Chapter 7
Energy Storage Technologies; Recent Advances, Challenges, and Prospectives

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Abstract Fossil fuels are the origins of conventional energy production, which has been progressively transformed into modern innovative technologies with an emphasis on renewable sources such as wind, solar, and hydrothermal. Recently, the challenges concerning the environment and energy, the growth of clean and renewable energy-storage devices have drawn much attention. Renewable energy sources are the primary choice, which addresses some critical energy issues like energy security and climate change. But, renewable energy sources have interrupted and irregular supplies that should be stored in efficient, safe, efficient, reliable, affordable, and clean ways. Hence, energy storage is a critical issue to advance the innovation of energy storage for a sustainable prospect. Thus, there are various kinds of energy storage technologies such as chemical, electromagnetic, thermal, electrical, electrochemical, etc. The benefits of energy storage have been highlighted first. The classification of energy storage technologies and their progress has been discussed in this chapter in detail. Then metal–air batteries, supercapacitors, compressed air, flywheel, thermal energy, superconducting magnetic, pumped hydro, and hybrid energy storage devices are critically discussed. Finally, the recent progress, problems, and future prospects of energy storage systems have been forwarded. The chapter is vital for scholars and

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A. K. Bohre et al. (eds.), *Planning of Hybrid Renewable Energy Systems, Electric Vehicles and Microgrid*, Energy Systems in Electrical Engineering,
https://doi.org/10.1007/978-981-19-0979-5_7

scientists, which provides brief background knowledge on basic principles of energy storage systems.

Keywords Renewables · Metal–air batteries · Energy storage · Thermal energy · Pumped hydro storage · Superconducting magnetic

Nomenclature

ESSs	energy storage systems
EMES	electromagnetic energy storage
CESTs	chemical energy storage technologies
EMES	electromagnetic energy storage
PHES	pumped hydroelectric energy storage
MESTs	mechanical energy storage technologies
FEST	flywheel Energy Storage technology
TES	thermal energy storage
FC	fuel Cells
SHS	sensible heat storage
LHS	latent heat storage
ECES	electrochemical energy storage
NiCd	nickel-cadmium batteries
FBs	flow batteries
LIBs	lithium-ion batteries
MABs	metal-Air Batteries
HESSs	hybrid energy storage systems

7.1 Introduction

Recently, the world population is increased in an amazing manner, which leads to the growth of global energy demand. Thus, this demand has been maintained using fossil fuels as a source of energy (Sadeghi et al. 2021). However, their inadequate assets, climate change issues, and energy security issues have been forced to focus on alternative energy technologies. Renewable energy sources have great advantages related to environmental effects and energy security, which is not a constant supply of energy (Zhao and Guo 2021). Hence, renewables need to be stored in safe, eco-friendly, effective, and reliable ways for later use. Energy storage systems (ESSs) can be divided according to different principles (Komala et al. 2021). They can be divided as chemical, electromagnetic, thermal, mechanical, and electrochemical, associated with the kind of stored energy. Energy in the form of potential or kinetic can be stored in mechanical ESSs (Cheng et al. 2021). Betties gained special attrition for ESSs because this electrochemical energy storage was studied highly. Moreover, chemical energy storage such as ammonia, methane, and hydrogen are frequently studied technologies (Hu et al. 2021). Additionally, latent or sensible heat storage is a type of thermal ESSs. Electromagnetic energy storage is an emerging technology, which needs special attrition. The purpose of this chapter is to deliver a detailed discussion on energy storage technologies, which is used as a reference for different scholars and industries involved in the area. However, there are a limited number of reviews on energy storage technologies and their application (Wang et al. 2021). Hence, in this chapter, we discussed the recent advancements in basic energy storage tools such as electromagnetic, electrochemical, thermal, mechanical, and chemical, energy storage devices (Nguyen et al. 2014). Finally, challenges and prospectives are discussed to identify the gaps and to forward import directions for the enhancement of energy storage technologies.

7.2 Benefits of Storing Energy

ESSs can be classified based on different systems such as (Pickard 2012).

- Chemical,
- Electrochemical,
- Electromagnetic,
- Thermal, and
- Mechanical.

Thus, each system has its own characteristics and efficiency. The criteria for choosing suitable ESSs are shown in Fig. 7.1. The criteria for selecting ESSs, such as storage cost, adaptability, environmental impact, capacities, and efficiency, can be used in the selection process.

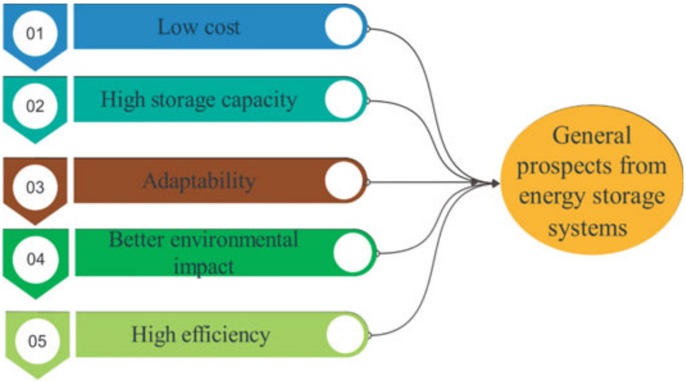

Fig. 7.1 Schematic illustration of criteria for selecting appropriate energy storage systems

In fact, ESSs have many characteristics, and each energy storage system has different expectations, depending on the requirements of the end-user. Though, when demand and supply do not balance each other, all will be used together to provide clean, affordable, efficient, safe, and reliable energy. Recently prepared various ESSs have similar features with traditional energy generation technologies. Additionally, they produce some different properties, which make the energy method further complex (Papaefthymiou et al. 2010). Various energy production technologies from hydroelectric power plants, the energy produced by storage systems are restricted, which means in an energy storage system, the peak power production can be kept for a certain period of time, associated with the energy previously stored in the system. Moreover, furthermore to limited power generation capacity, most energy storage systems also have cycle limits. Though, in addition to the problems, ESSs still have significant advantages and can meet energy needs without or with limited supply. In addition to these main benefits, they also have technological, environmental, and economic merits, which make them an essential foundation in energy technology. Figure 7.2 displays selected vital conditions to be provided in the designing process of ESSs. For instance, if the system contains a higher discharging and charging power rating, however a lower capacity, it may be utilized for fast and short-lived emergencies, mobile power supplies, etc. It is a good choice, but it is not appropriate for periodic energy storage. Moreover, systems with lower capital costs and higher operating costs will be more suitable for short-term storage such as emergency and peak

Fig. 7.2 Schematic illustration of criteria used to estimate the performance of ESSs

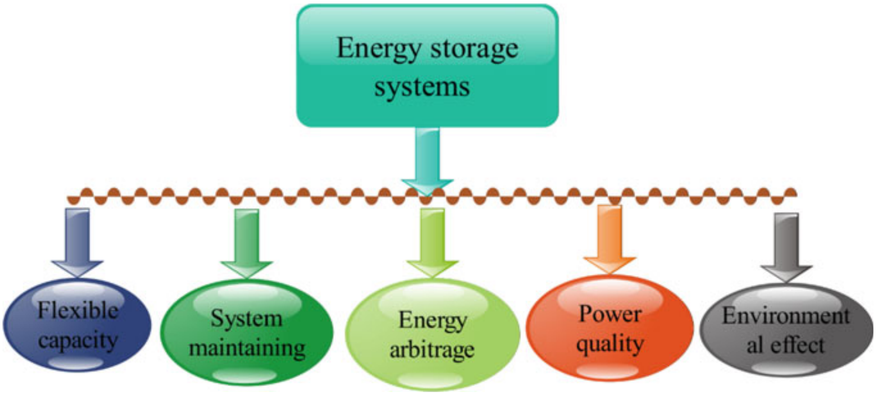

Fig. 7.3 Schematic illustration of benefits of ESSs

demand needs. Oppositely, technologies with low operating costs and high capital are further appropriate for long-term energy requirements like periodic storage.

Depending on the location of the facility, utility rates and power load, and other factors, energy storage can be the best means for facilities to cut electricity bills. The price of ESSs is declining, and the figure of customer-defined ESSs that has been installed is rapidly increasing. Moreover, to increase the use of renewable energy for power generation, improved energy storage technology also has the following advantages (Fig. 7.3) (Liu et al. 2010):

- **Environmental issues**: Energy storage has different environmental advantages, which make it an important technology to achieving sustainable development goals. Moreover, the widespread use of clean electricity can reduce carbon dioxide emissions (Faunce et al. 2013).
- **Cost reduction**: Different industrial and commercial systems need to be charged according to their energy costs. Solar photovoltaic power generation can decrease total power consumption, but these merits do not permanently coincide with the peak usage hours of buildings (Luo et al. 2015).
- **Maximize usage time**: ESSs can transform power consumption from expensive periods when demand is high to low-cost power periods when demand is low. If the electricity price structure changes over time, and the peak demand period shifts to the evening when there is no light, this can reduce the risk of reducing the value of on-site solar energy. This also enables facilities to take full advantage of time-of-use pricing and reduces the risk of electricity price structure changing the cost of electricity.
- **Emergency backup**: Power backup is a significant part of a resilient plan. Moreover, by using this infrastructure on a daily basis to reduce demand costs, its reliability and availability can be improved during shutdowns compared to independent battery systems and diesel generators used only during shutdowns (Tewari and Mohan 2013).

- **Economy**: Increase the economic value of wind energy and solar energy (Pearre and Swan 2015).
- **Work**: Creates work in transportation, engineering, construction, financial, and manufacturing departments (Heymans et al. 2014).

7.3 Energy Storage Technologies

In this section, a brief overview of chemical, electromagnetic, electrochemical, mechanical, and thermal ESSs with their technical status will be presented. Thus, ESSs can store energy in different systems for future utilization (Zhao et al. 2015). The prospect of energy storage is to be able to preserve the energy content of energy storage in the charging and discharging times with negligible loss. Hence, the selected technologies primarily change electrical energy into various forms during the charging process for efficient storage (Kirubakaran et al. 2009). The most widely used storage technologies can be categorized according to the kind of energy stored, as shown in Fig. 7.4. Moreover, there are various types of technologies such as end-use applications, which are used as ESSs. The typical example is the adjustment of energy consumption peak and time demand. Other examples include utility control of electric water heaters, pre-cooling, adjustment of municipal water time, etc. to reduce cooling requirements during the day (Whittingham 2008).

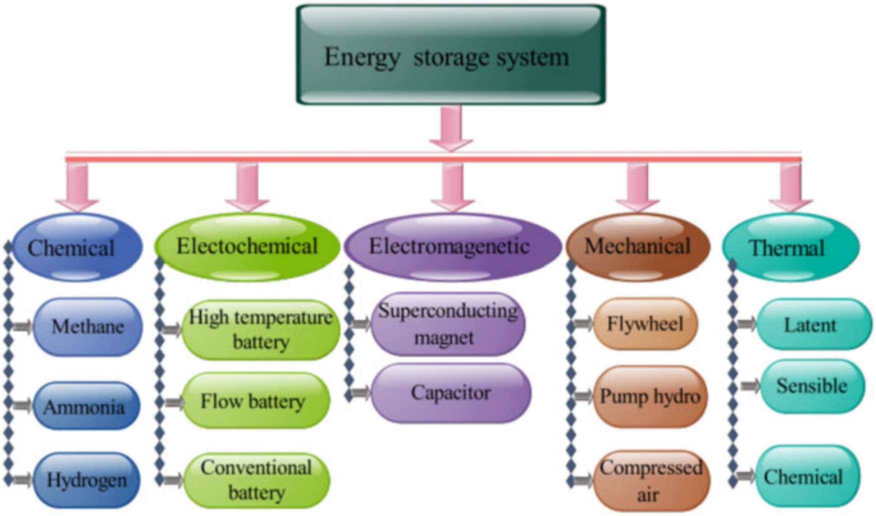

Fig. 7.4 Schematic illustration of the classification of selected ESSs

7.3.1 Chemical Energy Storage Technologies (CESTs)

In CESTs, energy can be stored using various materials in the form of chemical energy. It can be categorized as follows:

- Biofuels,
- Hydrogen storage.

7.3.1.1 Hydrogen Storage

Hydrogen is a type of energy that can be transported and stored. Moreover, hydrogen gas has expensive storage, low energy density, and non-toxicity with combustion product of H_2O. Hydrogen can be fabricated via several methods such as electrolysis, natural gas, coal, and oil. It can be stored in various forms such as in metal-hydride, liquid, and gaseous forms. Thus, hydrogen storage in the form of metal-hydride and gas are very mature systems for hydrogen storage. However, the boiling point of hydrogen is 20 K, which is a challenge of hydrogen storage in the form of liquid. Hydrogen storage in the form of gaseous is associated with mechanical stability and material permeability in extreme pressure.

7.3.1.2 Biofuels

Biofuels are formed via biological methods instead of geological methods. Biomass is an organic substance acquired from the residues of animal and plant manure. Hence, biomass is employed to generate the biogas that can be utilized for local application or can be transformed into electricity via a generator. There are various types of biofuels such as solid biomass, biodiesel, gasoline, biofuel syngas, bio-alcohols, biogas, bio ether, green diesel, ethanol, and vegetable oils.

7.3.2 Electromagnetic Energy Storage (EMES)

In superconductors, the flow of direct current produces energy, which can be stored in the form of a magnetic field. Electricity storing in the form of electrical energy is a challenging activity because of different causes such as low efficiencies and high system losses. Hence, electrical energy might be changed to different types of energy for storage purposes in an affordable, safe, environmentally benign, and reliable way. In EMES, electrical or different type of energy is changed to electromagnetic energy using different devices such as superconducting electromagnets and capacitors. The two electrical conductors of a capacitor are separated using a dielectric material. Charge can be accumulated on the side of the applied current, while current is applied to the conductor. Thus, the conductor plates can be stored energy in the form of an

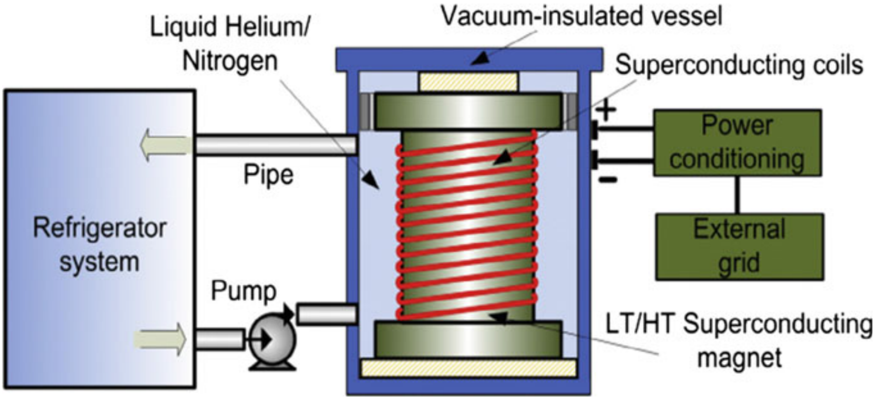

Fig. 7.5 Schematic diagram of electromagnetic energy storage technology. Reproduced with permission (Luo et al. 2015) Copyright (2015), Elsevier

electric field. Capacitors with higher energy density are called supercapacitors. For the generation of a magnetic field, superconducting magnetic energy storage is used via a cryogenically cooled superconducting coil. Hence, such types of technologies are appropriate for high-power requests when storing fluctuating and intermittent energy sources. EMES have various merits such as sensitivity to battery voltage imbalance maximum voltage threshold, and battery interdependence, as well as safety issues, such as explosion, chemical, fire, and hazards. Figure 7.5 displays the diagram of electromagnetic energy storage technology.

7.3.3 Mechanical Energy Storage Technologies (MESTs)

In MESTs, excess energy is changed into potential or kinetic energy for future utilization. There are various types of MESTs used as energy storage the typical examples are listed as follows:

- Flywheel,
- Compressed air storage, and
- Pumped storage.

7.3.3.1 Pumped Hydroelectric Energy Storage (PHES)

PHES is the best and most advanced technology utilized for energy storage. Presently, approximately 129 GW of pumped storage capacity has been installed worldwide. The basic working mechanism of pumped storage can be categorized into two steps. Primarily, electricity is applied to pump water from the lower reservoir to the upper reservoir. Then, water flows from the higher reservoir to the lower reservoir, the input energy is recovered through the turbine (Figueiredo and Flynn 2006). From this, we can conclude that pumped storage has very similar working principles with a hydroelectric power plant. According to reports, the total proficiency of the pumped storage system is between 70 and 85%, which depends on construction, size, service life, condition, and location status. The principal merits of pumped storage are its flexibility, which can be utilized as energy storage several times. The response time of the pumped storage system is also very short (a few seconds to a few minutes). The other merits of pumped storage are long service life, low operating cost, lack of circulating energy consumption, and low maintenance cost. However, the pumping system has very special location conditions. Furthermore, pumped storage usually needs high asset costs. However, pumped storage has been regarded as an efficient solution that can be utilized to balance the load of the power system and reduce peak energy demand. The PHES devices store energy in the form of potential energy, which is pumped from lower reservoirs to higher reservoirs (Fig. 7.6). In such type of technology, low-cost electricity (power during off-peak hours) is applied to run pumps to lift water from the lower reservoir to the upper reservoir. At the time of high power demand, the stored water is released via the hydraulic turbine to generate electrical energy. When necessary, the reversible generator assembly acts as a turbine. Recently, PHES systems have solar photovoltaic and wind power generation systems that can transfer water from lower reservoirs to upper reservoirs. This technology is currently used as a low-cost way of storing huge amounts of electrical energy; however, suitable geographic location and capital cost are crucial decisive issues. The preparations of most PHES power plants are extremely associated with site properties. If the topography and geological conditions of the area are favorable, it is said that there is sufficient water available for the development of PHES plants

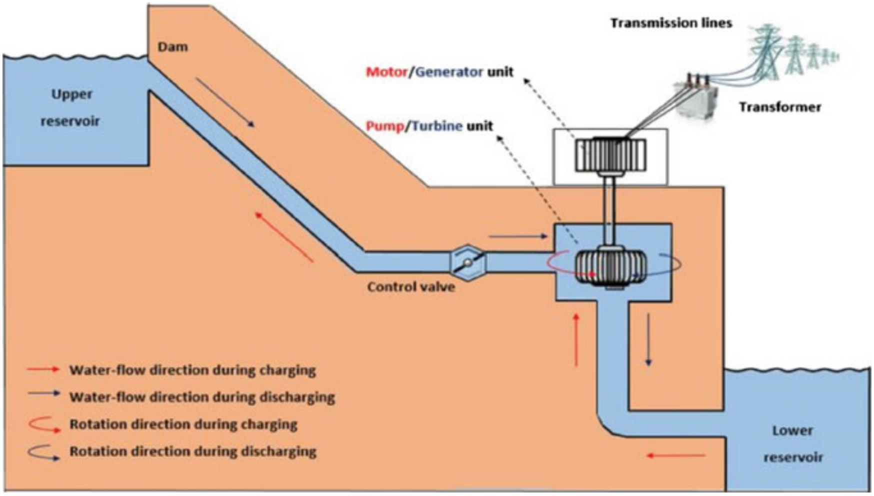

Fig. 7.6 Schematic diagram of pumped hydro storage plant. Reproduced with permission (Shaqsi et al. 2020) Copyright (2020), Elsevier

in the area (Zuo et al. 2015). Generally, PHES is considered to be the most effective technology to enhance the penetration rate of renewable energy in the power system, especially in small autonomous island power grids. Pumped storage technology and wind power, which are called hybrid power plants establish a feasible and realistic way for achieving high penetration rates of renewable energy, given that their elements are appropriately sized. At present, the pumped storage solution provides the most important commercial means for large-scale grid energy storage and increases the daily power generation capacity of the power generation technology (Beaudin et al. 2010).

7.3.3.2 Flywheel Energy Storage Technology (FEST)

In the flywheel, charging and discharging are performed by accelerating the inertial mass (rotor). The rotor is the main component of the flywheel. The capacity and energy density of the FEST are mainly influenced by the properties of the rotor, containing maximum speed, and inertia (Amodeo et al. 2009). The flywheel is suitable for various power applications in between 100 kW and 2 MW. The discharge time of the flywheel ranges from 5 s to 15 min. The capacity of the flywheel is approximately 0.5 to 1 kWh. The overall efficiency of the flywheel is about 70–80%, and its rated standby power consumption is about 1–2%. The merits of the 30 flywheels are its fast discharge and fast response time. Therefore, they are supposed for uninterruptible power supply and high-quality power supply utilization. However, the flywheel assembly is easy to wear during continuous operation, so the service life is short (about 100,000 charge and discharge cycles) (Amiryar and Pullen 2017). Therefore, reducing and ultimately eliminating the friction of all components is the main challenge facing the flywheel (Connolly et al. 2010). Though, because of the improvement of materials such as power electronics, magnetic bearings, and the development of high-speed motors, FEST has been recognized as a reliable choice for energy storage utilization (Sebastián and Peña Alzola 2012). The flywheel stores energy according to the principle of rotating mass. FEST is a mechanical storage technology that simulates the storage of electrical energy via changing electrical energy to mechanical energy. The flywheel stored energy in the type of rotational kinetic energy (Suzuki et al. 2005). Figure 7.7 displays a typical configuration of flywheel technology.

7.3.3.3 Compressed Air Energy Storage (CAES)

The CAES is a means of energy storage, which stored electrical energy as compressed air via a compressor. Moreover, in CAES electricity is utilized to compress the air, which stores the pressurized air using storage tanks such as gas chamber, underground mine, expired wells, and underground salt caverns at the energy storage time (Fig. 7.8). Hence, the mechanical level of CAES is determined by its charge life. At the time of charging, the compressor applies off-peak electric energy, which uses solar

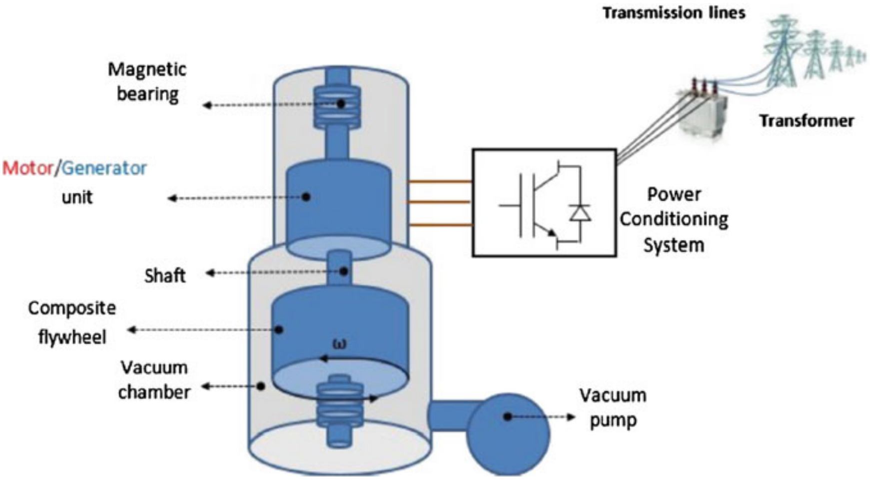

Fig. 7.7 Schematic diagram of the configuration of a flywheel technology. Reproduced with permission (Shaqsi et al. 2020) Copyright (2020), Elsevier

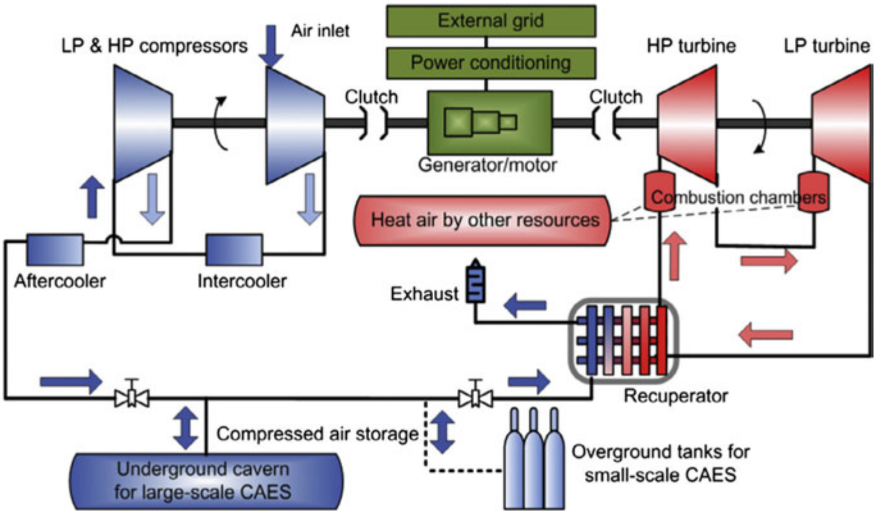

Fig. 7.8 Schematic illustration of CAES plant source. Reproduced with permission (Luo et al. 2015) Copyright (2015), Elsevier

and wind power to compress ambient air. The key variation between different CAES structures is associated with thermal engineering. However, CAES technologies can store energy for a long period of time associated with batteries. The main challenge of CAES design in large-scale application is laid in the management of thermal energy. In CAES, the compression produces unwanted temperature, which damages and decreases the operational efficiency of the technology (Ries and Neumueller 2001). Thus, the efficiency of CAES systems is between 40 and 75%, and the start-up time is around 5–15 min (Yang et al. 2011). In addition to pumped storage, flywheel, and compressed air storage, there are also different types of new mechanical energy technology under development. For instance, mechanical energy storage technology is based on the slope of a tram carrying rocks or sand in an electric car equipped with a motor-generator (Chen et al. 2009).

7.3.4 *Thermal Energy Storage (TES)*

TES is a means of thermal energy storage using heating (cooling) a condition, which is used for later application (Sharma et al. 2009). Moreover, in TES system, electrical energy (other types of energy) is changed into thermal energy in a cold state (for instance, coolers and ice storage) or in a hot state (for instance, solar thermal collectors). The typical example of high-temperature TES is a concentrated solar power plant, where the stored heat is utilized at cloudy and night time while solar energy does not exist (Fasano et al. 2015). The TES technologies can be classified into three kinds (Fig. 7.9) as follows:

- Latent heat,
- Chemical reaction storage, and

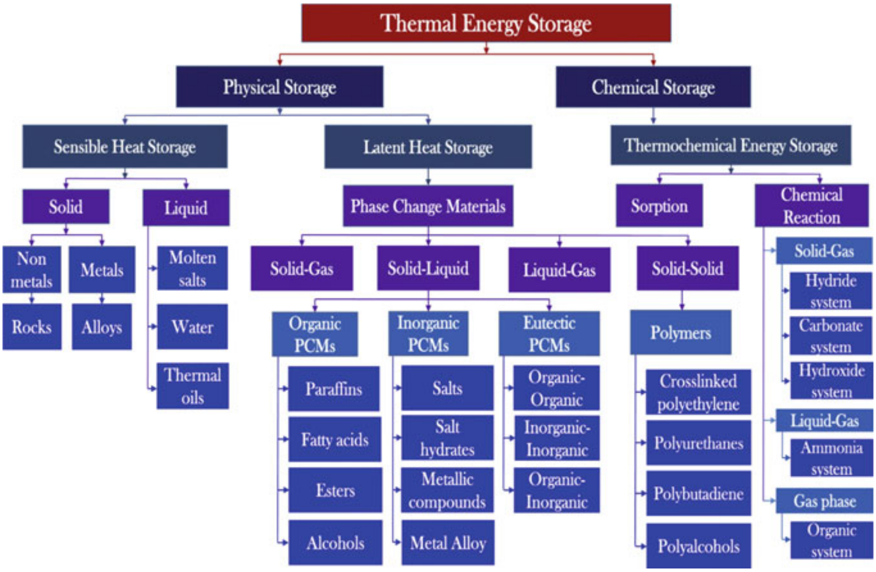

Fig. 7.9 Schematic illustration of TES materials. Reproduced with permission (Nazir et al. 2019) Copyright (2019), Elsevier

- Sensible heat.

The division of TES technologies materials is shown in Fig. 7.9. The overall efficiency of the TES system based on molten salt is relatively low, about 25% to 35%. However, their investment costs are also relatively low, which makes them ideal for TES technologies (Pintaldi et al. 2015).

7.3.4.1 Sensible Heat Storage (SHS)

The SHS is prepared via storing heat energy in different materials according to the change of temperature and heat capacity of the material throughout the charging and discharging route. The key merit of SHS is that discharging process and charging process is totally reversible as well as unlimited life cycles. Thus, the heat energy can be stored in different mediums such as solid, dual, and liquid. For SHS, we can use energy input either solar energy or electricity (Asjid et al. 2021; Velasco-Fernández et al. 2015). The figure displays that water is circulated in the loop easily because of the thermosiphon effect.

7.3.4.2 Latent Heat Storage (LHS)

LHS is associated with the amount of heat absorbed or released in the phase conversion of different materials (Rashidi et al. 2021). It depends on the phase conversion of the medium, for example, the phase change of solid to liquid using latent heat for energy storage. LHS materials typically include the following:

- **Organic materials**. These materials are used in buildings for cooling and heating due to their melting point, which lies in the range of 20–32 °C. Moreover, these groups of materials are flammable, noncorrosive, nontoxic, and chemically stable.
- **Inorganic materials**. This group includes materials such as metallic salt compositions and alloys, which are utilized in solar thermal applications. They have different characteristics such as cooling down quickly, good thermal conductivity, corrosive property, and high heat capacity (Alvi et al. 2021).
- **Eutectic mixtures**. This includes materials such as organic–inorganic, inorganic–inorganic, and organic–organic. They can be utilized in different buildings (Fatih Demirbas 2006). The schematic illustration of LHS is exhibited in Fig. 7.10.

7.3.5 Electrochemical Energy Storage (ECES)

In ECES technology, electrical energy is changed into chemical energy and stored for later use, which is changed back to electricity when the energy is needed (Dunn et al. 2011).

Five kinds of ECES technologies are discussed in this section:

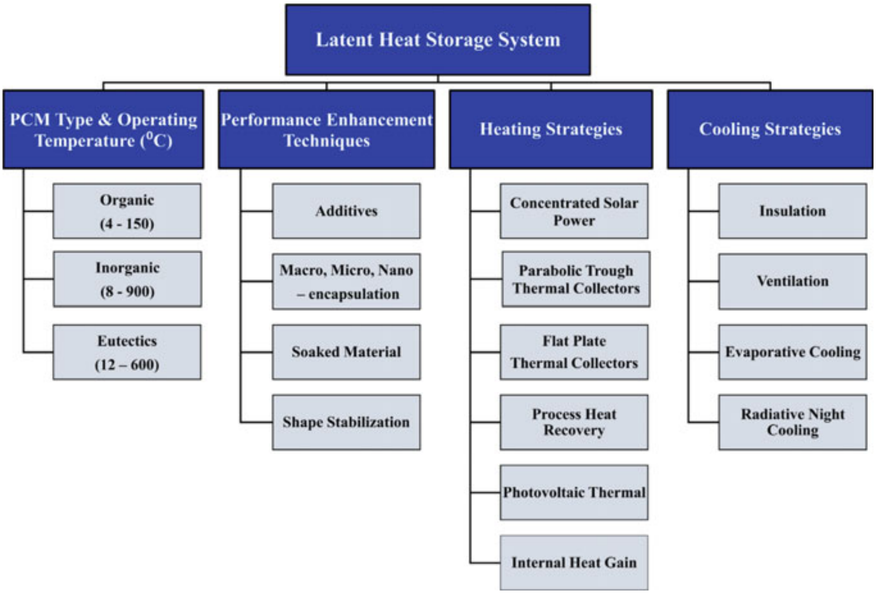

Fig. 7.10 Schematic illustration SHS in the solar water heater. Reproduced with permission (Nazir et al. 2019) Copyright (2019), Elsevier

- High-temperature batteries,
- Conventional batteries,
- Metal–air batteries,
- Flow batteries, and
- Fuel cells.

However, batteries have high maturity and cost-effective technologies yet there are a number of challenges for these systems (Singh et al. 2021). The main problems for this technology are the distortion of components and electrolyte degradation associated with electrochemical reactions that decrease the performance of the battery (Ibrahim et al. 2008).

7.3.5.1 Conventional Batteries

These electrochemical cells are composed of an anode, separator, electrolyte, and cathode. In the charging process, the electrolyte is ionized, and in the discharge process, a redox reaction occurs to recover the chemical energy stored in the ions (Kondoh et al. 2000). The kind of electrolyte utilized determines the kind of battery such as lithium–ion, nickel–cadmium, and lead–acid. Lead–acid batteries are cost-effective with the highest technological maturity in conventional battery technology. Though, lead–acid batteries (LABs) show some drawbacks such as low power, needs high maintenance, low specific energy, short life cycle, and toxicity. When the end-user needs high power quality, lead–acid batteries are the most desirable. Recently, LABs efficiency reached between 75 and 85%. Lead–acid batteries' lifespan is affected by different factors such as the quality of component materials, which is expected to serve 3 - 10 years (Thounthong et al. 2009). An LAB is composed of electrolyte (dilute aqueous sulfuric acid), lead (the negative active material), highly porous PbO_2 (positive active material), and separator (Fig. 7.11). Moreover, a lead alloy grid is used as a current collector and provides mechanical support (Divya and Østergaard 2009).

Nickel–cadmium batteries (NiCd): These types of batteries have a longer service life, about 10 to 15 years. Though, it has problems related to toxicity, which is because of cadmium. Moreover, the overall efficiency of NiCd batteries is slightly lower than that of LABs (60–70%), and the price is higher (Zhu et al. 2013). Despite these shortcomings, NiCd batteries have reached technological maturity and can be used commercially. Recently, the total output power of NiCd batteries installed worldwide is approximately 27 MW (Lacerda et al. 2009).

Advantages

- Compared to new technologies, NiCd is relatively cheap;
- NiCd shows better specific energy, as compared to LABs;
- NiCd batteries are table than other battery technologies;
- NiCd batteries can be assembled easily;
- NiCd has an advanced performance cycle life.

Disadvantages

- Cadmium is heavy metal with a toxic property, which causes diseases and thus needs to be recycled instead of thrown away;
- Compared with different batteries such as Li-ion, it has low energy density;
- It shows high self-discharge level.

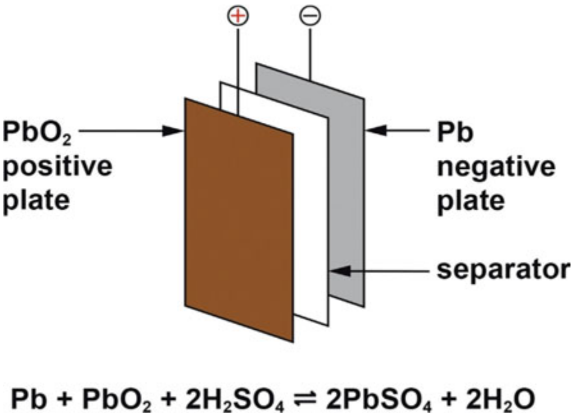

Fig. 7.11 Schematic diagram of components and working principle of a lead–acid battery. Reproduced with permission (May et al. 2018) Copyright (2018), Elsevier

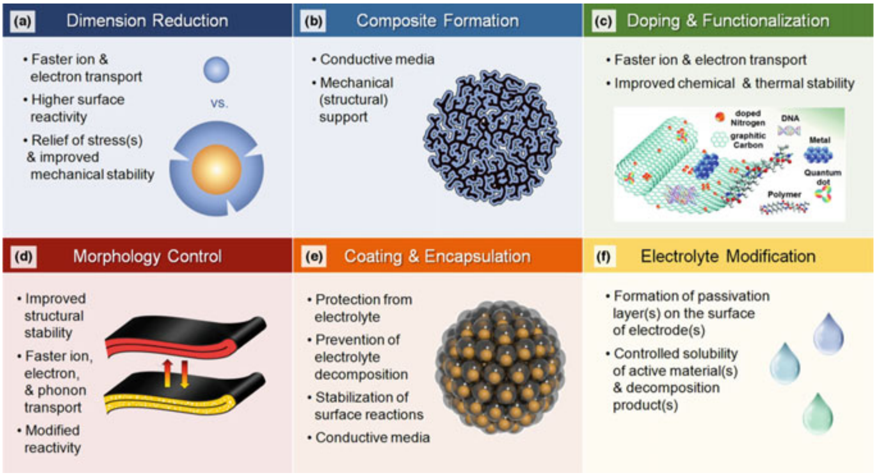

Fig. 7.12 Schematic illustration of approaches for performance improvement and their rationale. Reproduced with permission (Nitta et al. 2015) Copyright (2015), Elsevier

Lithium-ion batteries (LIBs): This battery system has longer service life, low standby loss, and high energy density that make the technology a promising choice and popular for different applications. Moreover, with the increasing acceptance of electric vehicles, LIBs have received more and more attention. Despite the cost challenges of LIBs (especially for larger applications), it has proven to be a huge benefit to connect them to the grid to support utilities. Furthermore, LIBs are more efficient (about 85–95%) and have a service life of about 10–15 years. The cost of LIBs is higher than that of NiCd and lead batteries because they are still somewhat new. Though, as this battery technology matures, their cost is expected to decrease (Hadjipaschalis et al. 2009). Li-ion batteries are the appropriate source of different portable electrochemical energy storage, which needs to enhance their performance and cost (Alvi et al. 2021). With the purpose of enhancing the electrode Li-ion batteries, different approaches have been designed (Wen et al. 2021). These approaches are presented in Fig. 7.12 and they are the same regardless of operating mechanism, crystal structure, and material type.

7.3.5.2 High-Temperature Batteries

These types of batteries show similar working mechanisms with conventional batteries, which are also named molten salt batteries. The difference between high-temperature batteries and conventional batteries is that high-temperature batteries contain solid electrolytes and operate at high temperatures. The most common types of high-temperature batteries utilized currently are sodium–nickel chloride and sodium–sulfur (NaS) batteries. The operating temperature of an NaS battery is approximately 300 °C to 360 °C. Associated with nickel chloride batteries, they have the advantage of longer energy storage time. Though, they are in the early stages of commercialization, they have not been admitted for large-scale grid application. The overall efficiency of NaS batteries is comparatively high, which is between 70 and 90%. Compared with nickel chloride batteries, NaS batteries have less impact on the environment. Sodium–sulfur batteries still face some challenges, namely toxicity, safety hazards caused by the high operating temperature and explosiveness of sodium, and high costs. The increase in material science and technological advancement of these batteries is expected to solve these challenges. Sodium–nickel chloride batteries operate at a temperature of 270 °C, which is slightly lower than that of sodium–sulfur batteries. The total efficiency of the sodium chloride nickel battery is about 85% to 90%, and the response time is relatively fast. Thus, corrosion at higher temperature, the service life of these batteries is not good; however, with recent developments in materials science, cost, life and other problems associated with these batteries can be solved (Baharoon et al. 2015).

7.3.5.3 Flow Batteries (FBs)

The electrochemical reactions that occur in FBs are very similar to high-temperature and conventional batteries. The difference between FBs is that in FBs, the electrolyte is retained in a container outside the reaction cell and is continuously pushed out of the reactor and into the reactor (Nguyen and Savinell 2010). FBs have various advantages such as easy control and monitoring of electrolyte concentration, easier electrolyte replacement, and continuous operation. However, these types of batteries have drawbacks such as high cost and high maintenance service, because of the extra technology requests to maintain electrolyte out/inflow. Moreover, FBs shows lower efficiency because of the energy demands of their auxiliary tools. Hence, in FBs, size has a great impact related to other batteries due to the space required additional equipment (Bueno and Carta 2006). FBs are divided into two categories: hybrid batteries and redox batteries. In hybrid FBs, one of the electroactive components deposited on the electrode surface is the fuel cell electrode and the other is the battery electrode (Weber et al. 2011). The hybrid FBs' storage capacity is linked with the size of the battery electrode. Redox FBs are composed of electroactive parts that are dissolved in the electrolyte. The redox FBs' storage capacity is associated with the capacity of the electrolyte as well as its power capacity is associated with the area of the electrode. The typical examples of redox FBs are vanadium and zinc bromide. Vanadium redox batteries can be utilized in various utilization such as peak demand management and renewable power storage (Leung et al. 2012). Currently, commercial-level vanadium redox batteries show 5 kW power capacities. Although zinc bromide batteries are in the early stages of advancement, they are affordable, have promising storage and high energy density technology. The zinc bromide battery has an important problem: due to the uneven accumulation of zinc on the electrode, it must be completely discharged every 5 to 10 cycles. Moreover, the corrosive issue of bromine is another problem (Leung et al. 2012).

7.3.5.4 Metal–Air Batteries (MABs)

MABs are composed of four components: an air cathode, an electrolyte, a metal anode, and separator, as shown in Fig. 7.13 (Clark et al. 2018; Worku et al. 2021a). The separator is an insulator that only allows ion conversion. During the discharge process, the metal is dissolved in the electrolyte, the metal anode undergoes an oxidation reaction, and the air cathode initiates an oxygen reduction reaction (ORR). Because of the open battery structure, MABs utilize air as the reactant, which has a higher specific capacity (Zhang et al. 2014). Despite their high energy density, these huge problems must be addressed before these systems can be put into practical use (Sharma and Bhatti 2010). In the next section among different metal–air batteries, two potential battery technologies are presented.

Li–Air Batteries (LABs): LABs are the most preferable battery technology, which can be used for electric vehicles because of their high energy density. Based on the type of electrolyte utilized, LABs can be categorized as follows (Fig. 7.14):

- Solid-state LAB,
- Aqueous LAB,
- Aprotic LAB, and
- Mixed aqueous/aprotic LAB.

Hence, in the above configuration, all battery systems have oxygen gas as cathode and lithium metal as anodic materials. Though, the configuration is similar, they possess different reaction mechanisms, which depend on the electrolyte applied.

Zinc–air Batteries (ZABs): ZABs are made up of metal electrolyte, separator, cathode, and anode. Figure 7.15 shows the schematic diagram of typical rechargeable ZABs. The air electrode is composed of a catalytically active layer and a gas diffusion layer, which are the essential parts in the charging and discharging process

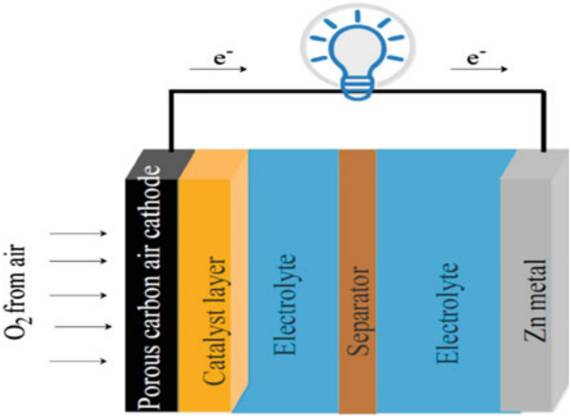

Fig. 7.13 Schematic illustration of MABs

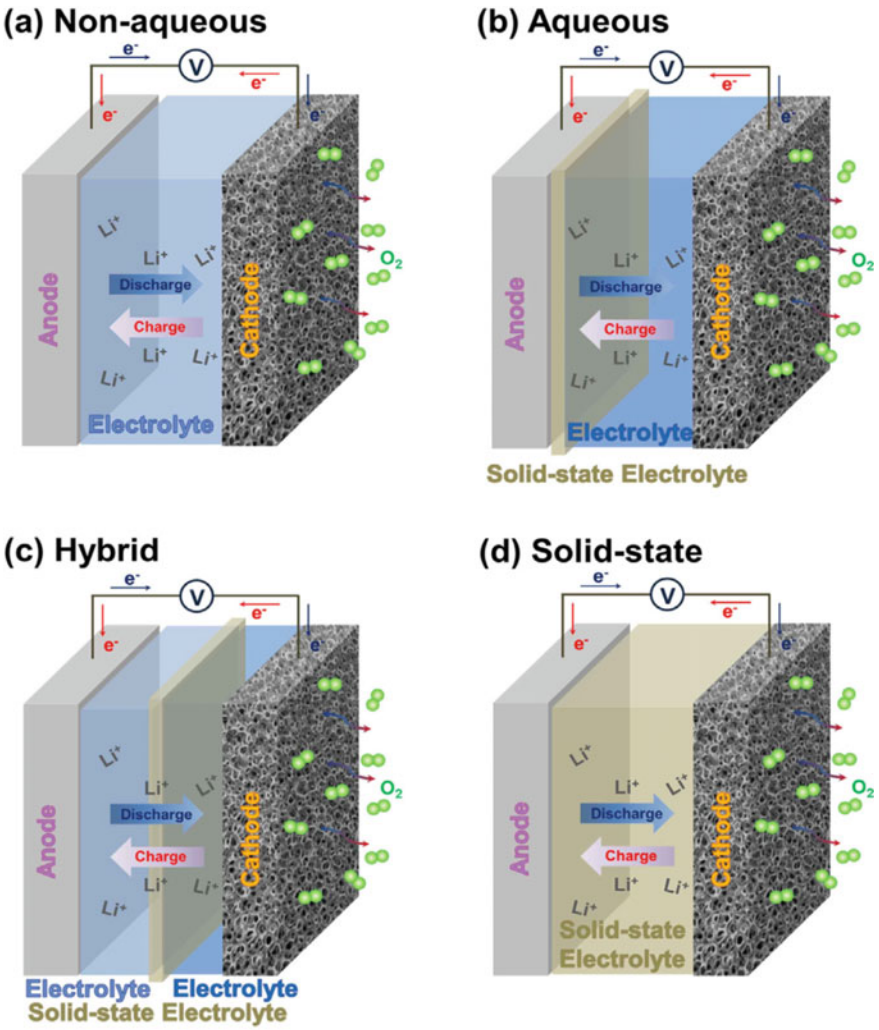

Fig. 7.14 Schematic illustration of Li–air batteries. Reproduced with permission (Tan et al. 2017) Copyright (2017), Elsevier

(Cho et al. 2015). Atmospheric oxygen in the gas phase is used as an active material for ZABs at the cathode part. ZABs are classified into two types as follows:

- Primary,
- Rechargeable (secondary).

Primary-based ZABs are stable with long storage life. Sealed primary ZABs show 2% capacity loss after a year of storage life. Thus, ZABs are found in different voltages and sizes. Like other primary batteries, primary ZABs can be connected

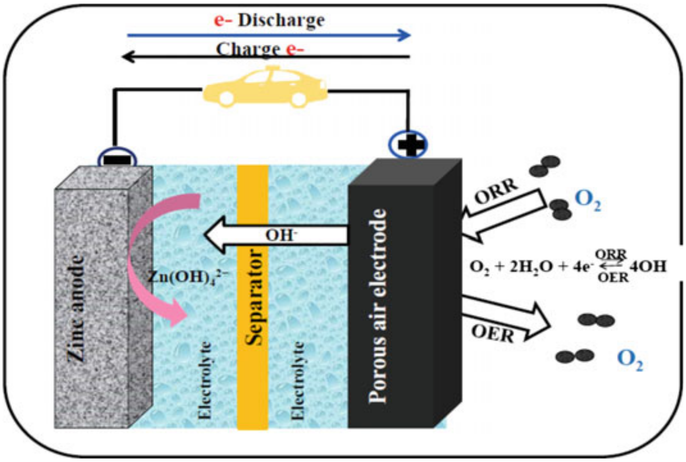

Fig. 7.15 Schematic illustration of rechargeable zinc–air battery

in series to fabricate higher voltage a battery (Harting et al. 2012). Primary ZABs are used in buoys railroad, and hearing aid applications. In mechanically recharged ZABs, Zn is consumed in the charge–discharge process and finally replaced by a fresh electrode, which can be utilized in grid storage. Hence, because of the different advantages, most researchers are focusing on electrically rechargeable ZABs (Worku et al. 2021b). The key challenge in the anode part is low utilization efficiency because of dendritic growth, corrosion, and passivation. Moreover, the main challenge of the air electrode is high overpotential and the sluggish property of oxygen reactions (Xu et al. 2018).

7.3.5.5 Fuel Cells (FC)

A fuel cell (FC) generates electricity by using oxygen and hydrogen through an electrochemical reactor. Recently, different types of FC devices have been fabricated, which have similar working principles. It uses pure hydrogen gas as a fuel; however, methanol, methane, natural gas, and other hydrocarbons can be utilized combined with oxygen. FC can be divided by the type of electrolyte they used. This division limits the type of electrochemical reactions that occur in the cell, the fuel required, cell operation the temperature range, the type of catalysts utilized, and other issues. Recently, there are various kinds of FC under development every one with its own potential applications, limitations, and advantages. The classifications of FC based on the electrolyte used are listed below:

- Solid oxide FC,
- Alkaline FC,
- Polymer electrolyte membrane FC,

- Reversible FC,
- Molten carbonate FC,
- Phosphoric acid FC, and
- Direct methanol FC.

7.4 Hybrid Energy Storage Systems (HESSs)

The energy storage technologies are built in a grid by integrating multiple devices, the system is termed as a HESSs (Bocklisch 2016). As a result, the merits of each system in an integrated device face difficult conditions can add up to meet specific needs, and improve technology performance (Komala et al. 2021). The main goal is to deal with the real-time harsh working environment that a single system cannot accomplish (Mandelli et al. 2015). The HEESS also helps to increase many ideal technologies such as power level, cost operating temperature, life cycle, discharge rate, and energy density. By combining the unique advantages of a single device or system, cycle efficiency can be improved. Generally, in the HESS system, a slow response system and a fast response system are mixed together to achieve higher and higher characteristics (Blechinger et al. 2014). The role and use of HESSs have been proven in various fields. In the field of electric transportation, the hybrid power of batteries and supercapacitors has been proven effective when used in electric vehicles (Henson 2008). In wind energy systems, the most practical method is to use battery supercapacitors to achieve energy smoothing and grid integration. Proposals to use battery–supercapacitor or fuel cell–battery hybrid power to support photovoltaic power plants have been widely proposed (Bocklisch 2016). The fuel cell–battery combination can well support the hybrid wind-PV renewable energy system (Álvaro et al. 2019). Therefore, the use of HESSs can be regarded as an ideal solution for different utilization in the future. However, to prove the feasibility and functionality of HESSs, further research and development must be carried out. Various storage technologies have been combined for different applications as shown in Fig. 7.16 Most commonly used in renewable energy sources can be classified as fuel cell /flywheel HESSs, supercapacitor/battery, fuel cell/supercapacitor, battery/flywheel, battery/CAES, SMES/battery, and fuel cell /battery (Samweber et al. 2015).

7.5 Challenges and Prospects of Energy Storage Technologies

The development and innovation of energy storage technologies have faced many challenges. For the commercialization, widespread dissemination, and long-term adaptation of the latest inventions in this field, these challenges must also be met. When ESSs are used and the storage system is in operation to store excess generated

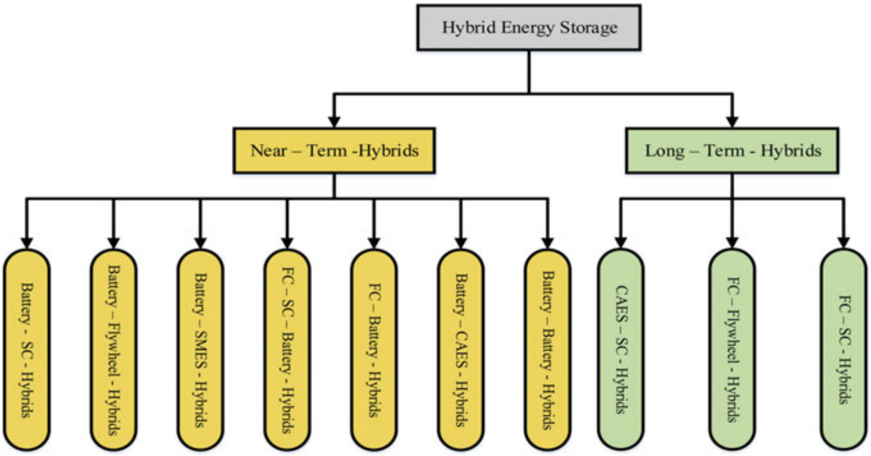

Fig. 7.16 Schematic illustration of different combination methods for hybrid energy storage technologies. Reproduced with permission (Hajiaghasi et al. 2019) Copyright (2019), Elsevier

energy, the world faces some constraints and challenges. According to reports, all equipment and systems have not released 100% of the stored energy for later use, which means that waste will definitely occur during storage and release. The implementation, operation, and replacement of energy storage technologies also require a large amount of capital. Certain energy storage devices may cause environmental impact, which starts from the extraction of materials used for manufacturing and continues until the end of their useful life until disposal. Therefore, research is needed to develop equipment that is not only more efficient, but must also be cost-effective and must have minimal environmental issues, particularly for the disposal of utilized equipment after the life cycle is completed. The current energy production mainly relies on fossil fuel power generation, which is not only costly but also impossible to update, so it cannot be maintained indefinitely. Furthermore, the electricity fabrication of fossil fuel power plants is bound to be related to carbon dioxide emissions, which can cause serious environmental pollution. In order to provide an effective power supply, optimal management of ESSs is a problem in modern power grids. Therefore, there is a big voice that can gradually reduce the dependence on the use of oil and natural gas for electricity production.

7.6 Conclusion

Energy storage systems have different merits, disadvantages, functions, and system maturity. Hence, the purpose of this chapter is to overview the advancement of key energy storage technologies, such as chemical, electromagnetic, thermal, electrical, and electrochemical energy storage systems. Self-discharge rate, specific power, environmental impact efficiency, power density, lifetime, power capital cost, specific energy, energy capital cost, and energy density are performance indicators for evaluating the state of ESSs. When we consider all selected economic, energy, environmental, and technical criteria at the same time, the findings of this chapter indicate the following:

- From MESSs, the average performance of pumped storage systems ranks the highest.
- From electrochemical energy storage technologies, high-temperature batteries showed the highest performance.
- From CESSs, ammonia shows the highest performance level.
- The TESSs based on molten salt have the highest performance level.
- From electromagnetic energy storage technologies, superconducting magnets showed an excellent performance level.

Hence, from electromagnetic electrochemical, thermal, chemical, and mechanical energy storage technologies, chemical energy storage technology showed the highest performance, whereas, electrochemical energy storage technology showed the lowest performance levels.

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