A review of the state of art and prospects in energy storage systems for energy harvesting applications

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ABSTRACT

Due to the increasing trend in worldwide energy consumption, many new energy technology systems have emerged in the past decades. The implementation of energy storage system (ESS) technology in energy harvesting systems is significant to achieve flexibility and reliability in fulfilling the load demands. In this paper, several types of energy storage technologies available in the market are discussed to view their benefits and drawbacks. The main aim of this review is to provide a platform for readers especially those who seek to know more about ESS at a glance, to decide which ESS technology is best suited for any specific applications. This review would serve as a base for the initial state to make the right decision by referring to the criterias and characteristics of energy resources to get the optimal ESS technology. A comprehensive comparison among the various types of ESS technologies is outlined and elaborated to provide a better and clearer picture to the readers. Last but not least, the relevant recommendations and alternative choices for services related to the harvesting of solar PV energy are described too. It is hoped that the findings of this review article may be helpful to all readers interested in ESS technology.

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1. INTRODUCTION

The demand for energy has been increasing due to the rapid development of industry and modern technologies. Energy harvesting is a technique that captures, harvests, or scavenges various unused or ambient sources of energy e.g., sun, heat, vibration, and wind, into electrical energy [1]–[44]. Sources for energy harvesting are divided into large scales such as solar PV [6], [13], [15], [33], [39], [45], [46], wind [46]–[50], tidal [30], [51], and geothermal [35], [40], [52], [53], and then on a small scale such as electromagnetic [6], [9], [32], mechanical [19], [37], [54], [55], and heat [2], [15], [24], [56], [57]. However, in recent years, large-scale energy harvesting has been more widely viewed and developed.

Energy harvesting on a large scale, such as using solar PV [6], [13], [15], [33], [39], [45], [46] and wind turbines [46]–[50], is subjected to fundamental limitations, such as its inherently intermittent nature. Because of this, the amount of energy that can be captured from solar photovoltaic or wind energy to satisfy the continuous load demand is much constrained. As such, there are cycles in which there is an abundance of energy and times when there is a shortage of energy production. On the other side, this challenge can be overcome by utilizing technology known as energy storage systems (ESS) [24], [41], [45], [46], [49], [51],

[53], [55], [57]–[79]. It is possible to store energy when there is any surplus of it and then delivers the surplus energy when there is a peak demand. Components that store energy can be utilized to perform a variety of purposes, namely network stability, frequency regulation, network operational support, voltage support, demand management, etc. [53], [64]. The ESS technology can be categorized into five distinct categories, depending on the types of energy that is being stored: such as mechanical, electrical, electrochemical, chemical, and thermal [65], [80]. This paper only focuses on three types i.e. mechanical, electrical, and electrochemical energy storage.

The major challenge faced by the energy harvesting solar photovoltaic (PV) or wind turbine system is its intermittency in nature but has to fulfil the continuous load demand [59], [73], [75], [81]. Therefore, in order to overcome the shortage during unavailability of PV/wind system, a suitable storage system is needed continuously delivering energy to the load [53], [57], [75]. This paper evaluates the technical performance of each type of EES based on the characteristics of each storage. Meanwhile, technical characteristics such as power rating, energy density, power density, response time, discharge time, round-trip efficiency energy, and life time are explained, which all parameters are needed to handle services in the solar PV/wind turbine energy harvesting system. Furthermore, this paper highlights recommendations or choices of appropriate types of ESS to handle existing services. Therefore, the review on the ESS and technologies can be useful for readers to determine the type of ESS in the solar PV/wind turbine energy harvesting system. The paper is organized as follows: section 2 focuses on the types of ESS technology that are presented and analyzed. Section 3 focuses on the comparison of the results of each type of ESS characteristics. Section 4: Cases of large-scale energy harvesting and energy storage requirements. The last, section 5, draws conclusions from the paper.

2. ENERGY STORAGE SYSTEMS

The current trajectory of events suggests that an increase in the production of energy harvesting devices and an existing high demand will result in a corresponding rise in the requirement for energy storage. As a result, we will require energy storage systems in the future that are capable of functioning for several days, weeks, or even months [53]. The capacity of energy storage systems that are already deployed will continue to expand at an exponential rate around the world until 2021. The China Energy Storage Alliance (CESA) 2020 global energy project data reveals that the global operational energy storage project capacity has reached 191.1 GW. These numbers were derived from the report. In comparison to 2019, this constitutes an increase of 3.4% [82]. The highest amount of energy is stored in pumped hydro systems, which account for 191.1 GW (90.3%), followed by electrochemical energy storage in the form of lithium-ion batteries, which account for 13.1 GW [82], as can be seen in Figure 1.

In literatures [45], [72], [80] energy storage systems (ESS) are generally broadly categorized in terms of the forms of energy stored and their functions. Furthermore, the most widely used method for categorizing ESS is based on the form of energy stored. Therefore, ESS can be categorized into five broad categories, namely mechanical, electrical, electrochemical, chemical, and thermal energy storage systems [65], [80] as shown in Figure 2.

This paper will focus on three distinct types of ESS, namely mechanical, electrical, and electrochemical systems. These are energy storage (ES) technologies that are now available on the market. Potential energy can be converted into usable forms through a process known as mechanical storage. The term "electric energy storage" refers to a type of technology that allows for the direct storage of electrical energy. Electrochemical storage is a type of energy storage that makes use of chemicals in order to store electrical energy. Each of these stores has its own rate capacity, power and energy density, response time, efficiency, longevity, self-discharge time, and discharge time [60], [80], [83].

2.1. Mechanical energy storage systems

Mechanical energy storage systems can be divided into two categories in terms of response time, power, and energy rating. Slow-response and typically large-capacity EES are represented by pumped hydro storage (PHS) and compressed air energy storage (CAES). Both are mature technologies. PHS utilizes water pumped into high reservoirs during times of lower electricity demand and released to consumers during peak energy demand [66].

This principle is the same as the one in hydroelectric power. PHS is the most dominant energy storage widely applied in the world by contributing about 90.3% (172.5 GW) of the world's energy storage capacity [82]. The CAES system [84] utilizes air and stores it in underground caves, pipes, or ships [85]. If necessary, the air is passed through an air turbine or driven by fuel to a gas turbine [56], which is combined with a generator that produces electricity [71].

The flywheel energy storage (FES) system stores electrical energy in the form of rotating kinetic energy [19]-[21]. This system exemplifies the mechanical system that has a quick response and is hence known as the FES system. During the phase known as "charging," the motor, which is attached to the mass that is rotating through the shaft, is sped up by means of the application of electrical energy. During the phase known as the discharge, the rotating mass transmits the kinetic energy that it has been storing to a generator that is connected to the same shaft [60]. Having a moment of inertia (J) and a speed of rotation (ω), a flywheel is able to store energy (E), which is represented by the mathematical expression [65] as (1).

$$E = \frac{1}{2} J\omega^2 \quad (1)$$

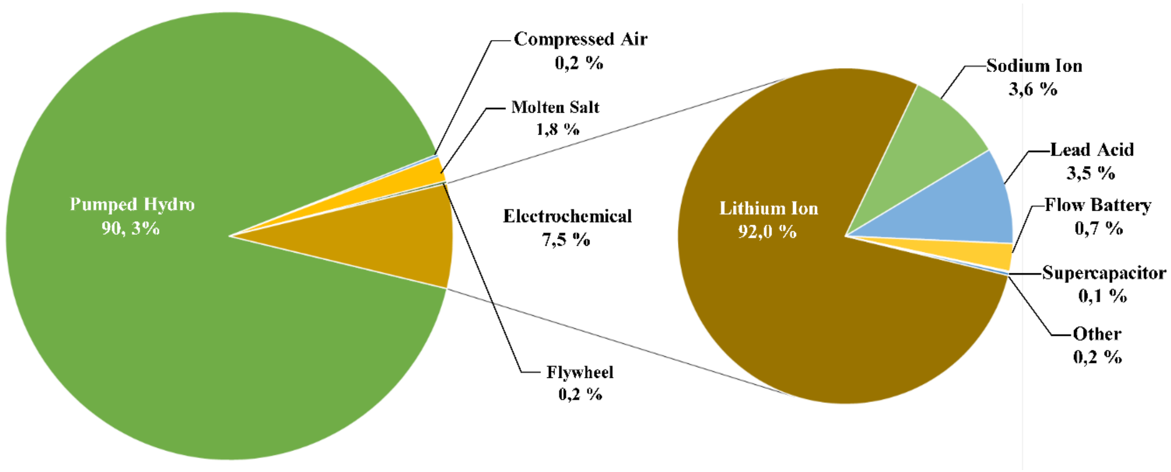

Figure 1 Global ESS market by total installed capacity end of 2021 [82]

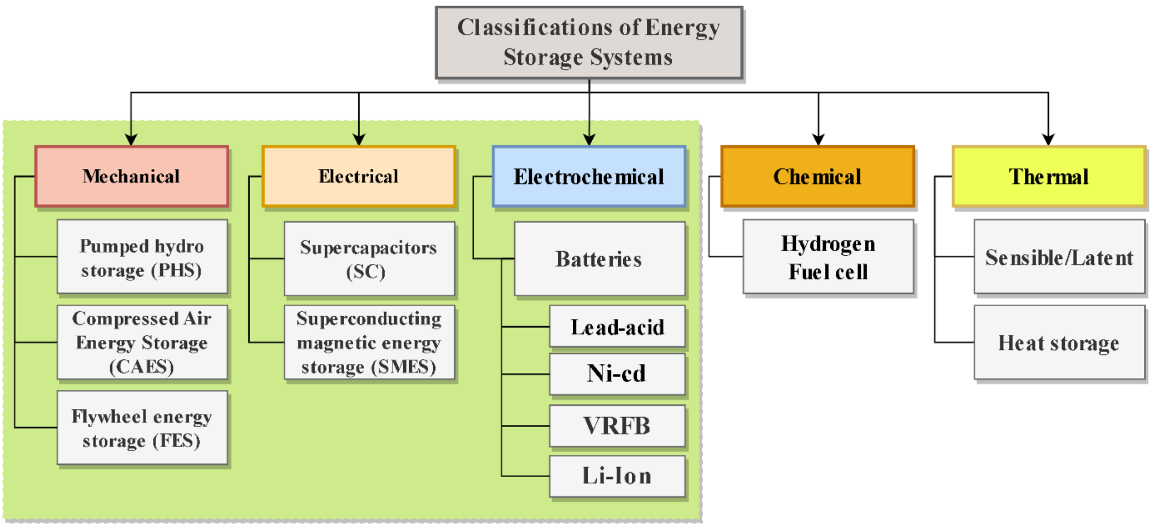

Figure 2. Classification of energy storage systems

2.2. Electrical energy storage systems

The two primary varieties of electrical energy storage devices are known as supercapacitors (SC) and superconducting magnetic energy storage (SMES) [51], [66], [74]. SC and SMES stand for superconducting magnetic energy storage. In addition to their more common names, supercapacitors may also be referred to as ultracapacitors or double-layer capacitors (DLC). Supercapacitors are a commercially viable technology that finds use in a variety of technical settings. The amount of energy that can be stored by a supercapacitor is determined by two factors: the capacitor's capacity, which is typically measured in thousands of Farads, and the square of the cell voltage. To be more specific [62], [84], the stored energy, denoted by the letter E, can be calculated as (2):

$$E = 0.5 \cdot C \cdot V^2 \quad (2)$$

where C is the capacitance in farads, and V is the voltage in volts.

The SMES system stores electrical energy in the magnetic field generated by the direct current (DC) in the superconducting coil, which has been cryogenically cooled to a temperature below its superconducting critical temperature [80]. A superconducting coil unit, a power conditioning subsystem, and a refrigeration and vacuum subsystem are the three primary components that make up a typical SMES system [47], [86]. These three subsystems are what make up a typical SMES system. Because of the resistance of the wire, any current that moves through a coil will, on average, result in the loss of energy in the form of heat. However, if the coil is built of a material that can be turned into a superconductor at very low temperatures, such as mercury or vanadium, then the resistance will become zero, and the electrical energy can be stored with nearly no loss [80].

2.3. Electrochemical energy storage systems

These technologies include lead-acid batteries, Ni-Cd batteries, Na-S, VRFB batteries, and Li-Ion batteries [66], [83], [27]-[29]. There are several types of electrochemical storage, such as lead-acid, lithium-ion, nickel cadmium, nickel metal hydride, and flow batteries. In general, there are two types of storage batteries (primary (disposable) and secondary (rechargeable)). Charging and discharging a battery is a redox (reduction-oxidation) process. The reduction process occurs when charging. Electrons are transferred to the battery when the voltage is stationary. Meanwhile, the oxidation process is released when electrons are transferred from the battery to the load. Lithium-ion, lead-acid, Vanadium Redox, nickel metal hydride, nickel cadmium, and Zinc Bromine are all types of rechargeable batteries [87].

The lead-acid battery is one of the oldest, most efficient, and widely used types of batteries. This storage is found in several applications, including automobiles (i.e., cars), electronic devices (watches, uninterruptible power supply (UPS), etc.), substation backup power and communication systems. These batteries come in two models, namely, rechargeable and non-rechargeable. Lead-acid batteries generate a voltage when a reaction occurs between lead electrodes, sulfuric acid, and electrolyte water. The electrolyte water in lead-acid batteries is involved in chemical reactions during charge and discharge. By adding a carbon-based material to the negative electrode, it can reduce sulfation and increase the conductivity [88], [89].

The Ni-Cd battery [83], [89], consists of two electrodes, one positive (nickel oxide hydroxide, NiO(OH)) and one negative (metal cadmium, Cd), an electrolyte, and a separator. Nickel oxide hydroxide is the positive electrode, while metal cadmium (Cd) is the negative electrode. The equation that describes the entire reaction that occurs during discharge is denoted by the symbol (3).

$$2NiO(OH) + Cd + H_2O \rightarrow 2Ni(OH)_2 + Cd(OH)_2 \quad (3)$$

Ni-Cd battery technology is a kind that is quite old and there is no recent research and findings. Ni-Cd batteries are used in utility/telecommunications backups and consumer electronics. Batteries contain highly toxic heavy metals that can pollute the environment (soil), but there are recycling facilities that can safely dispose of these batteries.

Vanadium redox flow batteries (VRFB) work on the principle of reduction-oxidation. This battery employs vanadium ions in 4 oxidation states to store chemical potential energy [90]. The positive electrode reaction is represented in (4).

$$VO^{2+} + H_2O \longleftrightarrow VO_2^{+} + 2H^{+} + e^{-} \quad (4)$$

The negative electrode reaction is represented in (5),

$$V^{3+} + e^{-} \longleftrightarrow V^{2+} \quad (5)$$

This type of battery generates electrical energy from the exchange of ions between the anode and cathode.

Lithium-ion batteries [91], also known as Li-ion batteries, are made up of electrodes (the positive electrode is metal oxide and the negative electrode is carbon) and an electrolyte (lithium salt). Li-ion batteries work between the electrodes during the chemical reaction of charging and discharging [91]. The overall reaction is represented in (6).

$$iC_6 + CoO_2 \longleftrightarrow C_6 + LiCoO_2 \quad (5)$$

This type of battery has also been widely used in electric vehicles, electronic devices, and utility applications. Lead-acid batteries do not pose a major environmental impact when compared to Li-ion batteries. These batteries tend to explode when exposed to high temperatures or short circuits. The main advantages of Li-ion batteries are their high energy, power density, high capacity, efficiency, long life, low internal resistance, and self-discharge. However, the disadvantages include high cost, requiring power electronics, safety concerns, having a relatively high internal resistance, and being impossible to charge at low temperatures [91].

3. OVERALL COMPARISON OF ENERGY STORAGE TECHNOLOGIES

3.1. Technical criteria

In this section, the whole part of ESS is compared and analyzed from the engineering perspective and criteria to get the potential use of ESS. The most of relevant engineering parameters such as power rate, energy density, power density, response time, discharge time, round-trip efficiency energy, and lifetime, are used to evaluate the technical performance of each selected EES [51], [60], [66], [70], [76], [35]-[38]. Graphical based analyzed are presented in detail as part of evaluation of ESS performance. The technical characteristics of all selected EES types are summarized in Table 1.

Table 1. Comparison of characteristics of storage technology types [12]-[14], [51], [27]-[29], [35]-[39]

No	Types of technology ESS	Power Rate capacity (MW)	Density		Response time (ms-hr)	Round-trip Efficiency (%)	Discharge time (ms-hr)	Life time (year)	Environmental Impact
			Energy (Wh/L)	Power (W/L)					
1	Battery (Lead-acid)	0-40	50-80	10-400	sec	70-90	sec-hr	5-15	High
2	Battery (Ni-Cd)	0-40	60-150	150-300	sec	85-90	sec-hrs	10-20	High
3	Battery (VRFB)	0.3.3	16-33	0.5-2	sec	85-90	Sec-hrs	5-10	Medium/low
4	Battery (Li-ion)	0-100	200-500	500-2000	20 ms-sec	93-95	min-hr	5-15	Medium/low
5	Supercapacitor	0-0.3	2.5-15	500-5000	8 ms	95-98	ms-hr	20 +	Very low
6	SMES	0.1-10	0.5-15	1000-4000	<100 ms	95-98	ms-8 sec	20 +	Low
7	Flywheel	0-0.25	20-80	1000-2000	<4 ms-sec	93-95	ms-15 min	15+	Very low
8	PHS	10-5000	0.5-1.5	0.5-1.5	min	65-87	1-24 hr+	40	High/medium
9	CAES	5-1000	3-6	0.5-2	1-15 min	70-89	1-24 hr +	20-40	Medium/low

3.1.1. Energy and power density of EES comparison

Both the energy density (Wh/L) and the power density (W/L) of a battery are measurements of how much energy and power the battery possesses in relation to its volume. Watt-hours per liter and watts per liter are two common ways that it is stated [57]. In this particular scenario, the lithium-ion BES type has a high-power density (500-2,000 Wh/L) in addition to a high energy density (200-400 Wh/L). Lithium-ion has a lower mass per unit of energy and power than other types of BES due to its high energy density and power density. In addition, the ESS Supercapacitor (500-5000 W/L), SMES (1000-4000 W/L), and flywheel (1000-2000 W/L) types also have high power density. However, it has a low energy density supercapacitor (2.5-15 Wh/L), SMES (0.5-15 Wh/L), and flywheel (20-80 Wh/L).

3.1.2. Power rating and discharge time of EES

A power rating, often known as MW, is an output or a measurable measure that is used to measure the real-time demand that may be satisfied by a storage facility. The amount of time that a storage device is able to function while still producing its rated output is referred to as its discharge time (E/P). According to the information shown in Table 1, ESS PHS and CAES have greater power rating ranges and longer discharge durations than the other systems. Where, PHS power rating is 10-5000 MW and discharge time 1-24 hr+. Meanwhile, CAES power rating is 5-1000 MW and discharge time 1-24 hr+. Despite the fact that the flywheel ESS, SMES, and SC all have a low power rating and a relatively quick discharge time.

3.1.3. Response time of EES comparison

Response time refers to the amount of time that must pass before the system is able to supply energy at its maximum rated power. As can be seen in Table 1, ESS like flywheels (<4 ms-sec), SC (8 ms), and SMES (<100 ms) all have quick response times measured in milliseconds. Seconds or even minutes can pass before the electrochemical ESS registers a response. ESS, such as PHS and CAES, are available in a matter of minutes to hours.

3.1.4. Round-trip efficiency of EES comparison

The percentage of electricity that is first stored and can afterwards be retrieved is referred to as the alternating efficiency. The amount of energy that is wasted during the storing process is directly proportional to the efficiency of the round trip. When compared to other forms of storage, the cycle efficiencies of ESS Lithium-ion, FES, SMES, and SC batteries are significantly higher than 90%, as Table 1 demonstrates. In the meanwhile, the efficiency of all varieties of electrochemical ESS, PHS, and CAES fall somewhere in the region of 70–90%.

3.1.4. Life time of EES comparison

Table 1 outlines the potential lifespan, or amount of time, that a certain storage device may be put to use. When compared to other elements' lifespans, PHS and CAES have the greatest potential for survival (40 years). Lead-acid, VRFB, and lithium-ion are the three types of batteries that can be found in the poor life span category (5–15 years).

3.2. Impact on environment of ESS comparison

If it is not disposed of properly, the waste that is generated as a result of the substance of the ESS can be harmful to both human health and the natural environment. According to the information shown in Table 1, the ESSs that include electrochemical, PHS, and CAES are the ones that have the most detrimental effect on the surrounding environment. On the other hand, ESS, which includes flywheel, SMES, and SC, are the lowest.

A final comparison of the different types of ESS is discussed. There are eight characteristics that become the focus of comparison, power rate capacity, energy density, power density, response time, round-trip efficiency, discharge time, life time, and environmental impact. It should be underlined that the characteristics of response time and environmental impact have inverse or negative values. This means that the bigger the position, the smaller the value that appears on the graph, so that the best ESS performance assessment can be seen by measuring the total area of the rating characteristic values of each ESS. The overall comparison of the ESS characteristics discussed is shown in Figure 3.

4. CASES OF LARGE-SCALE ENERGY HARVESTING AND ENERGY STORAGE REQUIREMENTS REQUIRED

A lot has been said about how ESS could help energy harvesting systems work for application services [59], [80], [81], [84], [40]-[43] as shown in Figure 4. It covers a wide range of issues, including power quality maintenance, power system protection, and energy management, etc. [80], [44]-[46]. Table 2 summarizes the selected and promising EES options for various service applications with suitable characteristics. A brief description of most of the services is given follows:

i) Transmission and distribution stabilization: ESS is used to support synchronous operation of power transmission lines or distribution units to regulate power quality while the system operates under normal conditions [47], [50], [75].
ii) Ramping and load following: ESS assists in following changes in load in electricity demand. "Ramping and load following" is a mode in which operation follows a flexible load to operate the storage system [59], [68], [98].
iii) Time shifting: Time shifting is achieved when electrical energy is stored while the energy harvesters are easy to obtain electrical energy from and then the stored energy is used during periods of peak demand [75], [99], [100].
iv) Peak shaving and load leveling: utilizing energy stored during off-peak periods to offset electrical power generation during peak power demand periods [63], [96], [101]. Meanwhile, load leveling is a method to balance the large fluctuations associated with electricity demand [69], [95], [102].
v) Black-start: EES can give the system the ability to start-up from a shutdown state without drawing power from the grid [48], [54], [61].
vi) Voltage regulation and control: Because the electric power system reacts dynamically to changes in active and reactive power, the magnitude and profile of the voltage in the network are affected [43], [57]-[59]. With the function of the EES facility, the control of the dynamic behavior of the voltage can be improved.

As shown in Table 2, ESS such as Li-Ion batteries, flywheels, and SMES are recommended for service transmission and distribution stabilization. Li-ion, flywheel, and PHS batteries are recommended for lean service and load following. PHS, CAES, and Li-ion and flywheel batteries are recommended for time-shifting, peak shaving, and load leveling services. Black start, voltage regulation, and control services are recommended for battery Li-ion, flywheel, SMES, and PHS. After being evaluated, Li-ion and flywheel batteries are ESS types with future prospects. Where, both types have characteristics that are able to handle various requirements for each type of service in energy harvesting applications.

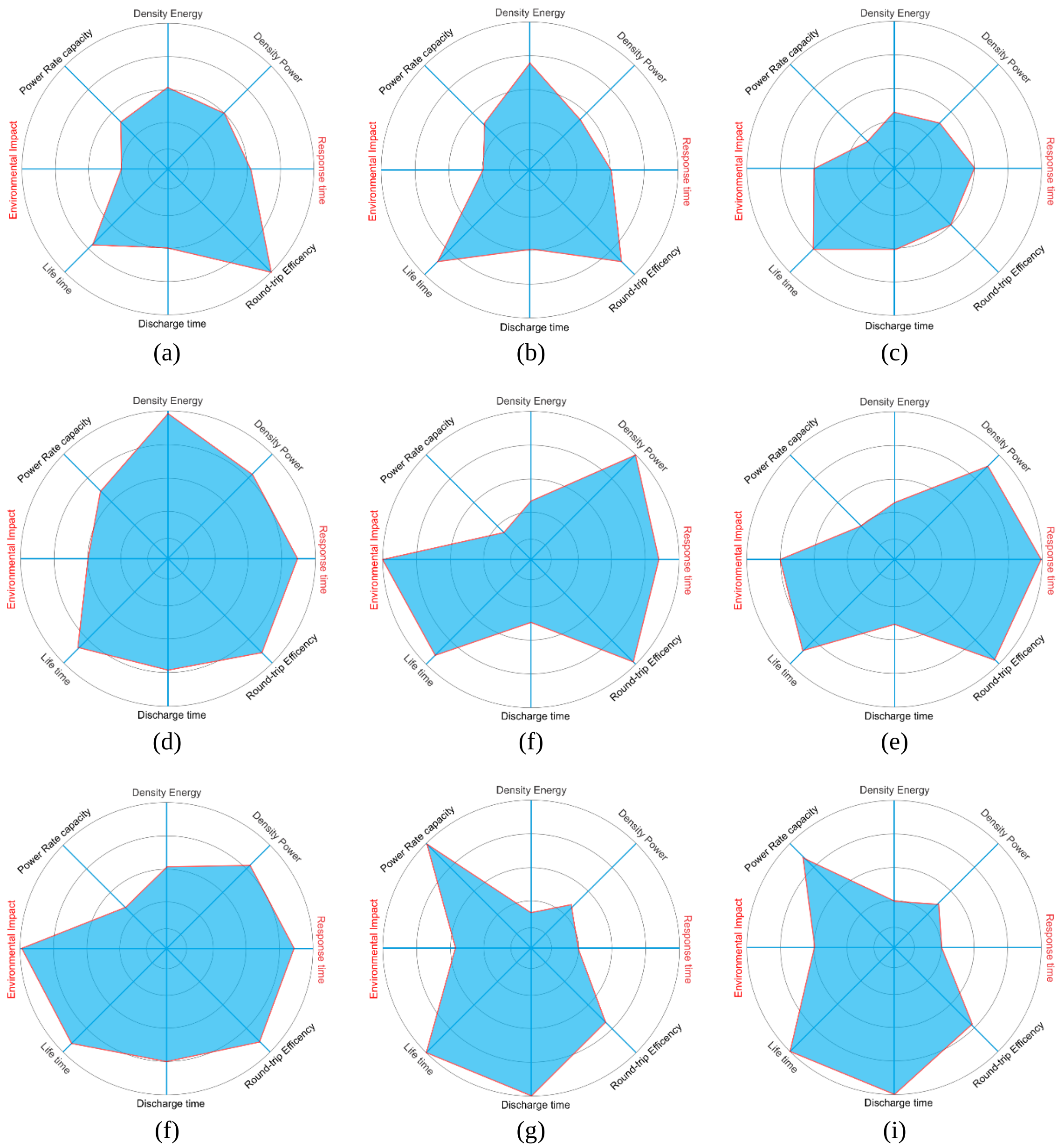

Figure 3. Performance comparisons of various ESS, i.e. (a) battery lead-acid, (b) battery Ni-Cd, (c) battery VRFB, (d) battery Li-ion, (e) supercapacitor, (f) SMES, (g) flywheel, (h) PHS, (i) CAES

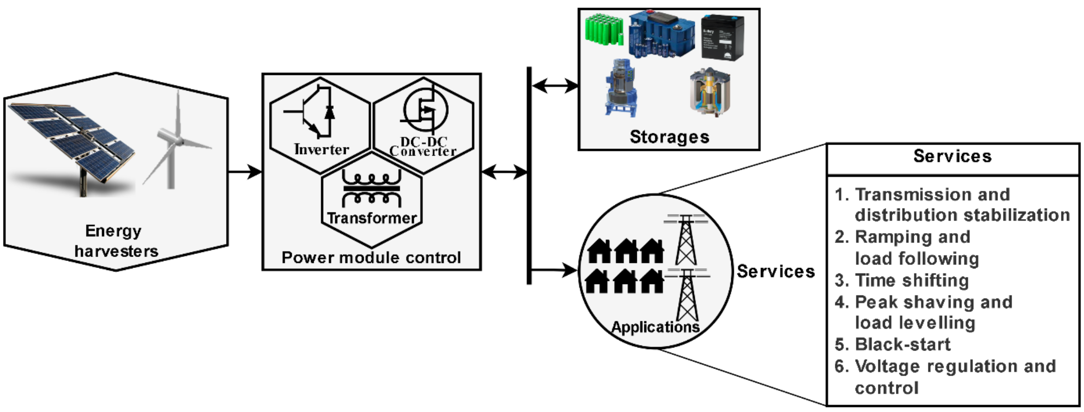

Figure 4. Energy harvesting systems work for application services

Table 2. Summary of the requirements for each service, as well as recommendations for energy storage [54], [59], [80], [81], [84], [95]–[97]

Service	Required characteristics						ESS type recommendation
	Power rating	Power density	Energy density	Response time	Discharge time	lifetime (year)	
Transmission and distribution stabilization	up to 10MW	high	high	~milliseconds	milliseconds-seconds	< 20	battery Li-ion, flywheel, and SMES
Ramping and load following	up to hundreds of MW	high	high	up to ~1 second	minutes to a few hours	< 20	battery Li-ion, flywheel, and PHS
Time-shifting	~1-100 MW	moderate	high	minutes	~3–12 hr	<15	PHS, CAES, and battery Li-ion and flywheel
Peak shaving and load levelling	~100 kW–100MW and even more	moderate	high	minutes	hour level, ~<10h	< 20	PHS, CAES, battery Li-ion and flywheel
Black start	Up to ~40 MW	moderate	high	minutes	seconds to hour	< 25	battery Li-ion, flywheel, SMES, and PHS
Voltage regulation and control	Up to a few of MW	high	high	~milliseconds	seconds to hour	< 20	battery Li-ion, flywheel, SMES, and PHS

5. CONCLUSION

Based on the reviews above, the requirements for the ESS technology that most suited for the application in solar PV/wind energy harvesting must fulfil the high energy density and high-power density, fast discharge time, fast response time, and high cycle efficiency. Among the ESS technologies, Li-ion batteries and flywheels are seen to be more competitive solutions for energy storage in solar PV/wind energy harvesting system. This is because the Li-ion batteries are equipped with high energy density (200-500 Wh/L) and high-power density (500-2000 W/L). This type of battery has low load and small in physical size. This battery also boasts a round-trip efficiency of 93%-95% and features quick response time (20 ms–few seconds). Nevertheless, this battery has a shorter lifetime (5-15 years) and a longer discharge time than other forms of ESS (min-hours) as compared to other counterparts. The ESS flywheel technology provides high power density (1000-2000 W/L), round-trip efficiency of 93-95%, and quick response time (<4 ms–few seconds). Furthermore, it has a lifespan of more than 15 years. However, a relatively quick discharge time (from milliseconds-15 min). flywheels still have downsides, such as a low energy density (20-80 Wh/L), which means the flywheel will have a greater load. In short, the ESS plays an important part in the future energy harvesting. In addition to storing and releasing energy when needed, ESS technology provides other advantages, such as supplying backup electrical energy when a generator or a network component fails. As a result, it can control network stability and respond promptly to variations in load. Additionally, additional requirements apply to services like as transmission and distribution stabilization, lean and load following, time-shifting, peak shaving and load leveling, black start, and voltage regulation and control. The Li-ion battery and the flywheel are the most likely service storage technologies among the present ESS technologies. This is due to the storage's superior qualities as compared to other ESS.

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