Energy Storage Technologies: Past, Present and Future

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Abstract Decentralization of the main grid into microgrid levels largely depends upon the energy storage penetration level. The limits of the energy storage duration have been pushed with the increase in the penetration of renewables, from intermittent to hours based upon the application requirement. Energy storage technologies are majorly categorized into mechanical, chemical, thermal, electromagnetic and its combination depending upon the application requirement. Energy storage helps in decoupling the energy production and demand, thereby reducing the effort of constant monitoring of the load demand. Storage offers economic benefits of reduction in generation station energy to meet the average demand rather than the peak demands. This also helps in the appropriate sizing of the transmission lines and balance of plant for the average power demands. The storage technologies are compiled and evaluated based upon project/market requirement parameters such as energy/power density, specific energy/power, efficiency, cycle life, capital energy/power costs, technical maturity and its environmental impact, keeping in view their capacity and its microgrid application. Although every storage technology has its own advantages and disadvantages, with focus on the incremental development of existing technology, certain storage technology has the potential to meet the requirement with increased reliability and longevity of the decentralized system.

Keywords Energy · Power · Storage · Density · Cycle life · Technical maturity · Cost

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1 Introduction

The modern energy economy has undergone rapid growth change, focusing majorly on the renewable generation technologies due to dwindling fossil fuel resources, and their depletion projections [1]. Figure 1 shows an estimate increase of 32% growth worldwide by 2040 [2, 3]. Asia, North America and Europe has the highest share whereas Asia, Africa and Latin America has shown 1.9%, 2.7% and 1.5% respectively increase per year (2015–2040) [4].

The overall consumption of the electricity worldwide has gain momentum as shown in Fig. 2, where Asia and Africa have the highest YoY % increase of 3.4 and 4.5% respectively [2–4].

The global challenge is well-known, i.e. transforming power and transportation systems through the integration of reliable energy storage systems which can provide a solution to complete the energy transition towards renewables.

Energy storage (which is not only batteries) systems represent a set of technologies and methods that are used to store various forms of energy. Energy storage can be used to manage power supply, to create a resilient energy system and to bring cost savings to both prosumers and utilities.

Energy storage will play a major role in the future for residential, commercial and industrial sectors, and will lead to a transformation of both the power and the transportation sectors. Depending on the sector and the needs, energy storage applications will be a significant part of the future energy system. The goal for a 100%

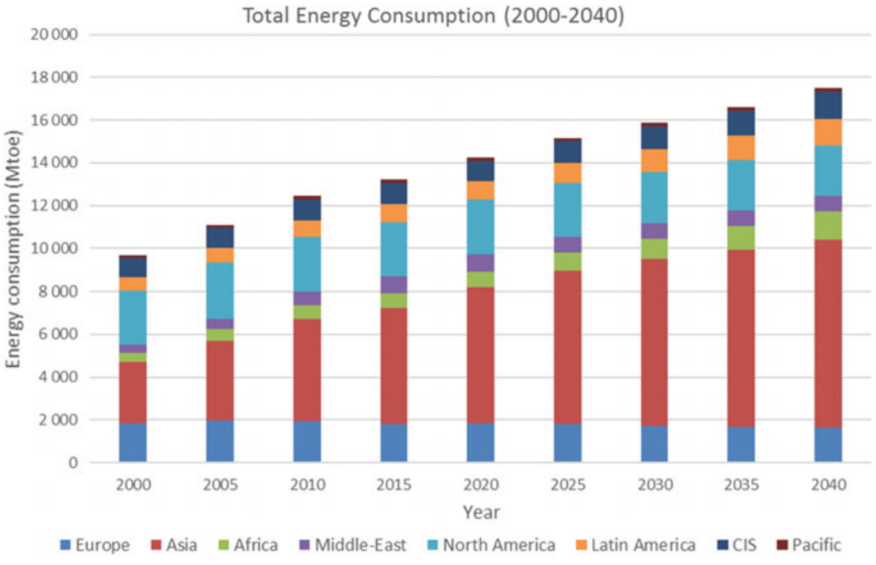

Fig. 1 Total energy consumption of world in Mtoe (2000–2040) [3]

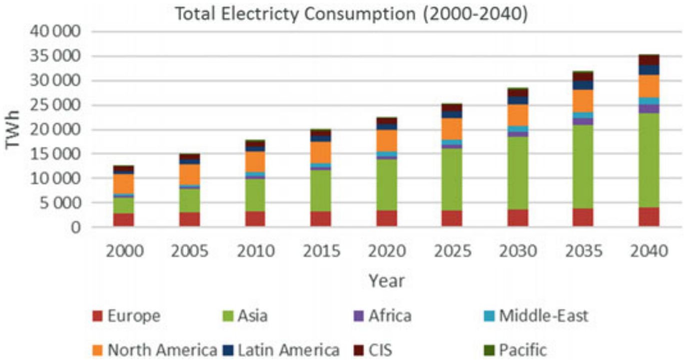

Fig. 2 Total electricity consumption of world in TWh (2000–2040) [2, 3]

renewable energy system could be achieved in the future, thanks to state-of-the-art batteries and development in the other forms of storage systems.

2 Energy Storage Technologies Overview

There are different forms of energy storage depending on two scales, power and time. Certain energy storage technologies are used to store power for different periods of time based upon the application requirement. In this context, understanding which energy storage technology is appropriate in each case is crucial.

As shown in Fig. 3, it is broadly classified into four categories; namely mechanical, electromagnetic, chemical and thermal storage. Out of this, currently pumped hydroelectric (of mechanical storage system) is dominant in terms of deployed forms of energy storage (nearly 99%) [5, 6].

Storage system has no immediate environmental or air quality impacts, helps in demand charge reduction, allows participation in demand response programs and in maximizing time-of-use rates. In remote areas, storage systems plays a vital role of resilience power supply as emergency backup. With the aforesaid commercial advantages, it also helps in the optimal sizing of the transmission lines and equipment followed by the mitigation of problems associated with the intermittency of the renewable energy generation.

In 2017, pumped storage accounts for 96.28% (153 GW) out of the Global utility scale energy storage capacity (by technology), followed by electro-mechanical (1.3 GW), electro-chemical (2.3 GW) and Thermal (2.3 GW) [3]. More than 75% of stationary grid-connected storage capacity was operating in only 10 countries as of 2017 [5].

Technologies such as flywheels and superconductors are having high parasitic losses, are useful for very short duration applications in power quality and regulation. Technologies with lower parasitic losses drop (e.g., pumped hydro), become

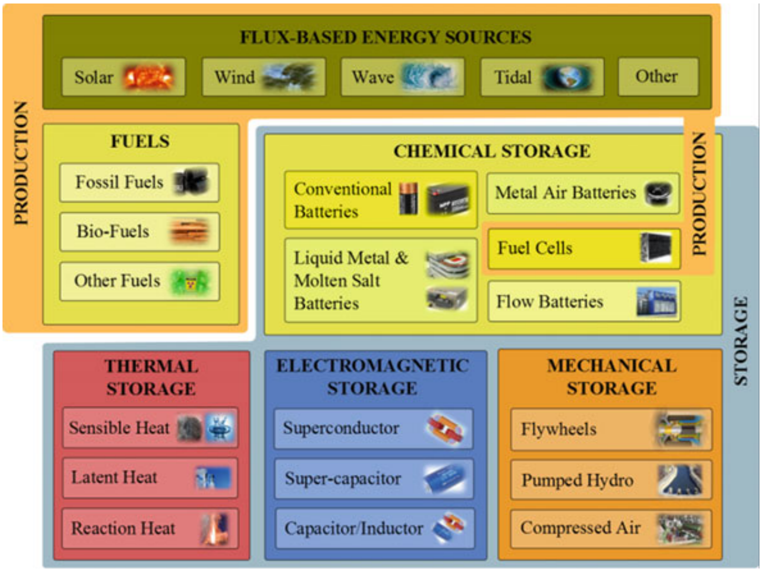

Fig. 3 Pictorial view of the energy storage systems and generation [3]

more relevant for longer term energy management. In the next subsection, positive and negative aspects of each class of technology are represented and concluded in identifying key issues and likely future trends in the energy storage landscape. Figure 4 represents the share of renewables and its trend (region-wise) over the period from 1997 to 2017. The drive for the renewables (due to paradigm shift in the application requirements) has pushed the limitation of the storage duration from seconds to months.

The energy storage system scales are categorized based upon their power rating as well as their application (storage duration) based upon the categories mainly power quality and regulation, bridging power and energy management as shown in Tables 1

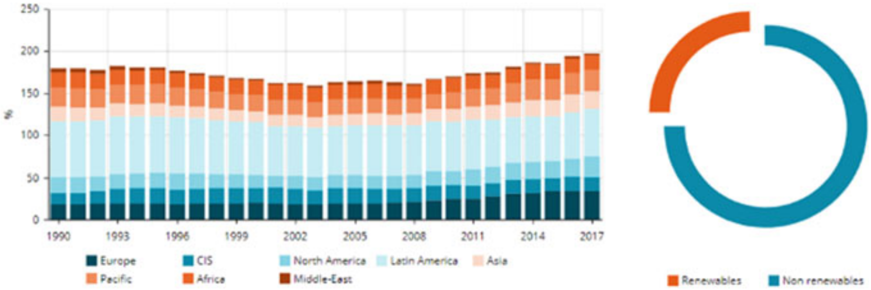

Fig. 4 Distribution trend of renewables (region-wise) and its overall share [4]

Table 1 Categorization of energy storage scales and their applications

Category	Applications	Power rating
Small scale	Mobile devices, electric vehicles, satellites, etc.	≤1 MW
Medium scale	Office buildings, remote communities, etc.	10–100 MW
Large scale	Power plants, etc.	≥300 MW

Table 2 Categorization of energy storage scales and their applications [7]

Category	Applications	Storage duration
Power quality and regulation	Fluctuation suppression/smoothing	≤1 min
	Dynamic power response	
	Low voltage ride through	
	Line fault ride through	
	Uninterruptable power supply	
	Voltage control support	
	Reactive power control	
	Oscillation damping	
	Transient stability	
Bridging power	Spinning/contingency reserves	1 min–1 h
	Ramping	
	Emergency backup	
	Load following	
	Wind power smoothing	
Energy management	Peak shaving/generation/time shifting	1–10 h
	Transmission curtailment	5–12 h
	Energy arbitrage	
	Transmission and distribution deferral	
	Line repair	
	Load cycling	
	Weather smoothing	
	Unit commitment	Hours–days
	Load leveling	
	Capacity firming	
	Renewable integration and backup	
	Seasonal storage	≥4 months
	Annual smoothing	

and 2. The energy storage technologies are classified based upon the application requirement with storage duration.

2.1 Mechanical Energy Storage

Mechanical energy storage has the highest share across all the energy storage technologies. It is comprised of systems such as, pumped hydro storage (PHS), flywheels (FES) and compressed air energy storage (CAES). These systems are widely used and are advantageous on large scale in various commercial, industrial, and residential uses (Table 3).

Mechanical energy storage systems have a huge potential to grow, pertaining to its various beneficial factors such as, technical maturity, regulation of power and frequency, relatively lower environmental impact, high energy/power densities and long duration [8–10]. However, lack of site availability, high capital costs, safety issues and disapproval of governments in initiating capital inducement projects, along with the development of recent modern technologies can hinder the mechanical energy storage market [11, 12].

Table 3 Comparison of different mechanical energy storage technologies based upon listed parameters [7]

Parametrics	PHS	CAES	FES
Scale/application	Large/energy management	Large/energy management	Medium/power quality
Technical maturity	Mature/fully commercialized	Proven/commercializing	Mature/commercializing
Environmental impact	High/medium	Medium/low	Low
Specific energy (Wh/kg)	0.3–1.5	3.2–60.0	5.0–200.0
Energy density (kWh/m^3)	0.5–1.5	0.4–20.0	0.25–424.00
Specific power (W/kg)	0.01–0.12	2.20–24.0	400–30,000
Power density (kW/m^3)	0.01–0.12	0.04–10	400–2000
Efficiency (%)	65–87	57–89	70–96
Cycle life (cycles)	10–60 k	8–30 k	10–100 k
Energy cost (USD/kWh)	1–291.20	1–140	200-150 k
Power cost (USD/kW)	300–5288	400–2250	30.28–700

2.2 Chemical Energy Storage

This type of energy storage has the highest diversity of research and energy storage products which are commercialized presently. This includes traditional batteries, molten salt/liquid metal batteries, metal air batteries, fuel cells and flow batteries.

(1) *Traditional batteries*

Tables 4 and 5 shows comparison between most known and generally used forms of chemical storage in traditional batteries category, namely Zinc Silver oxide (Zn–Ag), Alkaline Zinc Manganese Dioxide (Zn–Mn), lead Acid (Pb–Acid), Lithium-ion (Li–Ion), Nickel Metal Hydride (Ni–MH), Nickel Cadmium (Ni–Cd), Nickel–Iron (Ni–Fe) and Nickel Zinc (Ni–Zn) [13].

Batteries can help when the demand of energy is higher than the available energy at specific times and places. Batteries can help to compensate for different limitations of the power system [13–15].

Table 4 Comparison of different chemical energy storage technologies based upon listed parameters [7]

Parameter	Zn–Ag	Zn–Mn	Pb–Acid	Li–ion
Scale/application	Small/energy management	Small/energy management	Medium/energy management	Small, medium/energy management
Technology maturity	Fully commercialized	Fully commercialized	Fully commercialized	Fully commercialized
Environmental impact	Low	Medium	High	High/medium
Specific energy (Wh/kg)	81–276	80–175	10–50	30–300
Energy density (kWh/m^3)	4.2–957	360–400	25–90	94–500
Specific power (W/kg)	0.09–330	4.35–35	25–415	8–2000
Power density (kW/m^3)	0.36–610	12.35–101	10–400	56.80–800
Efficiency (%)	20–100	36–94	63–90	70–100
Cycle life (cycles)	1–1500	1–200	100–2000	250–10,000
Energy cost (USD/kWh)	3167–20,000	100–1000	50–1100	200–4000
Power cost (USD/kW)	741,935–7,140,620	1000–11,900	175–900	175–4000

Table 5 Comparison of different chemical energy storage technologies based upon listed parameters [7]

Parameters	Ni-MH	Ni–Cd	Ni–Fe	Ni-Zn
Scale/application	Small/energy management	Small, medium/energy management	Small, medium/energy management	Small/energy management
Technology maturity	Mature/fully commercialized	Mature/fully commercialized	Mature/limited development	Mature/limited development
Environmental impact	High	High	Low	Low
Specific energy (Wh/kg)	30–90	10–80	27–60	15–110
Energy density (kWh/m^3)	38.90–300	15–150	25–80	80–400
Specific power (W/kg)	6.02–1100	50–1000	20.57–110	50–900
Power density (kW/m^3)	7.80–588	37.66–141.05	12.68–35.18	121.38–608
Efficiency (%)	50–80	59–90	65–80	80–89
Cycle life (cycles)	300–3000	300–10,000	1000–8500	100–500
Energy cost (USD/kWh)	200–729	330–3500	444.27–1316	250–660
Power cost (USD/kW)	270–530	270–1500	8167–16,312	270–530

(2) *Molten Salt, Liquid metal and Metal Air batteries Traditional batteries*

Molten salt (Sodium Sulphur-NaS and Sodium Nickel Chloride-NaNiCl) and liquid metal are the typical class of high temperature chemical batteries (as in Table 6) which uses molten salts and liquid metals which acts as electrolyte as well as the electrodes [13, 16].

Metal air batteries (Zinc Air and Iron Air) are the cross-over of fuel cells and traditional chemical batteries, having one anode electrode and other as oxygen electrode (catalyzes the production of hydroxyl ions).

Although the typical nature of chemistries of electrolytes, electrodes and its stability, non-distributed charge–discharge patterns due to dynamic load variations, and sensitivity to change in environmental conditions, still traditional batteries are the mostly used storage devices till date in portable applications mostly due to high energy/power densities [17–19].

(3) *Fuel Cells*

Fuel cells (FC) are generally energy generation devices rather energy storage devices, which takes hydrogen and oxygen as input and produces electricity and water as output. The fuel is oxidized at anode and reduced at the cathode [20, 21].

Table 6 Comparison of different chemical energy storage technologies based upon listed parameters [7]

Parameters	NaS	NaNiCl	Zinc air	Iron air
Scale/application	Medium, large/energy management	Medium, large/energy management	Small/energy management	Small/energy management
Technology maturity	Proven/commercializing	Proven/commercializing	Mature/commercialized	Early stage research/developing
Environmental impact	Medium/low	Medium/low	Low	Low
Specific energy (Wh/kg)	100–240	85–140	10–470	8–109
Energy density (kWh/m^3)	150–345	108–190	22–1673	100–1000
Specific Power (W/kg)	14.29–260	10–260	60–225	18.86–146
Power density (kW/m^3)	1.33–50	54.20–300	10–208	250
Efficiency (%)	65–92	21–92.50	30–50	42–96
Cycle life (cycles)	1000–4500	2000–3000	1–500	100–5000
Energy cost (USD/kWh)	150–900	100–345	10–950	10–150
Power cost (USD/kW)	150–3300	150–10,000	100–4000	950

The hydrogen fuel can also be derived from the natural gas, methanol, ethanol, hydrocarbon gas and ammonia with the help of reformers.

Table 7 shows the comparson between four main types of fuel cell system namely, Proton Exchange Membrane (PEMFC), Solid Oxide (SOFC), Direct methanol (DMFC) and Molten Carbonate (MCFC).

Fuel cells technologies is cleaner, quieter and higher efficiency as compared to other technologies. They do have higher specific power/energy and energy densities. However, water and thermal management [22] along with the setup of Hydrogen ecosystem are the critical areas of concern along with its high capital intensive and lifespan, which restricts its economical viable uses to aerospace and large scale grid backup generation application [23–25].

(4) *Flow batteries*

Flow batteries are very much similar in operation to fuel cell systems. To generate electricity, the electrolytes containing dissolved active material flow through the fuel cell. This are classified into 2 types, namely Redox flow batteries and halide/metal batteries as compared in Table 8 [13].

Redox flow batteries usually have 2 tanks storing electrolytes (known as catholyte and anolyte), series/parallel connected bipolar cell stacks and pumping system. Metal/Halide batteries are those which utilizes deposition of metals as a means of storing energy [13, 26, 27].

Flow batteries are having good depth of discharge, simplicity in operation and uses non-toxic materials in their operation but due to lack of cost competitive ness, loses its race with other chemical storage technologies.

Metal/halide batteries has high efficiency and utilises inexpensive materials, resulting in potential of becoming cost competitive due to abundance availability of the electrolyte materials [27, 28].

2.3 Electromagnetic Storage

Electromagnetic storage generally covers storage in inductors (magnetic field) and capacitors (electric field) [29, 30]. With advancement in the technologies, this has been extended to super conductors and supercapacitors (Electrochemical double-layer capacitors) [31] for large scale applications as compared in Table 9.

Super conductors have long cycle life, high efficiency, fast response with very high discharge rates, because of which is used mostly in power quality and stability applications [29, 32]. The major hurdle faced by such technology is the high costs (to maintain the stringent operation parameters) and the mismatch between power capacity and its energy performance.

Supercapacitor usually have low capacitance resulting in making it not suitable for high power applications, however combining them other storage systems such as battery systems will help in increasing life span of battery system by absorbing the

Table 7 Comparison between types of fuel cell systems based upon listed parameters [7]

Parameters[a]	PEMFC	DMFC	MCFC	SOFC
Scale/application	Small, medium/energy management	Small/energy management	Medium/energy management	Medium/energy management
Technology maturity	Proven/commercializing	Proven/developing	Proven/developing	Proven/commercializing
Environmental impact	Low	Low	Medium/low	Medium/low
Specific energy (Wh/kg)	100–450	140.30–960	369–607	410–1520
Energy density (kWh/m^3)	112.2–770	29.90–274	25–40	172–462.09
Specific power (W/kg)	4–150	2.10–20	12–36.70	10–63.34
Power density (kW/m^3)	4.20–35	1–300	1.05–1.67	4.20–19.25
Efficiency (%)	22–85	10–40	45–80	50–65
Energy cost (USD/kWh)	70–13,000	30,670–3190	146–175	180–333
Power cost (USD/kW)	0–10,200	15,000–125,000	3500–4200	481–8000

[a] Cycle life is not applicable for fuel cell systems as source is external to the system

Table 8 Comparison among the types of flow batteries based upon listed parameters [7]

Parameters	Vanadium redox (VR)	Zinc bromine (ZB)	Polysulphide bromine (PB)
Scale/application	Medium, large/energy management	Large/energy management	Large/energy management
Technology maturity	Proven/commercializing	Proven/developing	Proven/developing
Environmental impact	Medium/low	Medium	Medium
Specific energy (Wh/kg)	10–50	11.10–90	10–50
Energy density (kWh/m^3)	10–33	5.17–70	10.80–60
Specific power (W/kg)	31.30–166	5.50–110	NA
Power density (kW/m^3)	2.50–33.42	2.58–8.50	1.35–4.16
Efficiency (%)	60–88	60–85	57–83
Cycle life (cycles)	800–16,000	800–5000	800–4000
Energy cost (USD/kWh)	100–2000	110–2000	110–2000
Power cost (USD/kW)	175–9444	175–4500	330–4500

Table 9 Comparison among the types of flow batteries based upon listed parameters [7]

Parameters	Superconducting magnetic (SMES) [30]	Supercapacitors (ELDC) [33]
Scale/application	Medium, large/power quality	Small, medium/power quality
Technology maturity	Proven/commercializing	Proven/commercializing
Environmental impact	Low	Low
Specific energy (Wh/kg)	0.27–75	0.07–85.60
Energy density (kWh/m^3)	0.20–13.80	1–35
Specific power (W/kg)	500–15,000	5.44–100,000
Power density (kW/m^3)	300–4000	15–4500
Efficiency (%)	80–99	65–99
Cycle life (cycles)	10,000–100,000	10,000–1,000,000
Energy cost (USD/kWh)	500–1,080,000	100–800
Power cost (USD/kW)	196–10,000	100–800

surges and spikes during the transient operations and also fast delivery of the stored energy during requirement of the load [30, 31, 33].

2.4 Thermal Energy Storage

Thermal storage systems (TES) are used in mainly thermal power plants (industry scale) [34, 35]. Since mechanical, chemical and electromagnetic storage technologies are focusing on electricity storage, however the thermal storage needs to be coupled to heat engines or some thermoelectric generators for electricity generation (useable form).

Thermal storage is further categorized into three types namely, sensible heat, latent heat and reaction heat whose comparson is given in Table 10. This system contains three main components: the containment system, the thermal material and heat exchanger.

Thermal storage has wide range of applications in existing power plants and potential for the solar power plants, where the heat loss can be utilized to increase

Table 10 Comparison of different types of thermal storage systems based upon listed parameters [7]

Parameters	Sensible heat (STES)	Latent heat (LTES)	Chemical reaction heat (CTES)
Scale/application	Medium/bridging power	Medium, large/energy management	Small, medium/energy management
Technology maturity	Mature/commercializing	Proven/commercializing	Proven/developing
Environmental impact	Low	Low/uncertain	Low/uncertain
Specific energy (Wh/kg)	10–120	150–250	250
Energy density (kWh/m^3)	25–120	100–370	300
Specific power (W/kg)	NA	10–30	NA
Power density (kW/m3)	NA	NA	NA
Efficiency (%)	7–90	75–90	75–100
Cycle life (cycles)	NA	NA	NA
Energy cost (USD/kWh)	0.04–50	3–88.3	10.90–137
Power cost (USD/kW)	2500–7900	200–300	NA

the overall system efficiencies (also with the use of phase change material, PCM for storing solar heat [36, 37]). Research is underway for the underground thermal storage technology, which can take advantage of the planet's inner heat.

3 Conclusion

The energy storage technologies are vast and out of which twenty-seven types of storage technologies are considered. The technologies are compared based on parameters such as technical maturity, specific energy/power, energy/power density, efficiency, cycle life, energy/power cost, environmental impact and its applications.

Ni–MH, Ni–Cd, ZnAg, ZnMn and Pb-Acid from chemical energy storage systems and PHS spearheaded the technology maturity stage, however recycling and disposal of the batteries are still critical to the environment. Due to low loss storage and high share among energy storage systems (nearly 99%), PHS is mostly used for the energy management applications.

FES (followed by SMES) and flow batteries has the lowest and lowest impact respectively on the environment among other storage technologies. Superconducting at room temperature condition would be a game changer for energy storage Flow batteries has the potential for cost competitive when compared with CAES along with the improvements in power/energy capacities,

Fuel cells (SOFC followed by MCFC), FES, Metal Air (Zn–Air followed by Fe–Air), Super capacitors, SMES, SMES, leads in the specific energy (Wh/kg), specific power (W/kg), energy density (kW/m^3), power density (W/m^3), efficiency (%), cycle life (cycles) parameters respectively.

Fuel Cells (SOFC followed by MCFC) is far more than PHS, CAES and flow batteries in terms of energy performances, which means huge reduction of land requirement/usage, whereas Metal Air (Zn–Air followed by Fe-Air) shows higher power performances among others. This helps in putting fuel cell systems for large scale applications in future.

Li-ion has significant potential in the small scale applications such as electric vehicle applications due to its high energy/power densities as against molten salt, NaS, NaNiCl, NiCd, NiZn and NiMH which are having shorter life cycles and requires complex thermal management.

Energy cost (USD/kWh) and power cost (USD/kW) is highest for SMES (followed by Supercapacitors) and Zn–Ag (followed by DMFC) respectively, which makes its commercialization restraint. CAES has the lowest energy cost, with high power/energy capacities making it a good contender for utility scale energy storage applications.

Thermal energy storage systems are the major focus areas for the already installed generation systems as well for the renewables energy systems (mainly PV solar) for efficiency improvements. Hence, these systems are going to be integrated part of other storage systems. Furthermore, with respect to grid power quality management and regulation, FES, supercapacitors and SMES systems are the three main storage systems.

Other storage systems which are yet to be explored are biomass energy storage [38], gravity-based storage [39], mechanical spring systems-based storage [40], rail energy storage (RES) [41], phase change material (PCM) storing solar heat energy [36, 37].

The advancements in the energy storage systems from small scale to large scale, with duration from seconds to months are largely driven by the application requirements as well as the policies, standards and regulations adapted by the countries to reduce the impact of fossil fuel consumption on the environment with rapid modernization of the industry and transportation sector.

For the development of the energy storage technologies, continual effort needs to be in place for the improvement of the existing technologies as well as disruption of new technologies. But due to decreased energy cost of the competitors and lower investment in the new technology, the consumer patterns are unchanged which focuses on lower cost and increased performance of technology.

4 Assumption

Discharge rate assumed is 1C-rate. Data has been collected from multiple online databases available online. Specific power and energy are calculated based upon the dry mass of the systems. In case of energy generation systems such as fuel cell, 24 h time duration is considered for evaluation. Specific system dimensions for concerned systems are considered based upon the online available brochure/technical datasheet for the volume-based densities computation. Maximum efficiency has been considered in case of non-availability of information. Cost comparisons are made based on the recent trends in the current market scenario assuming exchange rates are in the acceptable variable range.

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