been reported as the cheapest in the PHS. However, the construction of reservoirs and other infrastructures needs very high investment [80,81]. A review of low-head pumped hydro storage and its application for renewable source integration is presented in [82]. A case study on the potential of a pumped hydropower storage (PHS) system and its contribution to hybrid renewable energy power fluctuation minimization is presented in [83]. The authors used an optimization technique to decrease the PHS sites required for renewable energy source grid integration. The use of PHS with renewable energy sources to fully supply the Barbados grid with a renewable source is discussed in [84]. The authors used open source modelling and concluded that an 80% share of renewable energy sources is cost optimal; however, 100% of renewable systems face flexibility. A comparison between PHS and a fuel cell on a hybrid renewable energy system based on diesel/PV is discussed in [85]. The authors concluded that the use of PHS is more cost effective than fuel cells. A case study to techno-economically compare battery and micro PHS for renewable energy sources is presented in [86]. It was concluded that the use of a hybrid PV-wind-battery storage system is the best option in terms of economic benefits and reliability. Figure 11 depicts the basic operation of a pumped hydro storage system.

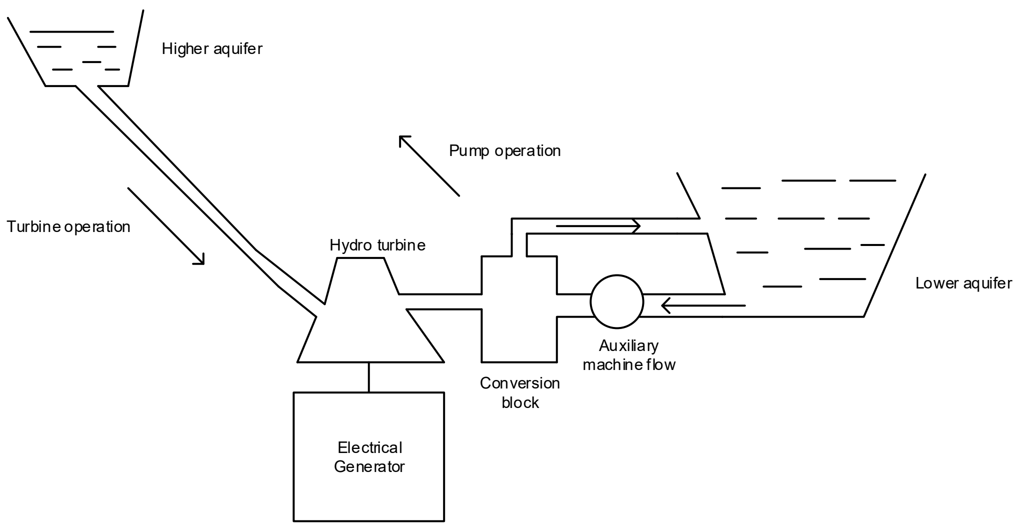

Figure 11. Working principle of Pump storage system.

4.5. Superconducting Magnetic Energy Storage (SMES)

SMES were proposed as an energy storage system because of their high response and efficiency (charge–discharge efficiency over 95%) [87]. The basic configuration of SMES consists of a refrigeration system, superconducting coils and a power conditioning unit. The energy is stored in the superconducting coil at a very low temperature. Figure 12 presents the operation of the superconducting energy storage system. The stored power in the coil can be absorbed or released depending on demand requirements. SMES have applications in load leveling, damping control and the load frequency control of power systems [88–92]. Generally, due to the high costs implied by the superconductive wire and refrigeration, SMES systems are used for military applications or energy storage over short periods of time [93].

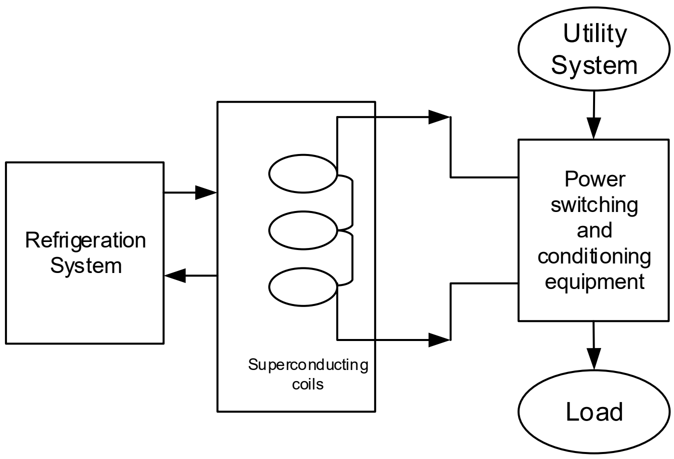

Figure 12. Superconducting Energy storage system.

4.6. Supercapacitor Energy Storage Systems (SCESS)

Among the different energy storage systems, SCESS have been a significant attraction for researchers due to their extraordinary characteristics such as fast charging–discharging, greater power density, lower maintenance cost and environmental-friendliness. Attributed to their outstanding performances, supercapacitors have found applications in diversified areas, e.g., uninterruptible power supplies (UPS), power electronics, renewables integration, and hybrid energy storage. However, the energy density is less than expected [94,95]. The most important advantage of supercapacitors as compared to rechargeable batteries is that supercapacitors in general possess a relatively low internal resistance and can store and deliver energy at a higher power rating.

SCESS help the grid ride through the fault, regulate the voltage and control the frequency and improve the power quality issues [96,97]. They have a high cycle life of around 12 years [98]. Currently, supercapacitors are used together with the batteries especially in smart grid applications due to their shorter discharge time. Figure 13 shows the operation principle of a supercapacitor.

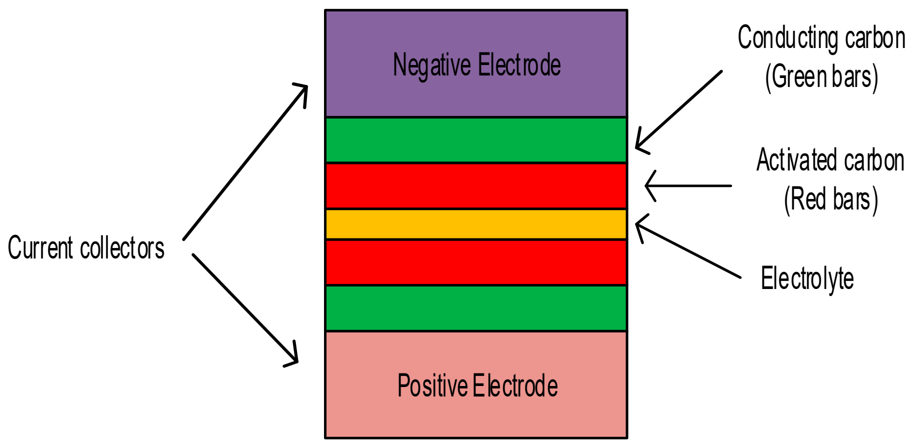

Figure 13. Supercapacitor energy storage system structure.

The use of supercapacitors to minimize the fluctuation of the power generated from PV and wind sources is reported in [99]. The authors connected the supercapacitor with a bi-directional buck-boost converter at the DC link to exchange power with the grid and renewable energy sources. Supercapacitors are also used to ride through a fault. During fault events, the power generated from the renewable energy sources will be stored in the supercapacitor and will be later used when the fault is cleared. Figures 14 and 15 show the topology of supercapacitors used in a PV source. The application of a battery supercapacitors hybrid energy storage system for microgrids is presented in [100]. An optimal design and energy management of an island mode fully renewable based microgrid integrated with battery and supercapacitors is described in [101].

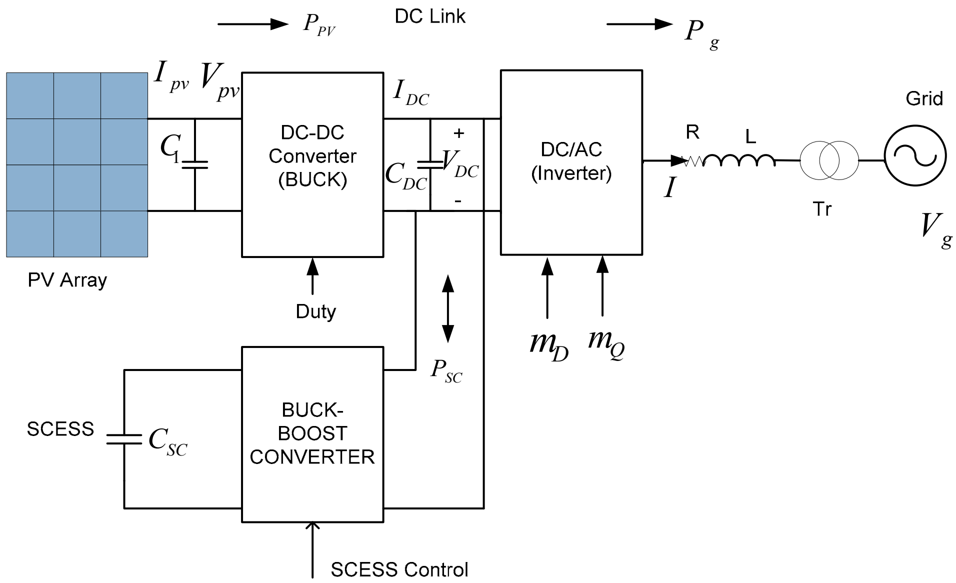

Figure 14. Supercapacitors connected to PV source to minimize the power fluctuation.

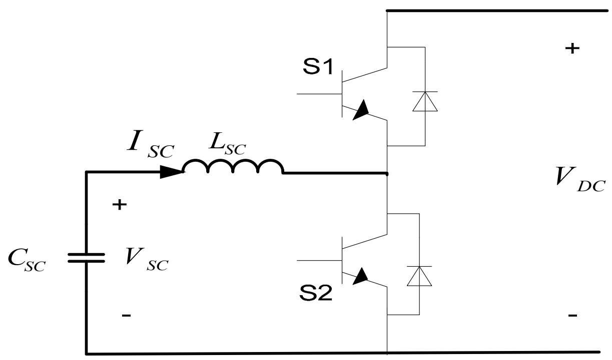

Figure 15. Supercapacitor connected with a bidirectional buck boost converter.

5. Discussion and Recommendation

Except for a few notable exceptions, such as pumped hydro, energy storage technologies are still in their infancy, and significant improvements and cost reductions are expected within a decade as they follow their anticipated learning curve. The life span and cycle life comparison of different energy storage systems is presented in Figure 16. A comparison of different energy storage systems in terms of power density, energy density, response time and efficiency is tabulated in Table 2.

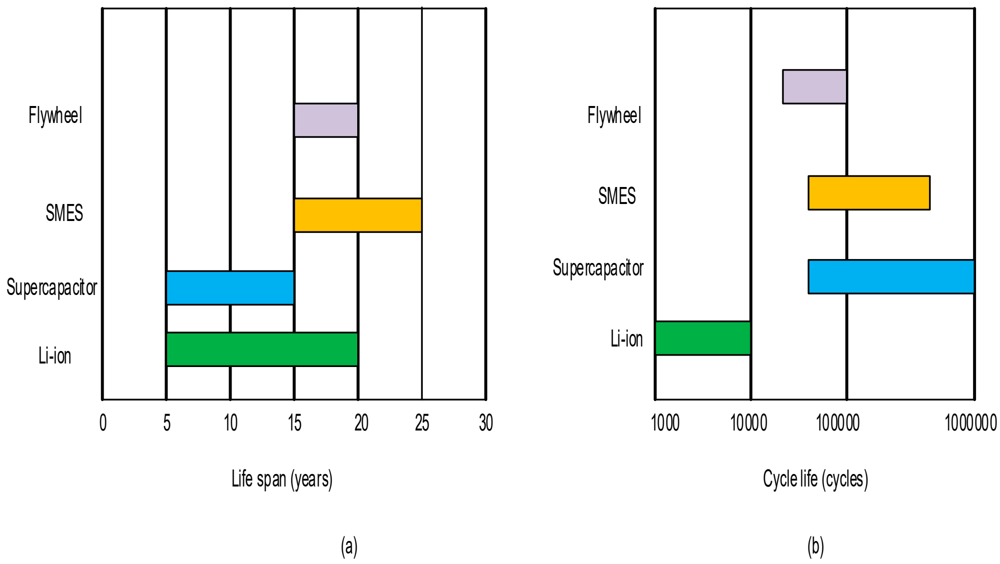

Figure 16. Comparison of different energy storage systems. (**a**) Life span; (**b**) Cycle life.

Table 2. Comparison of different energy storage systems.

Technology	Power	Energy Density	Backup Time	Response Time	Efficiency (%)
Pumped hydro	100 MW–2 GW	400 MWh–20 GWh	hours	12 min	70–80
CAES	110–290 MW	1.16–3 GWh	hours	12 min	99
BESS	100 W–100 MW	1 kWh–200 MWh	hours	seconds	60–80
Flywheels	5 kW–90 MW	5–200 kWh	minutes	12 min	80–95
SMES	170 kW–100 MW	110 Wh–27 kWh	seconds	milliseconds	95
Supercapacitors	<1 MW	1 Wh–1 kWh	seconds	milliseconds	>95

6. Conclusions

A comprehensive review of various electrical energy storage systems (ESSs) is presented in this paper. There are various ESSs available commercially but the requirement of DERs integration to the grid will not be met by a single energy storage system. The rapid growth of power generation from renewable energy sources makes the deployment of large scale and cost effective energy storage systems a necessity for the reliability of the power system. Since renewable energy sources are of different types, a broad range of storage systems are needed to accommodate the specific needs of each source. For the future, it is extremely difficult to predict which type of energy storage system will dominate the market but currently electrochemical energy storage systems dominate the market share. Among electrochemical energy storage systems, Li-ion batteries are considered a more competitive option for grid-scale energy storage applications as they have high energy density, light weight and high efficiency. For short-term power fluctuation minimization from renewable energy sources such as PV and wind, SCESS and SMES are the preferred options as they have high power density and a very short response time. PHS and CAES storage systems have future potential as they store energy for longer periods and generally have a larger power rating. However, PHS and CAES are limited by topographic constraints.

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