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Advancements in energy storage technologies for smart grid development

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ABSTRACT

In the modern world, the consumption of oil, coal natural gas, and nuclear energy has been causing by a serious environmental problem and an ongoing energy crisis. The generation and consumption of renewable energy sources (RESs) such as solar and wind tidal, can resolve the problem but the nature of the RESs is fluctuating and intermitted. This evolution brings a lot of challenges in the management of electrical grids. The paper reviewed the advancements in energy storage technologies for the development of a smart grid (SG). More attention was paid to the classification of energy storage technologies based on the form of energy storage and based on the form of discharge duration. The evaluation criteria for the energy storage technologies have been carried out based on technological dimensions such as storage capacity, efficiency, response time, energy density, and power density, the economic dimension such as input cost and economic benefit; and the environmental dimension such as emission and stress on ecosystem, social demission such as job creation and social acceptance were also presented in this paper.

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1. INTRODUCTION

Day-by-day the share of energy storage technologies with renewable energy sources (RESs) is gradually increasing. The economic growth of any developing and developed country depends upon electrical energy generation and consumption. Electrical energy consumption and production is an important factor for the growth of any nation. The future vision of the electrical energy system is the smart grid (SG). It is the great ambition and endeavor of our time. The integration of the RESs with the grid is an important component of the SG. Due to the increase in population and industrial area, the dependency on electrical energy is increasing day by day. The major challenge facing the modern world is low energy efficiency, environmental impact, low power quality, and varying load. The traditional grid contains centralized power generation and unidirectional power flow at the distribution side and weak integration, but an SG consists of centralized power generation and bi-directional flow of energy. The official definition of SG provided by the energy independence and security act 2007, which was approved by US Congress states that “an array of new functionalities and application is due to the implementation of two-way communication and bi-directional flow of energy [1]–[3]. National smart grid mission (NSGM), Ministry of Power, Government of India defines that the SG as an electrical grid with a combination of communication, IT system, and automation that can monitor the flow from the generation side to the consumption side and controls the power flow [4], [5].

An SG can be achieved by integrating the hybrid RESs with the grid, a more efficient transmission & distribution (T&D) system, and consumer integration. The main motivation is that the use of an SG reduces the need for expensive investments in the physical integration of the power generation, transmission, and distribution sides. The integrated renewable energy-based SG reduces the global climate change, ecofriendly power with low carbon foot emission [6]. The SG has two main principal visions; one is to enhance the integration of hybrid RESs with grid and end-user customers. The second one is by inserting the energy storage technologies and providing control automation to the grid which can improve the system reliability [7], [8].

The integration of RESs with energy storage is one of the important features of SG. Ma and Li [9] proposes a hybrid intelligent home renewable energy management system, which reduces the energy consumption by 48% and the RE consumption by 60% of the total energy generated. To control the consumer electricity resources properly, demand management is a very effective way. The proposed approach not only saves energy or reduces the electrical energy bills but also increases the efficiency of the power grid. Integration of smart buildings with SG will decrease the consumption of fossil fuel and increases the consumption of RES. Buildings are the biggest consumer of the electric grid and could be among the biggest producer of RE. There will be no smarter building without a smart user [10]. Butt *et al.* [11] presents the comparison between the SG and conventional grid. Various research activates associated with SGs are energy management, the internet of things (IoT), SG with electrical vehicles (EVs), microgrids, and integration of RESs, big data, and energy storage. Ourahou *et al.* [12] presents that electrical energy management is required to reduce CO_2 emission, pollution, and increase energy security. Maintaining the continuous electrical supply, increase power quality, and reduce electrical energy costs are the main challenge in the 21st century. The electrical network is more frangible. Due to the growth of the market, the frangibility will be increased. Therefore, to reduce the risk of incident, preparation, and monitoring are required. Zame *et al.* [13] proposes that SG provides various opportunities to improve the operations of the grid by increasing the use of two-way communication and bi-directional flow of energy. Energy storage technologies also enhance the efficiency of the operation of the grid. Two power plants working together (wind and pumped hydropower plant) which reduces the operating cost of the energy system have been presented in [14]. In the future, a significant saving can be done by using existing technology by integrating the transport sector, heat, and electricity. Abdelshafy *et al.* [15] presents that a double storage system means coupling of PHES and batteries storage systems which can reduce the cost of electricity by 22.2%. The main objective of this work is to select the energy storage technologies for SG development. A comprehensive review of the energy storage technologies, i.e., mechanical, thermal, chemical, electrical, and electrochemical energy storage were also presented in this paper.

2. CLASSIFICATION OF ENERGY STORAGE TECHNOLOGIES

Nowadays the energy storage technologies play an important role in the future of power generation. Storing the electricity directly is not cheaper, it can be simply stored in another form, and when we needed it can be converted into electricity. When the power is surplus or off-load period, the electrical energy can be stored in another form and the electricity cost is low at this time. During the peak demand time, the stored energy is converted into electricity to meet the load demands [16]. Various technologies are used for storing the energy and they are presented in this work. The future flow of the electrical system is shown in Figure 1.

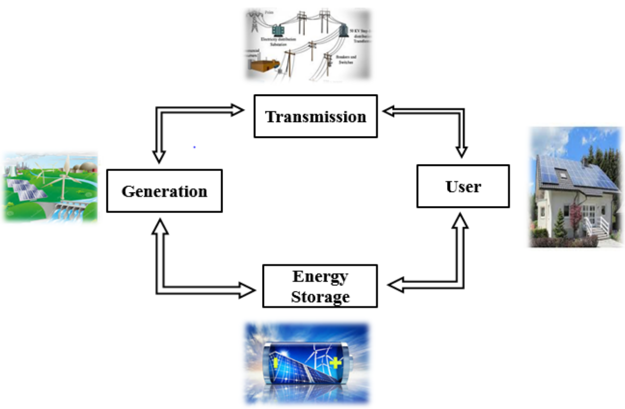

Figure 1. Future flow of the electrical system

The energy storage techniques are classified based on discharge duration and the form of energy stored [17]. Energy storage technologies are dependent upon the drain period or discharge period. Based on the discharge duration, they are classified into 3 categories, i.e., short-term, medium-term, and long-term. Long-term energy storage is classified as pumped hydro energy storage (PHES), hydrogen energy storage, and compressed air energy storage (CAES). Molten-salt energy storage, lead-acid, lithium-ion, sodium sulphur, redox flow energy storage falls under medium-term energy storage. Short-term energy storage is classified as flywheel energy storage, supercapacitor energy storage, and superconducting magnetic energy storage. Energy can first convert in a different form for storing and then converted back in a useful form. Based on the form of energy stored, the energy storage is classified into five categories [18], i.e., electrical energy storage, mechanical energy storage, thermal energy storage, electrochemical energy storage, and chemical energy storage [19]. This classification has been depicted in Figure 2.

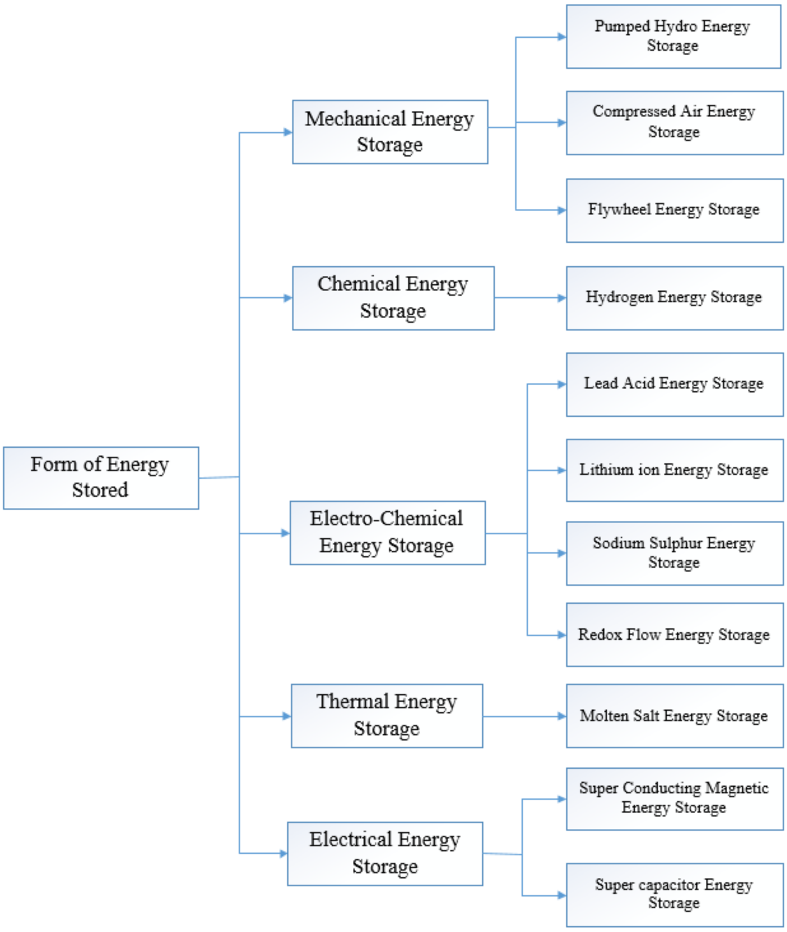

Figure 2. Classification of energy storage techniques based on the form of the energy stored

3. ENERGY STORAGE BASED ON THE FORM OF ENERGY STORED

3.1. Mechanical energy storage

3.1.1. Pumped hydro energy storage

Pumped hydro energy storage (PHES) system stores the energy in the form of potential energy (PE) by pumping the water from a lower to a higher reservoir. Whenever the energy is required, then the water is released from the higher reservoir to the lower reservoir, and the stored potential energy is converted into electrical energy by the water turbine during peak load time. While the off-load time, the potential energy is stored in a higher reservoir by pumping water from a lower reservoir [20]. The efficiency of the PHES lies between 75-85%. Some specific conditions are required for PHES such as availability of water, the difference in water level or water elevation, and land. If the conditions are not met, then PHES is impossible to install. Around the world, the size of the PHES is in the range of 100-5,000 MW. PHES system has a very long lifetime around 40-60 years and 10^4-6×10^4 cycles. The capital cost of the PHES system is around

600-2,000 \$/kW and the cost per unit of energy stored is around 5-100 \$/kWh. Energy density of PHES system is 0.2-2 W/L [21], 0.5-1.5 Wh/kg, 0.5-1.5 kW/km^3 and power density is 0.5-1.5 kW/m^3. PHES system is the best option for the renewable energy system as well as the power grid. Some of the main drawbacks of the PHES system are high capital cost, the size of the unit is very large, and topographic limitation [22].

3.1.2. Compressed air energy storage

In the Compressed air energy storage (CAES) system, the air is compressed and stored. During the energy demand or peak hours, the compressed air can be released to a turbine and generate electricity [23], [24]. The efficiency of the CAES lies in the range of 70-89 % and it is a mature technology. The lifetime of the CAES is 20-40 years and 10^4-3×10^4 cycles. The capital cost of the CAES system is around 400-800 \$/kW and the cost per unit of energy stored is 2-50 \$/kWh. The energy density 30-60 Wh/kg (mass), 2-6 kW/m^3 (volumetric), 2-6 W/l and power density is 0.2-0.6 kW/m^3 (volumetric) [25]. It requires less maintenance and operation costs. The main disadvantage of the CAES system is low volumetric energy storage capacity which requires high storage volume [26].

3.1.3. Flywheel energy storage

It is a type of kinetic energy (KE) storage system. In a flywheel, the energy is stored in the form of mechanical energy. During the charging time, the KE can be absorbed with the electric machine acting as the motor. While discharging time, the KE can be released with the electrical machine acting as a generator. While selecting a flywheel energy storage for an application some of the important points that should be considered are bearing, rotor material, container, generators characteristics, connection with the load, and cooling system. A flywheel is considered a short-term energy storage system as the flywheel can release a huge amount of energy within a second or less than a second [27]. The cycle efficiency of the flywheel lies in the range of 93-95% [28]. The lifetime of the flywheel energy storage system is 20-30 years and 10^4-10^5 cycles. Energy density is 20-80 WH/l, 10-30 Wh/kg, 20-80 Wh/m3, and the power density is 1,000-2,000 kW/m^3. The capital cost of the CAES system is around 250-350 \$/kW and the cost per unit of energy stored is 1,000-5,000 \$/kWh. The applications of flywheel energy storage are grid storage with stabilization and vehicle propulsion. Advantages of a flywheel energy storage system are no pollution; high energy storage capacity and it requires small area. The main drawback of flywheel energy storage is that flywheel cannot store energy for the long term [29].

3.2. Electrical energy storage

3.2.1. Supercapacitor energy storage

A supercapacitor is also known as an ultracapacitor. It is a high-power electrical energy storage technology. It consists of two electrochemical layers of charge to store energy. When the voltage is applied, ions are attached to the electrode while charging time, and ions are returned to the solution while discharging time. Supercapacitors are highly efficient in the range of 80-90% and the lifetime is more than 20 years and 100,000 cycles. The supercapacitor is considered a short-term energy storage technology with an energy density of 0.5-5 Wh/kg, 2-10 kW/m^{3,} and power density is more than 10^5. The capital cost of the CAES system is around 100-300 \$/kW and the cost per unit of energy stored is 300-2,000 \$/kWh [30]. The supercapacitor can operate at a temperature range from -40 to 70 °C. Various applications of supercapacitors are personal electronics, power buffer, and vehicle application. Some of the main advantages of supercapacitor energy storage are high response time, long life, high efficiency, and multisector integration. However, the main drawbacks are low energy storage capacity, low power output, and cannot be used in long term [31].

3.2.2. Superconducting magnetic energy storage

In superconducting magnetic energy storage (SMES) system, the energy is stored in the form of a magnetic field. It consists of a superconducting material that has no resistance. While the direct current (DC) flowing in a superconducting coil creates a magnetic field in which the energy is stored. To maintain the superconducting properties, a cooling system (liquid nitrogen) is required. SMES system is a short-term energy storage technology [32]. It requires less maintenance and achieves high efficiency, only 2-3% losses occur due to the conversion of alternating current to direct current. The cycle efficiency of the SMES system is 85-95%. The lifetime is more than 20 years and 10^4-10^5 cycles. Energy density is 0.2-14 kW/m^3 and the power density is 300-4,000 kW/m^3. The capital cost of the SMES system is around 200-300 \$/kW and the cost per unit of energy stored is 1,000-10,000 \$/kWh. Various applications of SMES are grid backup, pulsed power, and grid stabilization. Some of the main advantages are high efficiency, quick response, high power density, less charging time, and requires less maintenance. Some drawbacks of this technology are the high cost of energy, system complexity, and short-term energy-storing technology [33].

3.3. Electro-chemical energy storage

3.3.1. Lithium-ion batteries

The operation of lithium-ion batteries is different from normal batteries. In 1991, sonny has commercialized lithium-ion batteries. The electrolyte used in lithium-ion batteries consists of lithium salts i.e., $LiPF_6$. During the charging time, lithium-ion in the cathode becomes ions, which are moved from cathode to anode through an electrolyte. This process is vice versa while lithium-ion batteries start discharging [34]. The efficiency of lithium-ions lies between 90-97%. The lifetime is 5-15 years and 10^3-10^4 cycles. Energy density is 200-500 kW/m^3, 75-200 Wh/kg and power density is 1,500-10,000 kW/m^3 [35]. The capital cost of the lithium-ion energy storage system is around 1,200-4,000 $/kW and the cost per unit of energy stored is 100-2,500 $/kWh [36]. The main application of these batteries is in electric vehicles (EVs) [32]. The usage of lithium-ion batteries has been increased due to their advantages over the other technologies such as long-life span, high efficiency, energy density, power density, and low self-discharge performance. Some of the drawbacks of these technologies are highly reactive, flammable, and natural degradation [37].

3.3.2. Sodium sulphur (Na-S) batteries

Na-S batteries are also named as molten-salt batteries. In Na-S batteries electrodes consist of liquid sulphur and liquid sodium. Liquid sodium acts as an anode and liquid sulphur acts as a cathode. The anode and cathode are separated by a solid ceramic, sodium beta alumina which acts as an electrolyte. Na-S batteries are based on the electrochemical charge-discharge reaction [38]. Na-S required a temperature range of 300-360 °C to keep the sulphur and sodium in a molten state. The efficiency of Na-S is around 85% and the response time is in milliseconds. Energy density is 150-250 kWh/m^3, 10-250 Wh/kg, and power density is 140-180 kW/m^3, 150-240 W/kg. The life span of Na-S is 15 years and 4,500 cycles [39]. The discharge time of Na-S is about 6.0-7.2 hours [28]. The capital cost of a Na-S energy storage system is around 1,000–3,000 $/kW and the cost per unit of energy stored is 300-500 $/kWh. The main application of Na-S batteries is renewable energy stabilization and peak shaving [40]. The advantages of Na-S are high energy density and long cycle life. Major drawbacks of Ns-S are the need for thermal management and safety concerns due to the reaction of sodium with sulphur.

3.3.3. Lead acid batteries

These batteries consist of two electrodes, i.e., cathode (positive) and anode (negative). The cathode consists of lead dioxide (PbO_2) and the anode consists of lead. During the discharging, the anode and cathode electrode uses sulfuric acid (H_2SO_4) is converted it into lead sulfate ($PbSO_4$). During charging the lead sulfate ($PbSO_4$) is converted back into sulfuric acid [41]. The efficiency of these batteries is around 75-90%, energy density is 50-80 kW/m^3, 30-50 Wh/kg, and power density is 10-400 W/m^3, 75-300 W/kg. Due to the short life cycle of the 100-2,000 cycle, lifetime is 5-15 years and low energy density. These batteries are not used for grid storage applications. The capital cost of lead-acid batteries is around 300-600 $/kW and the cost per unit of energy stored is 200-400 $/kWh [42]. Lead-acid batteries were commonly used for EVs, but nowadays, they are replaced by lithium-ion batteries.

3.3.4. Redox flow batteries

In these batteries, electrolyte contains ions that move from the negative electrode to a positive electrode while charging and discharging through a membrane. A cooling system is required because while charging and discharging a huge amount of heat is produced. The chemical composition of electrolytes is vanadium and zinc-bromine. The operating temperature of redox flow batteries is usually 20-40 °C [43]. The efficiency range lies between 65-80%. The lifetime is 15 years and 10,000-20,000 cycles. Energy density is 16-33 kW/m^3, 15-50 Wh/kg, and power density is 0.5-2 kW/m^3. The capital cost of the redox flow batteries energy storage system is around 600-1,500 $/kW and the cost per unit of energy stored is 150-1000 $/kWh [44]. Various applications of redox flow batteries are the vehicle, off-grid, emerging power systems, grid energy storage. Some of the drawbacks are high cost, more complex than other batteries, and early stage of development. Various characteristics of electrochemical batteries have been presented in Table 1.

Table 1. Various characteristics of electrochemical batteries

Battery Type	Cycle at 80% DOD	Operating Temperature (°C)	Electrolyte	Life (years)	Life (cycles)
Lead-acid	600-1,250	-5 to 40	Sulfuric acid (H2SO4)	5-15	500-1,000
Lithium Ion	4,000	-30 to 60	lithium salts (LiPF6)	5-15	103-104
Sodium sulphur	4,000	300-360	Ceramic (sodium beta alumina Al2O3)	15	4,500
Redox flow	10,000	20-40	V/V, Fe/Cr, Zn/Br2, S/Br2, V/Br2, Ce/Zn, and Pb/Pb	15	104-2×104

3.4. Molten salt energy storage

Thermal energy storage means the storage of energy by heating or cooling a medium like phase change materials (PCMs), molten salts, and water. Molten salt is a mixture of 60% sodium and 40% potassium nitrate which is nontoxic and nonflammable. The molten salt is stored in liquid form in the cold storage tank. Molten salt is pumped to a receiver tower, where it gets heated by a concentrated solar power plant (CSP) through sunlight. The hot molten salt is then stored in an insulated hot storage tank. The hot molten salt is pumped to the superheater then goes to the steam generator which generates the steam and runs the mechanical steam turbine coupled with generators, and it generates the electricity. The cold molten salt again is stored in an insulated cold molten salt storage tank. Storing of energy is up to 20 hours. Molten salt can be used at a higher temperature range of 550-570 °C [45]. Molten salt is a mixture of KNO_3 and $NaNO_3$. Efficiency is in the range of 80-90%. Energy density is 80-500 kW/m^3, 80-250 Wh/kg. The capital cost of the molten salt energy storage system is around 400-700 $/kW and the cost per unit of energy stored is 3,500-7.000 $/kWh. The application of a molten salt energy storage system is hot water production, space heating, and electricity generation [46]. Some of the major drawbacks are molten salt is corrosive and limited to CSP technology.

3.5. Hydrogen energy storage

This storage system can convert the electricity into hydrogen by chemical conversion. The electrolyte can split water into oxygen and hydrogen. The process can be reversed, and hydrogen and oxygen generate electricity, which feeds to the grid. Hydrogen can be stored in different forms such as liquified gas, metal hydrides, and compressed gas. Efficiency is in the range of 35-55%, the lifetime is 5-15 years, and life cycles 1000+[46]. Energy density is 500-3,000 Wh/m^3, 500+ W/kg and power density is 500+ W/m^3. The capital cost of the molten salt energy storage system is around 500-10,000 $/kW and the cost per unit of energy stored is 6,000-20,000 $/kWh. This technology has low environmental impacts. Some of the major drawbacks of this technology are low round trip efficiency, the low energy density at ambient temperature, high capital cost, and safety concerns.

4. COMPARATIVE ANALYSIS OF ENERGY STORAGE TECHNOLOGIES

Various technical characteristics of energy storage technologies such as efficiency, lifetime, maximum cycle charging time, discharging time, self-discharge, energy density, power density, and capital cost, are presented in Tables 2 and 3. Technically PHES is matured, Hydrogen energy storage is under the developing stage, whereas all other storage systems are developed. Flywheel, supercapacitor, and SMES are the short-term energy storage technologies, sodium sulphur, lithium-ion redox flow, lead-acid batteries are the medium-term energy storage technologies, whereas PHES, CAES, and hydrogen energy storage are long term energy storage technologies.

Table 2. Various technical characteristics of energy storage technologies

Storage Type	Power Rating	Cycle Efficiency	Response Time	Maximum Cycle	Life Time	Charge Time	Discharge Time	Self-Discharge
PHES	(100-5000) MW	(75-85)%	sec-min	10000-6×100000	40-60 years	hour-month	1-24 hour +	very small
CAES	(5-300) MW	(70-89)%	min	10000-3×10000	20-40 years	hour-month	1-24 hour +	small
Flywheels	(0-250) kW	(93-95)%	ms-sec	10000-100000	15 years+	sec-min	ms - 15min	100%
Super capacitor	(0-300) kW	(90-95)%	ms	100000+	20 years+	sec-hour	ms - 60min	(20-40)%
SMES	100 KW-10 MW	(95-98)%	< 100 ms	100000+	20 years+	min-hour	ms - 8 sec	(10-15)%
Sodium Sulphur	50 kW-8 MW	85%	ms	4500	15 years	sec-hour	sec - hour	20%
Lithium-Ion	(0-100) kW	(85-95)%	ms	1000-10000	5-15 years	min-day	min - hour	(0.1-0.3)%
Redox Flow	30 kW-3 MW	(65-85)%	sec	10000-20000	15 years	hour-month	(1-24) hour+	small
Lead Acid	(0.05-40) MW	(75-90)%	sec	500-1000	5-15 years	hour-month	(1-24) hour+	small
Molten salt	(0-60) MW	(80-90)%	min	-	30 years+	hour-month	(1-24) hour+	1%
Hydrogen	(0-50) MW	(35-55)%	sec	1000+	5-15 years	hour-month	(1-24) hour+	almost zero

Table 3. Technical characteristics of various energy storage technologies such as power density, energy density, environmental impact, and capital cost

Storage Type	Power Density (KW/m^3)	Power Density (W/kg)	Energy Density (Wh/L)	Energy Density (Wh/Kg)	Energy Density (KW/m^3)	Friction Losses	Capital Cost ($/kW)	Capital Cost ($/kWh)	Environmental Impact
PHES	0.5-1.5	0	0.2-2	0.5-1.5	0.5-1.5	Yes	600-2,000	5-100	Negative
CAES	0.5-2	0	2-6	30-60	3-6	Yes	400-800	2-50	Negative
Flywheels	1,000-2,000	400-1,500	20-80	10-30	20-80	Yes	250-300	500-1,000	Almost Zero
Super capacitor	100,000+	500-5,000	2-10	0.05-5	2-10	No	100-300	300-2,000	Small
SMES	100,000+	500-2,000	0.2-2.5	2.5-15	10-20	No	200-300	1000-10,000	Negative
Sodium Sulphur	140-180	150-230	200-400	100-250	150-250	No	1,000-3,000	300-500	Negative
Lithium-Ion	1,500-1,000	150-315	20-70	75-200	200-500	No	1,200-4,000	100-2,500	Negative
Redox Flow	0.5-2	0	16-33	15-50	16-33	No	600-1,500	150-1,000	Negative
Lead Acid	10-400	75-300	50-80	30-50	50-80	No	300-600	200-400	Negative
Molten salt	-	0	43.5	80-250	80-500	No	400-700	3,500-7,000	Small
Hydrogen	500+	500+	600 (at 200 bar)	800-10,000	500-3000	No	500-10,000	3,500-7,000	Small Positive

The charging time and discharging time are less. The only main drawback of these technologies cannot be used for long-term energy storage technologies. The response time of the flywheel, supercapacitor, SMES, sodium sulphur batteries, lithium-ion batteries are approximately or about in milliseconds. PHES, CAES, and flywheels energy storage technologies have friction losses while other technologies do not have any type of friction losses. The self-discharging of hydrogen energy storage technologies is almost zero. The environmental impact of flywheel energy storage technologies is almost zero, whereas all other energy storage technologies have a little environmental impact. PHES technologies are the largest grid-connected energy storage technologies in the world.

5. CONCLUSION

A comparative overview of available energy storage technologies such as electrical, mechanical, electrochemical, thermal, and hydrogen energy storage has been presented in this work. These technologies include PHES, CAES, flywheel, hydrogen, molten salt, supercapacitor, SMES, lead-acid batteries, Na-S Batteries, Li-ion batteries, and redox flow batteries. Various evaluation criteria such as the economic dimension, technological dimension, environmental dimension, and social dimension are discussed in this paper. To enhance the efficiency and operation of the grid, energy storage technologies provide a significant role. After doing a comparative analysis among various types of energy storage technologies, the best way to use these energy storage technologies are integration. Among the various storage technologies hydrogen have low cyclic efficiency but the self-discharging time is almost equal to zero. Flywheel, SMES, and supercapacitor energy storage technologies are short-term energy storage technologies, but the response time of these technologies is very low. The environmental impact of the flywheel is almost equal to zero. Flywheel, CAES, and PHES have friction losses whereas all other technologies do not have any friction losses.

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