

CHAPTER 4

Single and Polystorage Technologies for Renewable-Based Hybrid Energy Systems

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Abstract

The uptake of renewable energy technologies is accelerating. This has led to the emergence of generation intermittency and fluctuation along with the already existing load variability. Consequently, there are critical concerns about the stability and reliability of future energy networks. Energy storage systems provide a wide array of technological approaches to manage power supplies in order to create a more resilient energy infrastructure and bring cost savings to utilities and consumers. This chapter provides an in-depth analysis of different electrical energy storage technologies currently deployed around the world. It also discusses the need for polystorage systems to hybridize the advantages of multiple storage technology while avoiding the shortcomings when used alone.

Keywords: EES, DSM, Pumped hydroelectric storage, Compressed air energy storage, Flywheel, Electrochemical storage, Electrical storage, Thermal storage, Chemical storage, Hybrid energy storage

1 INTRODUCTION

More than 80% of primary energy supply in the world comes from fossil fuels, and the demand has been projected to grow at about 2.3% per year from 2015 to 2040 [1]. This is threatening to further increase carbon dioxide levels and the average global temperature. At the United Nations Climate Change Conference in December 2015, world leaders agreed to limit the global average temperature rise to 2°C and to work toward an even lower rise of 1.5°C [2]. To minimize the adverse effects of global warming and consequent climate change, the integration of sustainable and renewable energy technologies is vital for the environment. The key challenge with renewable energy technologies is their variability—adding generation

intermittency and fluctuation to the existing load variability leads to critical concerns about the stability and reliability of future energy networks.

Different alternatives have been proposed to mitigate this problem including electrical energy storage (EES); demand side management (DSM) with load shifting; and interconnection with external grids [3]. All options have their niche potential for addressing the challenge; however, as renewable energy penetration into the grid increases, EES becomes the most critical option—not only for power quality, but also for energy management. EES can maximize the utilization of existing generation and transmission infrastructures while also preventing costly network upgrades. In relation to conventional power production, EES can improve overall power quality and reliability, which is becoming increasingly important for modern commercial applications.

EES is not a new technology or concept; it has been practiced for over a century. Twenty years after the invention of rechargeable lead acid batteries in 1859 [4], Thomas Edison invented the light bulb in 1879 and later developed the first centralized power plant in 1882 in New York City's financial district to light the shops and attract customers [5]. Demand soon increased, and lead acid batteries were found as a solution for storing electricity at low demand times and selling it to the shops at peak evening times. In 1896, a 300-ton, 400-kWh lead acid battery was used at a hydropower station to avoid outages from equipment breakdowns [6].

Over the last one and half centuries, battery storage has been developing along with other energy storage types, each with a certain learning rate. The objectives of electricity storage have also far exceeded the initial intention of peak shaving or short-term outage prevention [7]. Today, EES is used for many other reasons, such as delaying capacity/network expansion, regulating frequency and balancing voltage (preventing brownouts) [8]. As such, each energy storage technology is suitable for a given objective. Fig. 1 shows the role of EES at various locations across an electricity network.

At present, an electric power infrastructure functions largely as a just-in-time inventory system, in which a majority of energy is generated and then transmitted to the user as it is consumed. Without the ability to store energy, there must be sufficient generation capacity on the grid to handle peak demand requirements, despite the likelihood that much of that capacity sits idle daily as well as for large portions of the year. Correspondingly, the transmission and distribution systems must also be sized to handle peak power transfer requirements, even if only a fraction of that capacity is used during

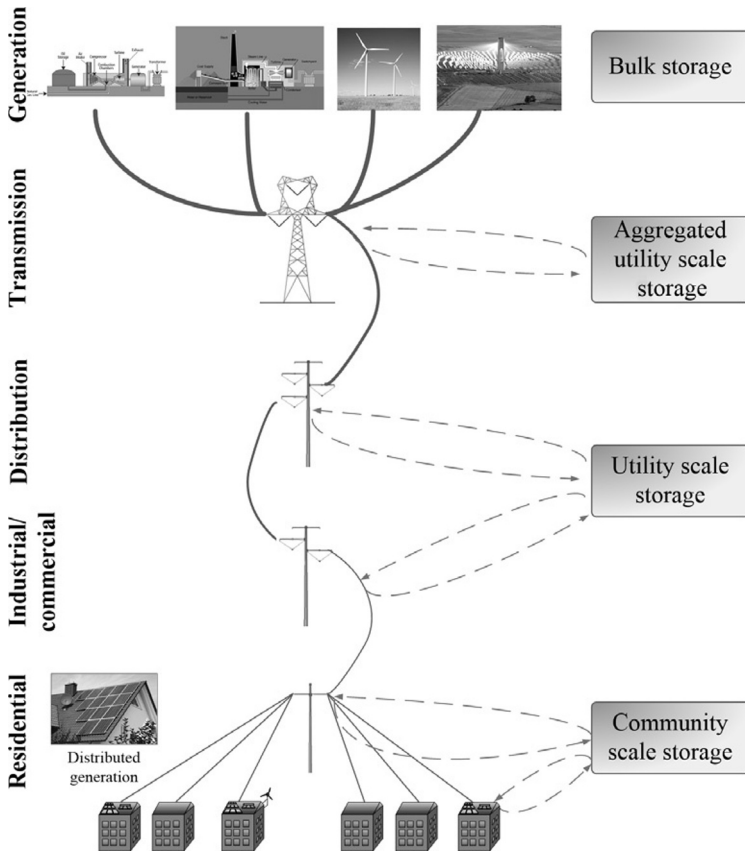


Fig. 1 The role of EES at various locations across an electricity network.

most of the year. Operationally, electrical power generation must be continuously ramped up and down to ensure that the delicate balance between supply and demand is maintained. By decoupling generation and load, grid energy storage simplifies the balancing act between electricity supply and demand and overall grid power flow. EES systems have potential applications throughout the grid, from bulk energy storage to distributed energy functions. [Table 1](#) shows the functional uses of EES systems and their associated value metrics.

EES technologies are usually categorized based on the application time scale: instantaneous (less than a few seconds); short term (less than a few minutes); midterm (less than a few hours); and long term (days) [9]. A detailed background of the historical development of various energy

Table 1 Functional uses of EES systems and their associated value metrics

	Functional use	Value metric
Bulk energy	Electric energy time shift	The price differential between energy prices during charge and discharge, which includes the following: <ul style="list-style-type: none"> • Arbitrage • Renewable energy firming and integration • Electric supply capacity: the avoided cost of new generation capacity (procurement or build capital cost) to meet requirements.
Transmission & distribution	Transmission upgrade deferral	The avoided cost of deferred infrastructure
	Distribution upgrade deferral	The avoided cost of deferred infrastructure
	Transmission voltage support	The avoided cost of procuring voltage support services through other means
	Distribution voltage support	The avoided cost of procuring voltage support services through other means
Reserve	Synchronous	Regulated env ^a : the avoided cost of procuring reserve service through other means Market env: the market price for synchronous reserve
	Nonsynchronous	Regulated env: the avoided cost of procuring reserve service through other means Market env: the market price for nonsynchronous reserve
	Frequency regulation	Regulated env: the avoided cost of procuring reserve service through other means Market env: the market price for frequency regulation service
Customer	Power reliability	The avoided cost of new resources to meet reliability requirements
	Power quality	The avoided cost of new resources to meet power quality requirements, or avoided penalties if requirements are not being met

^a Env, environment.

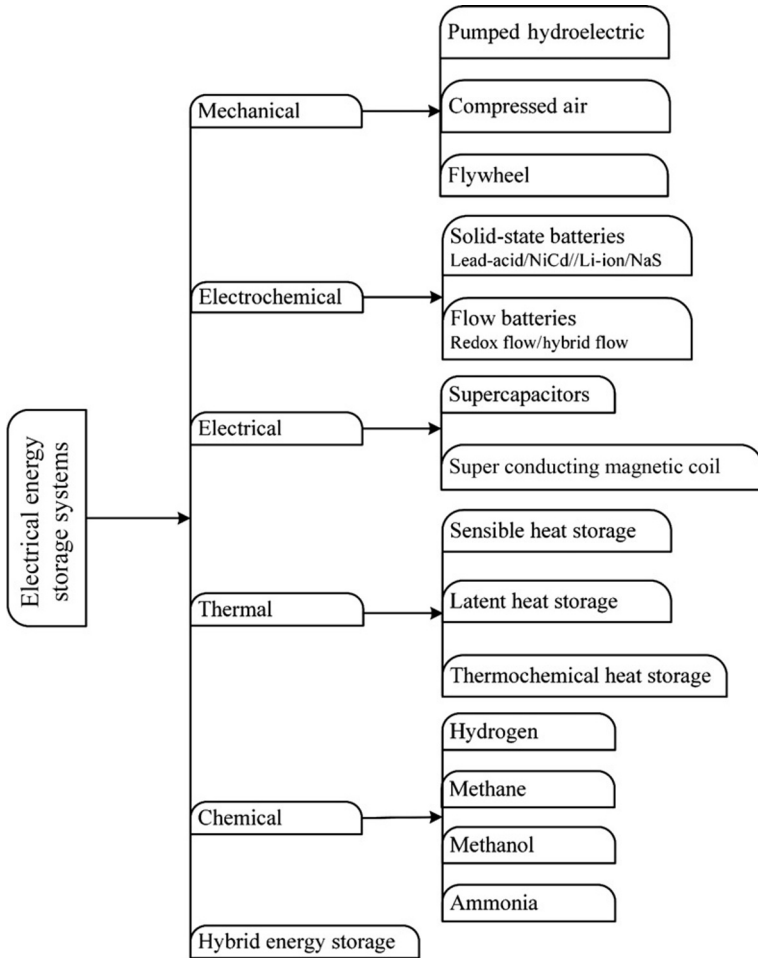


Fig. 2 Key electrical energy storage options.

storage options can be found in the *Electricity Storage Handbook* published by Sandia National Laboratories [10].

There are numerous potential energy storage options for the electricity sector, each with unique operational, performance, cycling, and durability characteristics. A widely used approach for classifying EES is the determination according to the form of energy used (Fig. 2). A comprehensive picture of the state-of-the-art technologies available for EES is addressed in this chapter.

2 MECHANICAL STORAGE

2.1 Pumped Hydroelectric Storage

Dams, built on the natural pathways of rainwater to create reservoirs, have been used as energy harvesting and storage systems for a long time in human civilization history. Thus, water can be collected during high-rain seasons to be used in a planned way, not only for water supply, but also for power generation. However, a pumped hydroelectric storage (PHS) system is a relatively new system designed for load management. With the development of inflexible, large-scale power plants, such as nuclear in the 20th century, there was a necessity for energy supply demand misbalance management. Technologies were required to respond quickly to market signals by absorbing the surplus electricity from the grid and supplying it during demand periods. Given the high costs of large-scale battery storage in those days, PHS became a successful alternative. A PHS system requires development of a second reservoir, called a lower reservoir, in a hydro power plant (Fig. 3). During electricity oversupply periods, the energy is used to pump the water from the lower reservoir to the upper one. Therefore, it stores energy in the form of water; that is, gravitational potential energy, which is later converted into electrical energy by allowing the water to flow back from the upper to the lower reservoir through a turbine generator. In this manner, energy is converted from electrical to kinetic to gravitational potential, then back to kinetic, and finally back to electrical again. PHS is now the current dominant energy storage technology. As of 2017, it accounted for >96% of worldwide bulk storage capacity and contributed to about 3% of a global generation with a total installed nameplate capacity of over 168 GW [11].

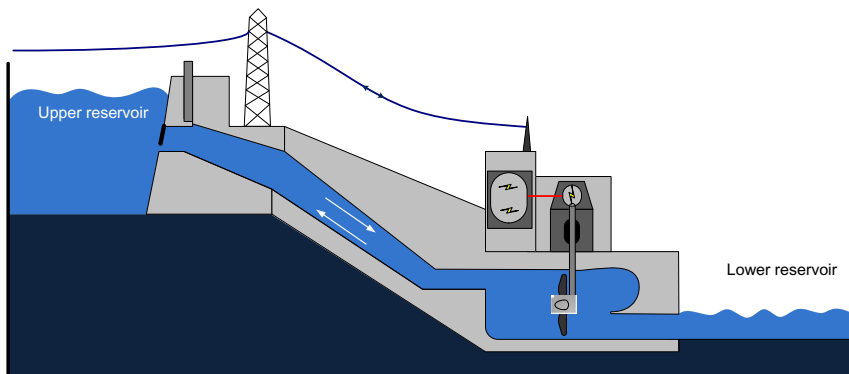


Fig. 3 Schematic of a pumped hydroelectric storage system.

The roundtrip efficiency of this process depends on the efficiencies of pump, motor, turbine, and generator as well as evaporation rates. Various PHS plants exist with power ratings ranging from 1 MW to 3003 MW, with approximately 70%–85% cycle efficiency and a lifetime of >40 years [12]. Due to the low energy density of pumped storage schemes, they are only appropriate for large-scale grid applications. PHS can be used to provide substantial benefits to the energy system including frequency control, ramping/load leveling and peak shaving, load following, and provision of standby reserve capacity.

The main downside of PHS is the need for favorable geography; both a lower and a higher reservoir are required as well as favorable landscape between them. The storage capacity depends on the sizes of the reservoirs, the power of the flow and the head of the water. The energy density is proportional to the height (head) between the two reservoirs; as such, it is only viable to construct a PHS facility if a certain head is available between the two reservoirs.

PHS projects have been providing energy storage capacity and transmission grid ancillary benefits in the United States (US) and Europe since the 1920s [13]. In late 2014, there were 51 PHS projects operating in the US with a total capacity of 39 GW [14]. Recently, with the advance of technology, investigations into underground PHS (U-PHS) and seawater PHS schemes are underway, such as a 300-MW seawater PHS scheme in Japan [12]. There are several large-scale pumped storage activities around the world, including Germany (1400-MW Atdorf plant) [15], Switzerland (1000-MW Linthal 2015 project) [16], and Portugal (136-MW Alvito project) [17]. In addition, wind or solar power generation coupled with PHS is now being developed, such as the Ikaria Island power station (Greece) [12].

2.2 Compressed Air Energy Storage

Compressed air energy storage (CAES) is largely equivalent to PHS in terms of applications, output, and storage capacity. Unlike a PHS, where energy is stored in elevation, CAES energy is stored in ambient air by compressing it and then storing it in underground caverns or aboveground facilities. When electricity is required, the pressurized air is heated and expanded in a turbine for power production.

CAES comprises a number of key subsystems such as compression, air storage, heat regeneration, and electric power generation (Fig. 4). The compression unit uses surplus electricity (from renewable or nuclear generators)

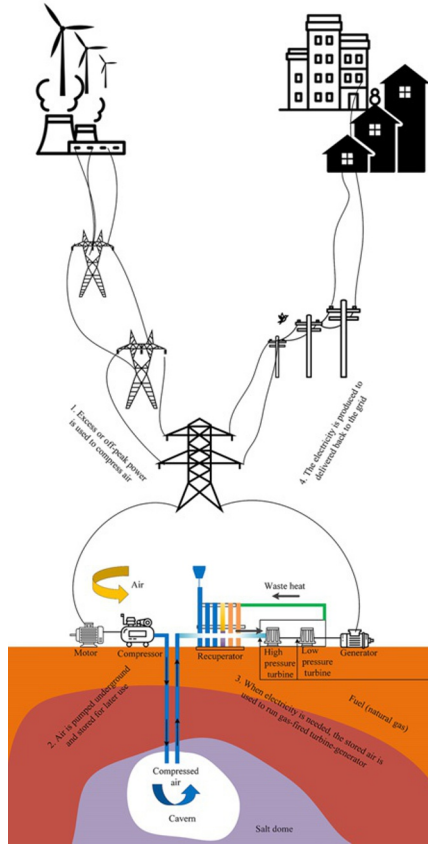


Fig. 4 Schematic of a compressed air energy storage system [4].

to drive compressors to produce high-pressure air, along with high-temperature compression thermal energy. The air storage subsystem is used to store high-pressure air (molecular potential energy) generated by the compressor. During the expansion process, the heat regeneration subsystem heats the high-pressure air, improving the entrance enthalpy of air expansion. The electric power generation subsystem is employed to drive the turbine to generate electricity with high-temperature air and, therefore, to achieve the ultimate conversion of molecular potential energy and thermal energy to electricity.

A CAES system stores air by three possible ways: diabatic, adiabatic, and isothermal. *Diabatic CAES* is basically the same as a conventional gas turbine except that the compression and expansion stages occur at different time periods. For example, when electricity is in excess, air is compressed and

stored in a reservoir, and when electricity is needed, air is heated with natural gas and expanded through a turbine. Worldwide, there are two diabatic CAES plants in operation: the Huntorf plant (290 MW) in Germany and the McIntosh plant (110 MW) in Alabama, USA [18]. The Huntorf plant was commissioned in 1978 to become the world's first CAES plant. The McIntosh plant incorporates a recuperator to reuse the exhaust heat energy [9]. When compared with the Huntorf plant, this recuperator reduces fuel consumption by 22%–25% and improves cycle efficiency by 42%–54% [12]. These two CAES plants have consistently shown good performances with 91.2%–99.5% starting and running reliabilities [12].

Adiabatic CAES is a system in which the heat produced due to the compressing of air is captured via a thermal energy storage system. When the electricity is needed, this stored heat is returned to the air before expansion through the turbine. This method does not require the use of premium fuels to heat the compressed air before expansion as the diabatic method requires. The world's first adiabatic CAES system is ADELE at Saxony-Anhalt in Germany, with a storage capacity up to 360 MWh and an electric output of 90 MW, aiming for around 70% cycle efficiency [9].

Isothermal CAES is an evolving technology that attempts to overcome some of the limitations of conventional CAES (diabatic or adiabatic). For example, current CAES systems use turbomachinery to compress air to around 70 bars before storage and, in the absence of intercooling, the air heats up to around 900 K, making it impossible to process and store. Isothermal CAES is technologically challenging, since it requires heat to be removed continuously from the air during the compression cycle and added continuously during expansion to maintain an isothermal process. There are currently no isothermal CAES plants available around the world, but several possible solutions have been proposed based on reciprocating machinery with a cycle efficiency of 70%–80% [9].

2.3 Flywheel

With the increasing share of renewable energy technologies in electricity networks, one of the emerging challenges of future smart grids is *inertia reduction*. Inertia is literally defined as “the resistance of any physical object to any change in its state of motion.” In power systems, the large rotating masses of the synchronous generators protect the grid by overcoming the immediate imbalance between power supply and demand. There is an ongoing debate that, with such a high penetration of renewable energies

(without rotating mass) to the grid, the inertia may decline to a level that puts the entire grid at risk. A counterargument is that although inertia will decline, there are several power electronic components, which can be used to protect the grid. One such option is the flywheel.

Flywheel energy storage (FES) follows the rotating mass principle to store energy in the form of rotational kinetic energy. An FES comprises a spinning rotor, motor generator, bearings, a power electronics interface, and a vacuum chamber or housing (Fig. 5). It is placed in a high-vacuum environment for reducing wind shear and energy loss from air resistance [12]. The FES is coaxially connected to a motor generator since it can interact with the utility grid through advanced power electronics. The amount of energy stored is dependent on the rotating speed of the flywheel and its inertia [19]; the flywheel is accelerated during energy storage and decelerated when discharging. FES systems can be classified by speed: two low-speed groups (steel material, rotation speed $<6 \times 10^3$ rpm) and one high-speed group (advanced composite materials—for example, carbon-fiber—speeds up to $\approx 10^5$ rpm) [12].

Some of the key advantages of FES are a high cycle life (hundreds of thousands); long calendar life (>20 years); fast response; high cycle efficiency (up to $\approx 95\%$ at rated power); high charge and discharge rates; high power

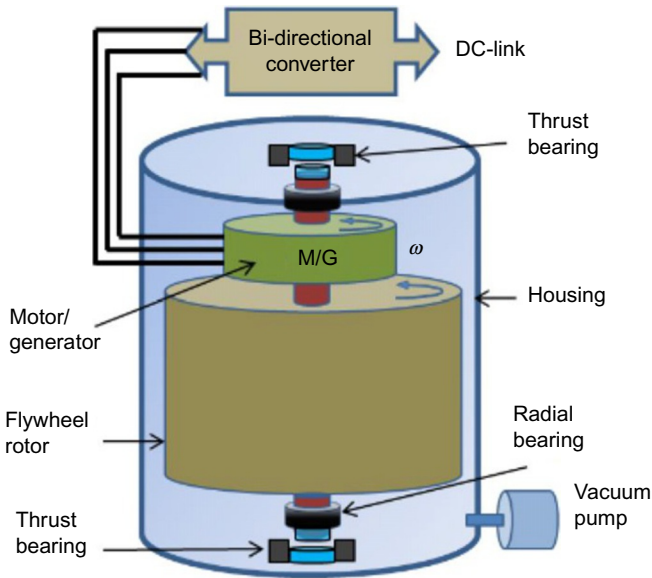


Fig. 5 Schematic of flywheel energy storage [19].

density; and low environmental impacts [19]. Additionally, FES can bridge the gap between short-term, ride-through power and long-term energy storage with excellent cyclic and load following characteristics.

FES systems can be used as substitutes for batteries, or in combination with batteries in uninterruptible power source (UPS) systems, because they can deal with shorter interruptions (subseconds), while batteries can be used for longer brownouts (seconds and minutes). This can protect batteries from frequent charges-discharges [19]. Flywheels are used in hybrid and electric vehicles for severe conditions such as harsh acceleration and uphill climbs. In 2014, VYCON Inc. installed an FES for the Los Angeles Red Line trains to recover their braking energy [12]. FES can also assist in the penetration of wind- and solar-based energy systems to improve their system stability. There has been a wide range of flywheel systems developed for integration with renewable energy systems; for example, ABB's PowerStore; Ureco Power; Beacon Power; and VYCON technology. These have all provided FES-based systems for wind- and solar-based energy [19].

3 ELECTROCHEMICAL STORAGE

Electrochemical storage can be categorized into two battery types: solid state and flow. Fig. 6 illustrates the various electrochemical storage options; Table 2 summarizes the characteristics of different battery technologies.

3.1 Solid-State Batteries

A solid-state battery is a rechargeable, portable voltaic cell. It comprises one or more electrochemical cells that accumulate and store energy through a reversible electrochemical reaction. Rechargeable batteries are produced in many different shapes and sizes, ranging from button cells to megawatt systems connected to stabilize an electrical distribution network.

3.1.1 Lead-Acid Battery

Lead-acid batteries have been used for >130 years [5] in many different applications, and they are still the most widely used rechargeable electrochemical devices for small- and medium-scale storage applications, currently occupying >60% of the total battery market, which has not been reduced by the rapid development of Li-ion batteries and other technologies [20]. Lead-acid battery applications include vehicles (70%), communications (21%), grid and off-grid energy storage (5%), and others (around 4%) [21].

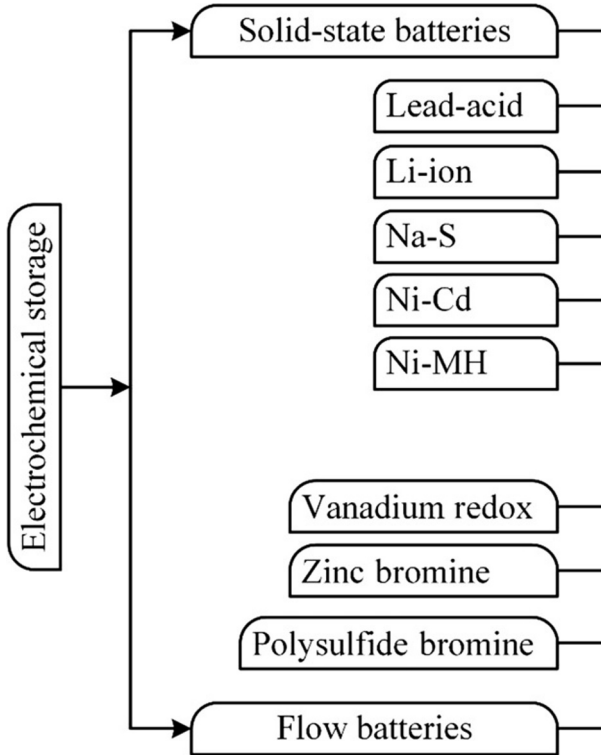


Fig. 6 Different electrochemical storage options.

Lead-acid batteries have high reliability within their lifetime, strong surge capabilities, and medium-to-high efficiency. They are usually good for uninterruptible power supplies, power quality, and spinning reserve applications [4]. However, they are poor for energy management purposes because they have a short life, require regular maintenance, have low energy density (Table 2), emit explosive gas and acid fumes, and have poor performance in cold conditions, which may require a thermal management system [4]. Although valve-regulated lead-acid batteries require less maintenance, and create fewer gas emissions and self-discharges than their nonvalve-regulated counterparts, they are primarily designed for backup power supply and telecommunication applications due to their decreased cycle life [21]. While cheap to install, the short lifetime of lead-acid batteries translates to a higher LCOE (levelized cost of energy).

Table 2 Characteristics of different battery technologies [12, 22]

Battery	Energy density (Wh/L)	Power density (W/L)	Specific energy (Wh/kg)	Specific power (W/kg)	Power rating (MW)	Rated energy capacity (MWh)	Daily self-discharge (%)	Lifetime (years)	Cycling times (cycles)	Cycle efficiency (%)	Discharge efficiency (%)
Lead-acid	50–90	10–400	25–50	75–300	0–40	0.001–40	0.1–0.3	5–15	500–1800	70–90	85
Li-ion	200–500	1500–10,000	75–200	150–2000	0.1–100	0.004–10	0.1–5	5–16	1000–20,000	75–90	85
Na-S	150–300	~140–180	100–240	90–230	8–34	0.4–244.8	≈0	10–20	2500–4500	75–90	85
Ni-Cd	15–150	80–600	45–80	150–300	0–40	6.75	0.03–0.6	10–20	2000–3500	60–83	85
Ni-MH	190–490	–	60–120	200–2000	–	–	0.5–4	2–5	180–2000	70–90	66–92
VRB	16–33	~<2	10–30	166	~0.03–50	2–60	Very low	5–20	12,000–14,000	75–85	75–82
ZnBr	20–65	~<25	30–80	45–100	0.05–10	0.05–4	Small	5–10	1500–2000 ⁺	~65–75	~60–70
PSB	~20–30	~<2	~15–30	–	0.004–15	0.06–120	Small	10–15	–	60–75	–

3.1.2 Li-Ion Battery

Lithium-ion batteries (Li-ion) have many desirable characteristics such as high efficiencies, a long cycle life, high energy density, and high power density (Table 2) [4]. These characteristics, along with their capability for fast discharge, have made them nearly ideal for portable electronics applications. The main downsides are that the DOD (Depth of Discharge) cycle can affect the Li-ion battery's lifetime, and the battery pack usually requires an onboard computer to manage its operation, thereby increasing overall costs.

Moreover, protection circuits are required due to Li-ion battery fragility and the use of flammable organic electrolytes raises issues about security and greenness. Nevertheless, Li-ion batteries have been successfully installed in both grid-connected and offgrid systems. Some large-scale energy storage projects have been installed around the world. For example, Japan's Sendai Substation installed 40 MW/20 MWh of a Li-ion battery pilot project for frequency regulation and voltage support. In addition, Japan's Tohoku Minami-Soma Substation installed 40 MW/40 MWh of Li-ion battery storage, with the aim of improving the balance between the renewable energy supply and the power demand [23]. The Zhangbei National Wind and Solar Energy Storage and Transmission Demonstration Project, Northern China, installed 14 MW/63 MWh of Li-ion batteries to provide electric energy time shift, renewable capacity firming, and ramping and frequency regulation in combination with a wind and a solar power plant [23]. A123 Systems has installed 36 MW/9 MWh of grid-connected lithium-ion battery storage in various locations, serving needs that include renewable integration and grid stability [24]. Tesla has installed the world's largest Li-ion battery storage 100 MW/129 MWh paired with Neoen's Hornsdale wind farm in Jamestown, Australia [25].

3.1.3 Na-S Battery

Sodium-sulfur (Na-S) batteries were originally developed by the Ford Motor Company in the 1960s, and subsequently the technology was sold to the Japanese company NGK. They have high power and energy density, high efficiency of charge/discharge, and a long cycle life (Table 2). These batteries also have pulse power capability over six times their continuous rating (for 30 s) [4, 26]. This feature makes Na-S batteries a candidate for applications in combined power quality and peak shaving.

Na-S batteries are currently being used by 190 locations in Japan, North America, Middle East, and Europe, providing an overall capacity of 530 MW and 3700 MWh for load leveling, renewable energy stabilization,

transmission and distribution network management, in microgrids, and for ancillary services [27]. For example, 108 MW of Na-S battery systems are being used by Abu Dhabi's main utility for grid-scale demand management to operate thermal generation efficiently. In Italy, 35 MW Na-S facilities, operated by the transmission operator Terna, store the surging supply of wind energy generated in the south of that country for transmission across the grid to the large power users in the north, thereby reducing transmission congestion and the curtailment of wind generation in the Italian grid. Moreover, in Japan, a 50 MW/300 MWh Na-S battery system was delivered to optimize the balance of supply and demand of power by absorbing excess solar PV generation to avoid limiting the output from solar facilities [27].

3.1.4 Ni-Cd Battery

Nickel-cadmium (Ni-Cd) batteries have high power and energy density, high efficiency of charge/discharge, and a low cycle life (Table 2). The primary demerit of Ni-Cd batteries is a relatively high cost because the manufacturing process is expensive. In contrast, Cadmium is a toxic-heavy metal, hence posing issues associated with the disposal of Ni-Cd batteries. Ni-Cd batteries also suffer from "memory effect," where the batteries only take a full charge after a series of full discharges [4].

To date, there have been very few commercial successes using Ni-Cd batteries for utility-scale EES applications. For example, in 2003, Golden Valley Electric Association BESS used 27 MW of a Ni-Cd battery bank for energy-storage applications. Ni-Cd has also been used for stabilizing wind-energy systems, with a 3-MW system on the island of Bonaire commissioned in 2010 as part of a project for the island with 100% of its power derived from sustainable sources [28].

3.1.5 Ni-MH Battery

Nickel-metal hydride (Ni-MH) batteries have a 1.5 to 2 times higher energy density than Ni-Cd [29, 30]. They exhibit high power capability, tolerance to overcharge/discharge, and environmental compatibility and safety, which make them appropriate for portable power tools and HEVs, although their energy density is relatively low compared to Li-ion batteries (Table 2) [22].

The major use of Ni-MH batteries is in the production of hybrid cars (hybrid electric vehicles, HEVs). In the year 2000, the total production of small Ni-MH batteries was up to 1 billion in Japan. China was one of the few countries to participate in the early development of Ni-MH batteries. Since 1995, China has built a number of manufacturing bases for the

large-scale production of Ni-MH batteries, such as the Tianjin Peace Bay Company, the Shenyang Sanpu Company, etc. China is now ranked the world's first in the production of Ni-MH batteries [22]. As of 2017, 85% of listed HEVs were based on Ni-MH batteries; however, with the rapid market development of HEVs, extensive research is ongoing to improve the energy density of Ni-MH batteries and their cycle lives.

3.2 Flow Battery

A recent commercial entrant to the electricity storage field is the flow battery, or redox flow battery (RFB). This is a type of rechargeable battery where rechargeability is provided by two chemical components dissolved in liquids contained within the system and separated by a polymeric membrane (Fig. 7). This technology is similar to a polymer electrolyte membrane fuel cell. The principle behind an RFB cell is two electrochemical reduction and oxidation reactions occurring in two liquid electrolytes. The reduction half-reaction at one electrode extracts electrons and ions from one electrolyte, while the oxidation half-reaction at the other electrode recombines them into the other electrolyte (Fig. 7). Ions migrate from one electrode to the other (from anode to cathode) through an electrolyte impermeable to electrons, which are thus forced through an external circuit and produce electricity. In order to keep the solutions in the liquid phase, the cell must operate at near room temperature. Both half-cells are connected to external

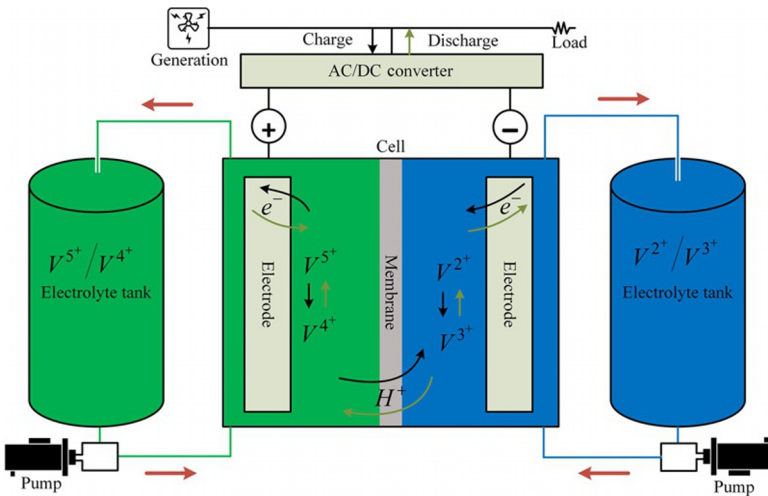


Fig. 7 Schematic of redox flow battery.

storage tanks to provide the required volume of electrolyte solutions circulated by pumps.

The potential applications of RFBs are numerous, including load leveling and peak shaving, continuous power supplies, emergency backup, and facilitation of wind and photovoltaic energy delivery. With regard to both economic and safety considerations, redox flow batteries are recognized as one of the most realistic candidates among electrochemical technologies for energy storage in the range of several kW/kWh up to tens of MW/MWh.

3.2.1 Vanadium Redox Flow Battery

Vanadium redox flow battery (VRFB) systems are the most developed among flow batteries because of their active species remaining in solution at all times during charge/discharge cycling, their high reversibility, and their relatively large power output (Table 2). However, the capital cost of these systems remains far too high for deep market penetration. In order to meet the proposed cost targets, recent investigations have highlighted the use of organic active materials in solid-state organic batteries, in which energy is stored within the cell, mainly in the form of a radical polymer [31].

Recently, it has been installed for several purposes. Examples of this technology in use are a 275-kW output balancer on a wind power project in the Tomari Wind Hills, Japan; a 200-kW output leveler on King Island, Australia; a 250-kW, 2-MWh load leveler in Utah, USA; and two wind and solar power projects (5kW each) installed in Kenya [32, 33]. Additionally, Hokkaido Electric Power Co. Inc. (HEPCO) and Sumitomo Electric Industries (SEI) Ltd. installed 15MW/60MWh of VRFB at the Minamihayakita Transformer Station in Abira-chou, Hokkaido, Japan—this is one of the world's largest redox flow battery operations in use [34].

3.2.2 Zinc-Bromine (ZnBr) Flow Battery

Zinc-bromine (ZnBr) flow batteries exhibit relatively high energy density, deep discharge capability, and good reversibility (Table 2). The disadvantages include material corrosion, dendrite formation, and relatively low cycle efficiencies compared to traditional batteries, which can limit its applications [12, 35].

Integrated ZBB (ZBB Energy Corporation) energy storage systems have been tested on transportable trailers (up to 1 MW/3 MWh) for utility-scale applications. Multiple systems of this size could be connected in parallel in much larger applications. ZBB systems are also being supplied at the

5 kW/20 kWh community energy storage (CES) scale, and are now being tested by utility companies—mostly in Australia [36].

3.2.3 Polysulfide-Bromine (PSB) Flow Battery

Polysulfide-bromine batteries (also called regenerative fuel cells or Regenesys) have a very fast response time; they can react within 20 milliseconds. Under normal conditions, PSB batteries can start charging or discharging within 0.1 s [37]; therefore, PSB batteries are particularly useful for frequency response and voltage control.

PSB systems have been tested in the laboratory and demonstrated at the multi-kW scale in the UK. In 2002, a 15-MW 120-MWh Regenesys PSB flow battery (24,000 cell) was built at Innogy's Little Barford Power Station in the UK to support a 680-MW combined cycle gas turbine plant. The Tennessee Valley Authority (TVA) in Columbus wanted a 12-MW, 120-MWh battery to avoid upgrading the network: the exact details of the project are not available as the project was never fully commissioned [38].

4 ELECTRICAL STORAGE

4.1 Supercapacitors

Supercapacitors store electrical energy without any conversion. They have low energy density but high power densities (5–15 kW/kg [39]) with lifetimes of about one million charge/discharge cycles. Depending on the charge storage mechanism, supercapacitors can be classified into three categories: electric double layer capacitors (EDLCs); pseudocapacitors; and hybrid supercapacitors formed by a combination of EDLCs and pseudocapacitors (Fig. 8).

In EDLCs, the capacitance is produced by the electrostatic charge separation at the interface between the electrode and the electrolyte. To maximize the charge storage capacity, the electrode materials are usually made from highly porous carbon materials [40]. In contrast, pseudocapacitors are based on faradaic redox reactions involving high energy electrode materials based on metal oxides, metal-doped carbons or conductive polymers. These electrode materials allow supercapacitors with higher energy density. The hybrid supercapacitors incorporate mechanisms from both EDLCs and pseudocapacitors [41].

The characteristics of supercapacitors enable them to meet instantaneous variations in electricity demand in combination with one or more

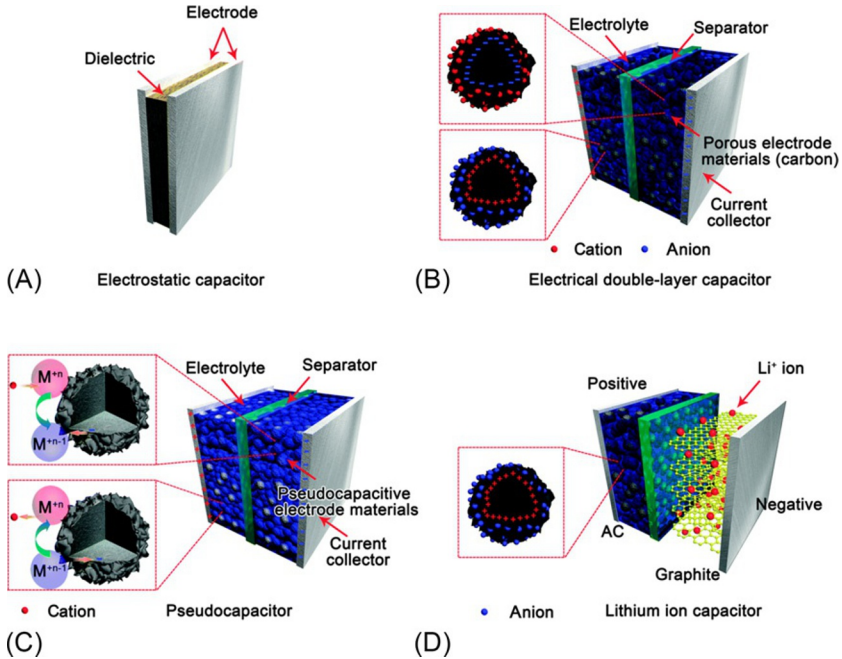


Fig. 8 Schematic diagram of (A) an electrostatic capacitor, (B) an electric double-layer capacitor, (C) pseudocapacitors, and (D) hybrid supercapacitors [40].

technologies that have superior energy density but lower effective power density, such as hydrogen stored as a metal hydride.

4.2 Superconducting Magnetic Energy Storage

In 1969, Ferrier [42] originally introduced the superconducting magnetic energy storage (SMES) system as a source of energy to accommodate the diurnal variations of power demands [43]. An SMES system contains three main components: a superconducting coil (SC); a power conditioning system (PCS); and a refrigeration unit (Fig. 9). It stores energy in a superconducting coil in the form of a magnetic field generated by a circulating current. The maximum stored energy is determined by two factors. The first is the size and geometry of the coil, which determines the inductance of the coil. Obviously, the larger the coil, the greater the stored energy. The second factor is the conductor characteristics, which regulate the maximum current. Superconductors can carry substantial currents in high magnetic fields [44].

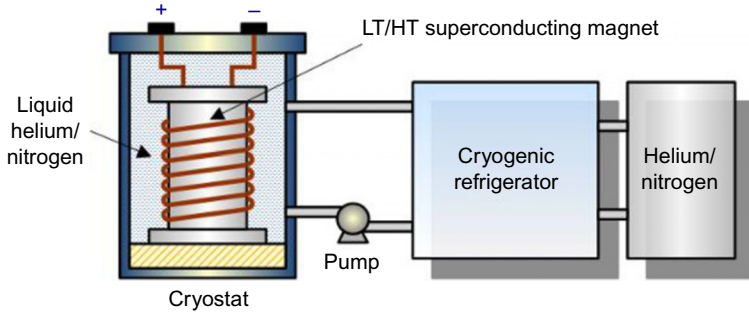


Fig. 9 Schematic of superconducting magnetic energy storage [4].

The magnetic field is created with the flow of a direct current (DC) through the superconducting coil. In SMESs, the superconducting coils are usually made of niobium-titanium (NbTi) filaments with a critical temperature of about 9.2 K [4]. To maintain the system charge, the coil must be cooled adequately. This has been achieved by cryogenically cooling to a temperature below its superconducting critical temperature, thereby enabling the current to circulate indefinitely with almost zero loss. Most importantly, the only conversion process in the SMES system is from AC to DC; thus, there are no inherent thermodynamic losses associated with the conversion. This leads to higher cycle efficiency, instantaneous charge and discharge (within a few milliseconds), and high storage efficiency [4].

Due to its characteristics, SMESs are more suitable for high power and short duration applications, since they are cheap on the output power basis—with a high-power density—but expensive in terms of energy storage capacity. As a result, SMESs have attracted attention for applications by solving voltage stability and power quality problems for large industrial customers, electric utilities, and the military (for example, microchip manufacture) [45]. Onsite SMES is suitable to mitigate the negative impacts of renewable energy in power quality related issues, especially with power converters (needed for solar photovoltaic and some wind farms), wind power oscillations, and flicker [46].

The main drawbacks of an SMES system are the need for significant power to keep the coil at low temperatures combined with the high overall cost of its employment [47]. Additionally, this technology is economically suitable for short cyclic periods only, with a maximum of hours of duration in storage; this is due to a high self-discharge ratio for longer periods (10%–15% per day) [4] and mechanical stability problems [44].

Since 2011, the U.S. Department of Energy Advanced Research Projects Agency for Energy (ARPA-E) has awarded a \$4.2 million grant to Swiss-based engineering firm ABB to create a 3.3-kW-hour, proof-of-concept SMES prototype. ABB is collaborating with superconducting wire manufacturer SuperPower, Brookhaven National Laboratory, and the University of Houston. The group's ultimate goal is to develop a 1–2 MWh commercial-scale device that is cost competitive with lead-acid batteries [48].

5 THERMAL ENERGY STORAGE

Thermal energy storage (TES) is generally considered as energy management options attached to renewable energy generation units; however, its standalone application at the demand side is also possible. In recent decades, TES systems have demonstrated a capability to shift electrical loads from high-peak to off-peak hours, so they have the potential to become powerful instruments in demand-side management programs [49]. TES can also be defined as the temporary storage of thermal energy at high or low temperatures; it has the potential to increase the effective use of thermal energy equipment and to facilitate large-scale switching. TES is normally useful for correcting the mismatch between supply and demand energy [50]. Certainly, TES is of particular interest and significance for solar thermal applications such as heating, hot water, cooling, air conditioning, etc. because of its intermittent nature. In these applications, a TES system must be able to retain the energy absorbed for at least a few days in order to supply the energy needed on cloudy days when the energy input is low [49].

TES comprises three parts: a storage medium, a heat transfer mechanism, and a containment system. TES stores the thermal energy in one of three forms such as sensible heat, latent heat or vaporization, and thermochemical reactions. At present, synthetic oil and molten salt are the most widely used sensible heat storage materials in large-scale concentrating solar power (CSP) systems. Other systems that utilize latent heat, thermochemical and novel sensible heat materials are still under development [51]. The characteristic data of each thermal energy storage are given in Table 3. Fig. 10 shows the different materials and systems of thermal energy storage.

5.1 Sensible Heat Energy Storage

Sensible heat storage means shifting the temperature of a storage medium without phase change. It is the most common simple, low-cost, and long-standing method. This storage system exchanges the solar energy into

Table 3 Characteristics and comparisons of the thermal energy storage systems [52]

Particulars		Sensible heat storage	Latent heat storage	Thermochemical storage
Energy density	Volumetric	Small: $\sim 50 \text{ kWh m}^{-3}$ of material	Medium: $\sim 100 \text{ kWh m}^{-3}$ of material	High: $\sim 500 \text{ kWh m}^{-3}$ of reactant
	Gravimetric	Small: $\sim 0.02\text{--}0.03 \text{ kWh kg}^{-1}$ of material	Medium: $\sim 0.05\text{--}0.1 \text{ kWh kg}^{-1}$ of material	High: $\sim 0.5\text{--}1 \text{ kWh kg}^{-1}$ of reactant
Storage temperature		Charging step temperature	Charging step temperature	Ambient temperature
Storage period		Limited (thermal losses)	Limited (thermal losses)	Theoretically unlimited
Transport		Small distance	Small distance	Distance theoretically unlimited
Maturity		Industrial scale	Pilot scale	Laboratory scale
Technology		Simple	Medium	Complex

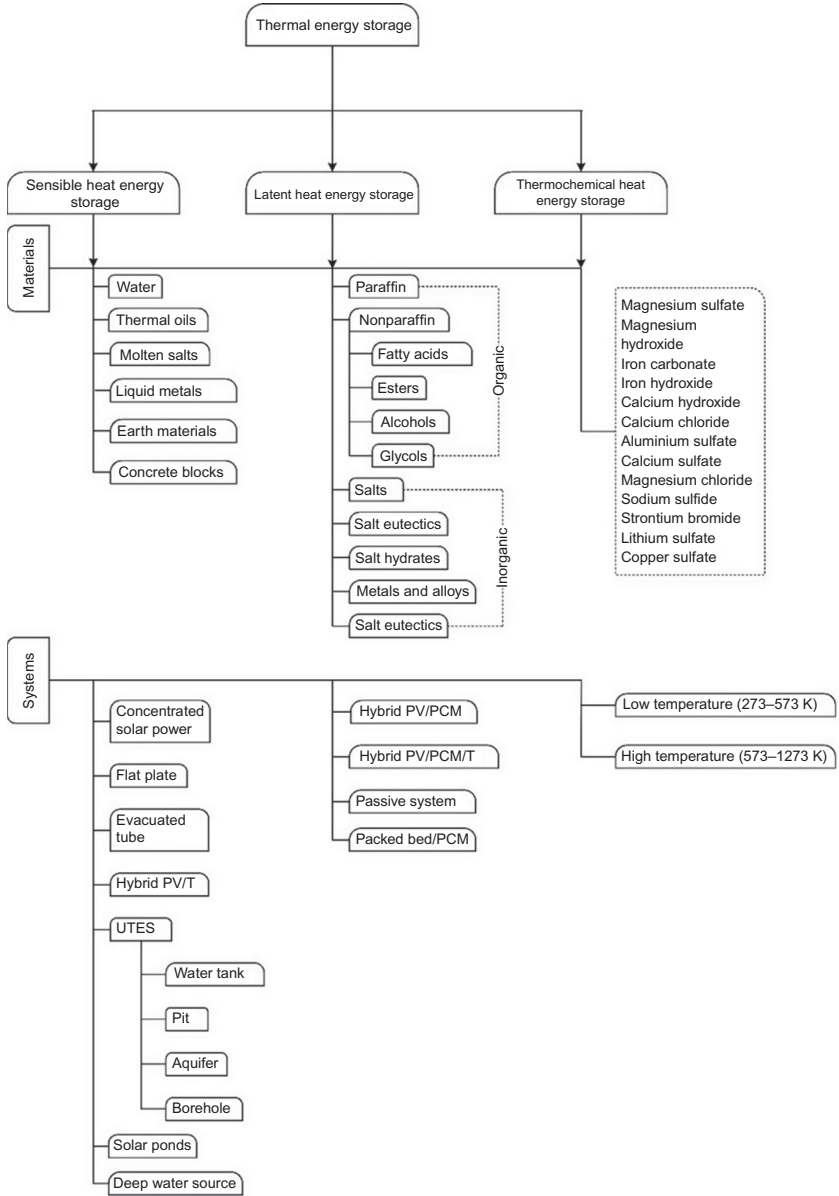


Fig. 10 Different materials (above) and systems (below) of thermal energy storage.

sensible heat in a storage medium (usually solid or liquid) and releases it when necessary. The amount of stored sensible heat in a material depends on its heat capacity (energy density) and the thermal diffusivity (rate at which the heat can be released and extracted) [51]:

$$Q = \int_{T_i}^{T_f} m C_p dT = m C_p (T_f - T_i) \quad (1)$$

where Q is the amount of heat stored, T_i is the initial temperature, T_f is the final temperature, m is the mass of heat storage medium, and C_p is the specific heat.

The storage materials absorb heat by the conventional heat transfer mechanisms of radiation, conduction, and convection. As the materials cool at night or on cloudy days, the stored heat is released by the same modes.

In terms of containment, sensible heat storage materials can be stored above ground or underground. The major methods employed for underground thermal energy storage (UTES) are aquifer storage and underground soil storage. Sensible heat storage is mainly demonstrated in space heating and domestic hot water supply for which the required temperature ranges from 40°C to 80°C [53]. Hence, water, rock-sort materials (for example, gravel, pebbles, and bricks) and ground or soil have been widely used as storage media in large-scale demonstration projects around the world [53]. Furthermore, all of the currently installed TES systems in utility-scale solar thermal electric plants store energy using molten salts, synthetic oil, liquid metals, or powders [51].

Water-based sensible heat storage systems use water as the storage medium or heat carrier fluid for storing/transferring heat. These systems can be classified as water tank and aquifer storage systems. Water tank or pit storage systems store water in an artificial structure made of stainless steel or reinforced concrete surrounded by thick insulation, and are usually buried underground (also called water pits) or placed on the roof or outside of a building [54]. Aquifer storage, however, uses natural water directly from the underground layer. An aquifer needs to drill at least two thermal wells (hot and cold). The aquifer geologic formation is employed as the storage medium and the groundwater is used as the heat carrier fluid [53]. One of the largest water-based sensible heat storages is in Pimlico, London, UK, consisting of three 8-MW_{th} boilers; two 2-MW_{th} combined heat and power (CHP) engines; and an accumulator that can store 2500 m³ of water at just <100°C. It provides heating and hot water to 3256 homes, 50 commercial properties, and three schools [55].

In rock-bed, sensible heat storage, the rock (for example, pebble, gravel or bricks) bed is usually disseminated with heat transfer fluid (water or air) to exchange heat (gained in summer and released in winter). Rock-based systems can endure higher temperatures in comparison with water-based systems; however, the energy density is low. Hence, they need larger volumes to store the same amount of heat storage, which is approximately three times higher than water-based storage systems [53]. In Qinhuang Island, China, a 300-m^3 pebble bed was constructed to store surplus heat from the 473.2-m^2 solar collector during the day and provide heating and hot water during the night [56].

Ground or soil sensible heat storage is another application of UTES aside from aquifer systems. In this system, ground or soil itself is used directly as a storage medium. The underground structure can store a large amount of solar heat, which is collected in the summer for later use in winter. In this storage system, the ground is excavated and drilled to insert vertical or horizontal tubes, so it is also called borehole thermal energy storage (BTES) or duct heat storage [53]. The Drake Landing Solar Community, Alberta, Canada, provides heating and hot water to 52 homes (around 97% of their year-round heat). The heat energy is captured from 800 solar thermal collectors located on the roofs of all 52 houses' garages. This is enabled by interseasonal heat storage in a large mass of underground rock. The thermal exchange occurs via 144 boreholes, drilled 37 m into the earth [57].

Before installing sensible heat energy storage systems, a few aspects need to be considered, such as local geological conditions, available site size, temperature levels of the reservoir, and legal issues about drilling and investment costs. Besides, sensible heat storage system suffers from heat loss problems. If thick insulation is installed, the temperature of the heat source may not allow the extracted heat to be used directly in the heating season. Therefore, the storage unit needs additional equipment, such as a heat pump, to upgrade the temperature level to satisfy the required heat load, which also incurs higher investment cost.

5.2 Latent Heat Energy Storage

Latent heat energy storage is a near-isothermal process that can provide significantly high storage density with smaller temperature swings in comparison with sensible storage systems. In addition, latent heat storage has the capacity to store heat of fusion at a constant or near-constant temperature that corresponds to the phase transition temperature of the phase change

material (PCM). Latent heat storage is based on the heat absorption or release when a storage material undergoes a phase transformation from solid to solid, liquid to gas, and solid to liquid, or vice versa. The storage capacity of a latent heat storage system with PCM is given by:

$$\begin{aligned}
 Q &= \int_{T_i}^{T_m} m C_p dT + m a_m \Delta H_m + \int_{T_m}^{T_f} m C_p dT \\
 &= m [a_m \Delta H_m + C_p (T_m - T_i) + C_p (T_f - T_m)]
 \end{aligned} \tag{2}$$

where a_m is the melted fraction and ΔH_m is the heat of fusion.

The most practicable routes of latent heat storage are solid to liquid and solid to solid. Solid-to-gas and liquid-to-gas transitions have a higher latent heat of fusion, but their large volume expansion, associated with containment problems, rule out their potential use in thermal storage systems [58]. Large volume changes render such systems complex and impractical. In solid-to-solid transitions, heat is stored when the material is transformed from one crystalline structure to another. This transition generally has less latent heat and slighter volume changes than a solid-to-liquid transition. Solid-to-solid PCMs offer the advantages of less rigorous container requirements and better design flexibility. Solid-to-liquid transformations have comparatively smaller latent heat than liquid to gas; however, these transformations involve only small changes in volume (<10%). Solid-to-liquid transition has proved its economic viability for use in thermal energy storage systems [58, 59].

PCMs themselves cannot serve as heat transfer mediums. Heat transfer mediums with a heat exchanger are required to transfer energy from source to PCM and from PCM to load. Therefore, heat exchanger design is an important part in improving heat transfer in latent heat storage systems. PCMs also have positive volumetric expansion on melting, and so volume design of the containers is also necessary, which should be compatible with the PCM used. Any latent heat storage system must possess at least these three properties: a suitable PCM with its melting point in the desired temperature range, a suitable heat exchange surface, and a suitable container compatible with the PCM [59].

During the phase change, the materials remain, theoretically, at constant temperature (real systems show a temperature stabilization around the melting temperature). PCMs undergo phase-changing processes by absorbing (endothermic process) and releasing (exothermic process) heat in the form of latent heat of fusion without the temperature changing in each period. The phase-changing temperatures of PCMs differ across a wide range,

making them applicable for various situations. The energy density of latent heat storage is typically 5 to 10 times higher than sensible heat storage. For example, Morrison and Abdel-Khalik [60] and Ghoneim [61] showed that to store the same amount of energy from a unit collector area, rock requires more than seven times the storage mass of Paraffin 116 Wax (P116-Wax), five times the storage mass of medicinal paraffin, and more than eight times the storage mass of $\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$.

A wide range of PCM is available for use in latent heat energy storage systems, thus providing application potential in a range of different temperatures from freezing to high-temperature storage applications. The different materials proposed for use as phase change materials include aqueous salt solutions, water, gas hydrates, paraffins, fatty acids, salt hydrates and eutectic mixtures, sugar alcohols, nitrates, hydroxides, chlorides, carbonates, and fluorides. The temperature range covered by these materials is from below -20°C to above 700°C .

Many of the phase change materials have low thermal conductivity, which can dwindle the rates of heat charging and discharging. To address this limitation, different approaches have been introduced. For example, Fukai, Hamada [62] introduced carbon-fiber brushes on the shell side of a heat exchanger to enhance the conductive heat transfer rates in a PCM. In the charging process, the brushes prevent the natural convection; however, the charge rate with the brushes is 10%–20% higher compared to the case without fibers. The brushes also improve the discharge process. The discharge rate using the brushes with one volume percent is about 30% higher than that without fibers. Zhang, Zhang [63] used expanded graphite (EG) to absorb liquid paraffin. The new composite resulted in a reduction in thermal energy storage charging time compared with using paraffin only. The EG exhibited the maximum sorption capacity of 92 wt% for paraffin at 800 W (microwave irradiation) for 10 s.

Previously, latent heat storage was mainly employed with construction as a passive method in building envelopes (walls, windows, ceilings, or floors). Here, “passive” means that the phase-change processes occur without resorting to mechanical equipment. PCMs are often mixed with other construction materials, such as concrete, or used alone to play a role in building envelopes. In greenhouse applications, north wall storage incorporated with PCMs is the most common technology for increasing the indoor temperature. However, most passive applications are not highly controllable and have low solar fractions, so they are limited to short-term storage [53]. However, for long-term storage, PCMs would provide more potential for

inactive storage such as when integrated with solar collector systems (for example, agriculture greenhouses and heat pumps) [53, 64]. In order to increase the storage capacity of a CSP system, it has been offered that latent heat storage could be used in conjunction with a steam accumulator by either inserting PCMs directly inside the steam accumulator or from the outside into the steam accumulator [51].

PCMs are beneficial with respect to reasonable cost, higher energy density, simplicity in system design, and the delivery of heat at constant temperature. However, for applications in heating and cooling systems, the technology should be improved in a few aspects (but not limited to), such as the need to improve the storage density to enable the integration of PCMs into buildings and HVAC systems, and to enhance the rate of heat discharge from PCMs that can be used for domestic hot water production.

An alternative option, in this category, is energy storage in molten metals. For instance, the Perryman Thermal Battery™ is a technology that stores energy in molten metals (e.g., nickel), with ceramic embodiment, at temperatures up to 2000°C [65]. The technology can be charged using a standard induction unit directly from AC or DC power sources. The efficiency loss from converting electricity to thermal energy using induction is only around 1.68% for AC electricity and 2.74% for DC electricity. Unlike the electrochemical cells, this technology has a negligible loss (~ 2% per month) without an aging problem. Depending on the conditions of use, it can last for many decades. Particularly, the ceramic embodiment has a long life with some working examples being in service for over 80 years. Furthermore, the technology does not involve materials with environmental impacts, and it faces minimal concerns for decommissioning and recycling. Perryman Thermal Batteries™ can be varied in scale from the size of a large basketball to very large industrial units holding over 30 MWh of thermal energy. Given its very high operating temperature, the technology has a high energy density (J/m^3) with a standard 29MWh industrial unit being approximately 6m tall, 2.4m wide and 26m^3 in volume (Fig. 11).

5.3 Thermochemical Heat Energy Storage

In a thermochemical heat storage system, reactions are reversible:



In this storage system, the thermochemical heat reserve is associated with the reaction enthalpy, ΔH . During the charging step, thermal energy is used

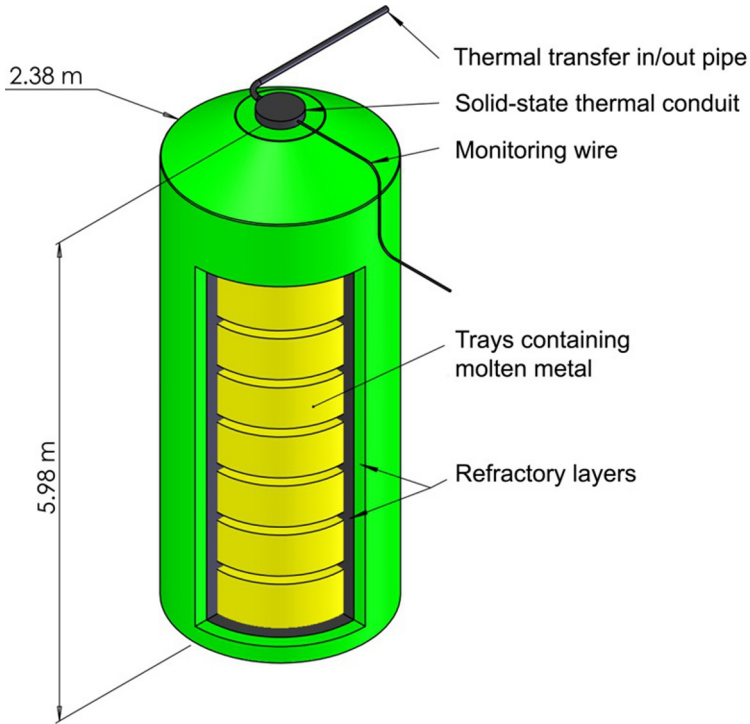


Fig. 11 Schematic of a 29 MWh Perryman Thermal Battery™ for energy storage in molten metals. (Image Courtesy of Virgil Perryman)

to dissociate a chemical reactant (A) into products (B and C). This reaction is endothermic. During the releasing step, the products of the endothermic reaction (B and C) are mixed together and react to form the initial reactant (A). This reaction is exothermic and releases heat. The products of both reactions can be stored either at ambient temperature or at working temperature. In this process, substance B can be a hydroxide, hydrate, carbonate, ammoniate, etc., and C can be water, CO , ammonia, hydrogen, etc. There is no restriction on phases, but usually A is a solid or a liquid and B and C can be any phase. The thermal energy stored in thermochemical material can be expressed as:

$$Q = n_A \Delta H \quad (4)$$

where n_A is the mol number of reactant A .

Thermochemical storage systems have several advantages. Their energy densities are 5 to 10 times higher than latent heat storage systems and sensible heat storage systems, respectively. Both storage period and transport are

theoretically unlimited because there is no thermal loss during storage, as products can be stored at ambient temperature for long periods with little or no degradation in stored energy content. However, the thermochemical energy storage is the least developed storage technology, requiring complex reactor design to achieve the desired operational performance [51]. Nevertheless, these systems suffer from the impediments commonly exhibited by other systems, including limitations in heat transfer, cycling stability, operating condition (pressure and temperature), reversibility, and costs. In addition, thermochemical systems can be restricted by reaction kinetics [66].

If successful reactors could be designed with performances close to predicted theoretical levels with no materials degradation on repeated cycling, then this may allow the realization of long-term, effective heat storage with compact energy storage systems. However, far more research is required on materials and reactor design—including humidification and regeneration processes—before this to be achieved [67]. Two review articles have investigated low-temperature (273–573 K), thermochemical TES [68, 69]. One is a state-of-the-art review on sorption and chemical reaction processes for thermochemical TES applications by Cot-Gores, Castell [70]. Recently, Pardo, Deydier [52] reviewed high-temperature (573–1273 K) thermochemical TES systems, which have the potential to become an important part of the sustainable handling of energy in the near future.

6 CHEMICAL ENERGY STORAGE

Chemical energy storage includes sorption and thermochemical reactions. *Sorption* is a physical and chemical process by which one substance becomes attached to another. Sorption is the common term used for both absorption and adsorption. *Absorption* is the incorporation of a substance in one state into another of a different state (for example, liquids being absorbed by a solid or gases being absorbed by water). *Adsorption* is the physical adherence or bonding of ions and molecules onto the surface of another molecule. In thermochemical reactions, energy is stored after a dissociation reaction and then recovered in a chemically reverse reaction (discussed in Section 5.3).

6.1 Hydrogen Storage

Batteries might be argued as suitable candidates for short-term energy storage and power quality management. However, their feasibility for energy management and long-term storage (that is, days, months and years) is questionable. In contrast, though hydrogen might not be a competitive solution

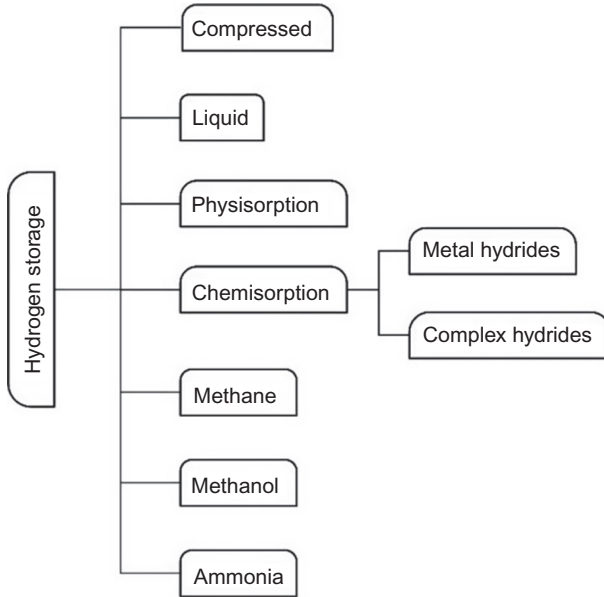


Fig. 12 Different hydrogen storage methods.

for short-term storage, it has the capability of energy storage at massive volumes; for example, terawatt hours of volume for a long period in various forms. Furthermore, any large-scale hydrogen distribution system must deal with storage to provide a buffer between production facilities and fluctuations in demand. Economically viable, environmentally benign, and sustainable mass storage techniques are therefore major research goals. Fig. 12 shows the available hydrogen storage methods.

The lower heating value (LHV) of hydrogen is 120 MJ/kg, compared to about 50 MJ/kg for methane and around 40 MJ/kg for petroleum products. The basic problem of storing hydrogen is its low density at ambient conditions (0.0823 kg/m^3 at 298 K and atmospheric pressure [71]). Storing 1 kg of hydrogen at atmospheric pressure and 25°C , therefore, requires a tank with internal volume 12.3 m^3 , which is impractical in most situations (such as even a small fuel-cell vehicle requiring at least 5 kg of H_2 , or an offgrid energy system requiring many kg of storage capacity). Therefore, there is a need for improving the volume intensity of hydrogen.

While liquefaction or cryocooling of hydrogen gas is possible [72], current storage systems (such as fuel-cell vehicles, onsite storage, or stand-alone applications) are mostly limited to compressed gas storage in cylinder/canisters. The drawback of compressed hydrogen is its lower volume

intensity, which makes the transportation costs higher—especially for delivery to distant locations. Solid-state hydrogen storage in metal hydride or complex hydride could be a potential option for standalone or stationary use due to favorable characteristics such as decoupling of power and energy ratings, low operating pressure, safety, and high volumetric energy intensity. However, various challenges need to be addressed, depending on the nature of the storage material, including the overall weight of the storage system, the limited storage capacity of the material used, degeneration with cycles, and cost.

6.1.1 Compressed

The simplest storage system is compressed H₂ gas. The advantages of this method include the ease of operation at ambient temperature and simplicity of storage and retrieval. Compressing hydrogen increases H₂ density to 23.32 kg/m³ at 350 bar (common in fuel-cell buses) and to 39.22 kg/m³ at 700 bar (common in commercial fuel-cell sedans) [71]. Cryocompression to 200 bar at 100 K achieves a density of 39.52 kg/m³ [71], matching that of 700-bar compression at 25°C and partially trading one technical difficulty (high pressure) for another (cryogenic temperature).

Compressed hydrogen storage is now a commercial reality in fuel-cell vehicles and refueling stations. The so-called type IV hydrogen storage tanks used in vehicles have a cylindrical composite structure with wound carbon fiber over a hydrogen-impermeable liner [73, 74]. From an electrical energy storage perspective, compressed hydrogen storage is technically viable, but (i) it necessitates expensive compression technology, which constitutes a parasitic load on the energy system, and (ii) it operates at a much higher pressure than common electrolyzers and fuel cells.

6.1.2 Liquid

Traditionally, liquid hydrogen storage is technically viable at small scales and has been trialed in vehicles but has been overtaken by compressed hydrogen storage. Its potential role in energy systems is not established; nonetheless, cryogenic storage at the scale of many m³ of liquid is a well-established technology in the space industry. Liquefied hydrogen becomes mandatory for large-scale export of pure hydrogen. Kawasaki Heavy Industry (Japan) is moving forward with the construction of small liquefied hydrogen carriers, initially at the 200-t scale [75].

Liquid hydrogen suffers from unavoidable losses from boil-off owing to heat flow into the reservoir from the exterior. Furthermore, hydrogen

liquefaction constitutes a parasitic load consuming around 35% of the LHV energy content of the liquefied hydrogen. It is best suited to centralized liquefaction plants with their attendant economies of scale. Remaining challenges include the total system volume and weight, the high cost of the tank, and the ortho-para conversion [76].

6.1.3 Physisorption

Hydrogen can be stored in its molecular form by physical adsorption onto the surface of a porous solid material. Dalebrook, Gan [77] reviewed different new techniques of hydrogen absorption and desorption and categorized them as physisorption storage (for example, zeolites, metal-organic frameworks (MOFs)) and chemical storage (for example, amines, formic acid). In physisorption, hydrogen remains in its molecular form and is absorbed and desorbed reversibly. In this process, the surface densities are higher than the bulk gas concentration due to gas-solid interactions [60], and storage materials may express gravimetric loadings as either total capacity (the entire quantity of deliverable hydrogen) or excess capacity (the gain in uptake promoted by an adsorbent).

Carbon-based materials (such as activated carbon, graphite, carbon nanotubes, and carbon foams) have received significant attention due to characteristics such as low weight, high surface area, and chemical stability [78, 79]. Graphene is a single layer of graphite and has a theoretical surface area of $2630 \text{ m}^2 \text{ g}^{-1}$ [80, 81], making it a suitable candidate for physisorption storage. Burrell, Gadipelli [82] showed that using different activation techniques rather than heat treatment could reduce the oxygen-to-carbon (O/C) ratio, which helps to improve the surface area and hydrogen uptake of graphene oxide frameworks (GOFs).

Microporous organic polymers (MOPs) are desirable for energy storage due to their high specific surface areas and tailored porosity. Wood, Tan [83] introduced a series of synthetic routes to enhance the interaction with hydrogen molecules. Recently, polymers of intrinsic microporosity (PIMs) [84] and hypercrosslinked polymers (HCPs) [85] have been investigated for physisorption-based hydrogen storage at low temperature. Covalent organic frameworks (COFs) show much finer control over the crystallinity and porosity properties in comparison to HCPs and PIMs [86]. Ding and Wang [86] critically reviewed COFs, covering materials design to applications. Zeolites contain well-defined open-pore structures, often with tuneable pore sizes, and demonstrate notable guest-host chemistry with important applications in catalysis, gas adsorption, purification, and

separation [87]. Additionally, these materials are inexpensive and have been widely used in industrial processes for many decades.

An extensive experimental survey has shown that the hydrogen storage capacity of zeolites to be <2 wt% at cryogenic temperatures and <0.3 wt% at room temperatures and above [88]. Recently, novel nanoporous materials (such as MOFs) have been applied to hydrogen storage [89–91]. MOFs are porous materials constructed by coordinate bonds between multidentate ligands and metal atoms or small metal-containing clusters, and are highly crystalline, inorganic–organic hybrid structures that contain metal clusters or ions (secondary building units) as nodes and organic ligands as linkers [92]. MOFs can be synthesized via self-assembly from different organic linkers and metal nodules. Due to the variable building blocks, MOFs have very large surface areas, high porosities, uniform and adjustable pore sizes and well-defined hydrogen occupation sites. These features make MOFs promising candidates for hydrogen storage based on physisorption.

6.1.4 Chemisorption

Storing hydrogen as a chemical metal hydride or complex hydride can provide high volumetric densities and low absorption pressures during hydrogen uptake.

Metal Hydrides

The class of materials collectively known as metal hydrides (MHs) contains a very wide variety of materials, including elemental metals, alloys, and stoichiometric nonmetallic compounds, with the common ability to dissociate hydrogen molecules at the surface of the material and absorb hydrogen atoms into the interior crystal structure. Absorption and desorption take place in a very wide range of pressures and temperatures, as illustrated in Fig. 13, where the most practicable materials are included from stationary hydrogen storage, namely, relatively heavy metal hydrides with high volumetric hydrogen density.

The advantages of metal-hydride storage in these situations come from (i) the decoupling of power and energy ratings, which makes it advantageous for long-term storage compared to batteries [93]; (ii) its ability to be tuned for low operating pressure suitable for direct coupling to an electrolyzer and near-ambient operating pressure; (iii) excellent safety coming from the low pressure and relatively slow kinetics of hydrogen release; and (iv) high volumetric energy density. For example, the classic intermetallic hydride LaNi_5H_6 contains only 1.4 mass% hydrogen but has a 100%-dense

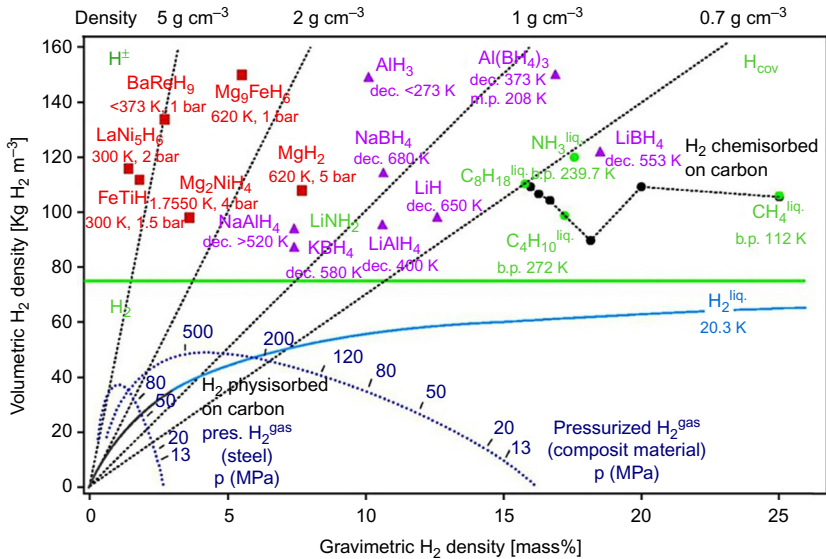


Fig. 13 Comparison of metal-hydride and other hydrogen storage materials [101].

volumetric capacity of approximately 115 kg m^{-3} at room temperature and $<1 \text{ MPa}$ pressure [94] compared to 70.8 kg m^{-3} at 20.3 K and 0.1 MPa for liquid hydrogen. A more detailed review of solid-state hydrogen storage is available in several review papers and books published within the recent decade [95–97].

Light-weight metals—such as Li, Na, and Mg—all form hydrides with high gravimetric hydrogen capacities. The release of the hydrogen, however, requires high temperatures ($>650^\circ\text{C}$ for Li, for example) due to the high enthalpy of formation. Magnesium hydride offers the greatest potential with 7.6 wt% and good reversibility, but desorption is kinetically limited. Webb [96] studied MgH_2 to improve the hydrogen sorption through mechanical modification of the material and through the addition of catalytic materials [96].

Alloying of different metals can modify the enthalpy of the hydride, and this has been investigated for hydrogen storage applications. Most useable alloys are AB_5 intermetallic compounds (for example, LaNi_5) for hydrogen storage with 1.4 wt% and equilibrium pressure $<2 \text{ bar}$ at room temperature [95]. AB_2 compounds are derived from the Laves phases with a hydrogen storage capacity of up to 2 wt% [77]. Body-centered cubic (BCC) alloys have maximum hydrogen capacities up to 4 wt% with reversible capacities of $>2 \text{ wt\%}$ [98–100].

Mechanical modification can provide fresh surfaces and defects for fast hydrogen diffusion. Ball milling is a mechanical process, which is widely used to enhance the surface area of metal hydrides so as to create micro/nanostructures and annealing treatments of the material [102]. In addition, ball milling can offer a synthesis path for new alloys. For example, the milling of magnesium and titanium with different ratios of hydrogen produces a ternary hydride with 3.7 wt% hydrogen content and improves the desorption kinetics promoted by the titanium component [103]. The crystalline Mg_2Ni alloy obtained by ball milling has excellent surface properties compared with those prepared by a conventional metallurgical method [104]. Nanostructuring techniques—such as ball milling, cold rolling, thin films, and nanoconfinement—all positively influence the reaction kinetics [105, 106].

Complex hydrides

Complex hydrides are metal salts, typically containing more than one metal or metalloid, where the anion contains the hydride. These complex metal hydrides typically have higher hydrogen gravimetric storage capacities and volumetric densities than simple hydrides. For example, the hydrogen content of LiBH_4 is 18 wt% [95]. Low-weight complex hydrides include the alanates $[\text{AlH}_4]^-$, amides $[\text{NH}_2]^-$, imides $[\text{NH}_4]^-$, and borohydrides $[\text{BH}_4]^-$. Alanates and borohydrides received attention due to their light weight and hydrogen capacity per metal atom. However, both have issues with poor reversibility and high stability, decomposing only at elevated temperatures.

Sodium alanate is a complex hydride of aluminum and sodium (NaAlH_4). Theoretically, NaAlH_4 contains 7.4 wt% of hydrogen [107]; however, the decomposition to release hydrogen is a multistep reaction with details in Refs. [108, 109]. The kinetics of the sodium alanate sorption can be improved with transition metal additives such as Ti [110].

Lithium alanates are very attractive due to the higher hydrogen content of 10.5 wt% and 11.2 wt% for LiAlH_4 and Li_3AlH_6 , respectively [111]. It has been theoretically predicted that lithium nitride (Li_3N) can store 10.4 wt% hydrogen, but the reversible hydrogen capacity is only 6 wt% [112].

Schlesinger and Brown [113] developed lithium borohydride (LiBH_4) from ethyl lithium and diborane, yielding a material containing 18.3 wt% hydrogen [114, 115]. Many attempts to destabilize the highly stable complex hydrides have been made by doping, catalyst addition, $\text{H}^{\delta+}/\text{H}^{\delta-}$ coupling,

size effects, partial cation substitution, or direct reaction with other hydride materials [116]. A quaternary hydride system (that is, $\text{Li}_3\text{BN}_2\text{H}_8$) with a theoretical hydrogen capacity of 11.9 wt% was prepared by ball milling [117, 118]. Solid sodium borohydride exhibits adverse thermodynamic effects for use as a recyclable hydrogen storage material [119]. Other borohydrides of potassium, magnesium, calcium, and zinc also decompose to hydrogen (details in Refs. [120–124]). Beryllium borohydride claims the highest hydrogen content at ≈ 20.7 wt% hydrogen, but the high toxicity and cost of the metal discourages its use in hydrogen storage applications [125]. A mixture of lithium borohydride, calcium hydride, and magnesium hydride has also been studied by Zhou, Liu [126].

Recent review papers provide far more detail on complex hydrides. Paskevicius, Jepsen [127] report that there are now well over 200 known compounds in the borohydride class of complex metal hydrides. Other articles highlighting the wide range of metal hydrides include a review of B–N and Al–N compounds [128], a review of metal boranes [129], and reviews of complex transition metal hydrides [130–133]. This is a nonexhaustive list that does not include amide/imide compounds.

6.2 Methane

The currently most developed hydrogen conversion process is methanation. Hydrogen reacts with CO_2 to yield methane according to the Sabatier reaction or biological methanation resulting in an extra energy conversion loss of 8% [134]. Müller, Müller [135] reported that 95% of the CO_2 is converted to methane in a demonstration plant. The reaction is highly exothermic, which leads to high conversion losses when the heat is not completely used.

The key advantage of power conversion to methane is the availability of a natural gas distribution network as well as the market. The first industry-scale, power-to-methane plant was developed by ETOGAS for Audi AG in Werlte, Germany [136]. The plant is using CO_2 from a waste-biogas plant and intermittent renewable power to produce synthetic natural gas (SNG), which is directly fed into the local gas grid [136]. In April 2014, KIT started a research project named HELMETH (Integrated High-Temperature Electrolysis and METHAnation for Effective Power to Gas Conversion, financed by the European Union). The objective of this project is the proof of concept of a highly efficient power-to-gas technology by integrating high-temperature electrolyzers such as SOEC with CO_2 methanation [136].

6.3 Methanol

Methanol is usually considered as a hydrogen carrier. It is a versatile fuel with many advantages over pure hydrogen. The key benefit is that its liquid phase at ambient conditions, thereby making it possible to be handled and distributed with an identical type of infrastructure by which liquid gasoline is distributed today. Methanol is easily turned into hydrogen through a catalytic process, using a fuel reformer. It can be done at a temperature of 200–300°C. Many other liquid fuels can be reformed into hydrogen, but the process requires a considerably higher temperature and greater energy consumption than methanol.

Usually, the electricity consumption for methanol production is higher than that of methanation because additional compressor power is required for the recycle stream. However, methanol synthesis has fewer conversion losses because it is less exothermic. Methanol seems to be a promising storage option because it has a higher volumetric energy density than hydrogen and methane, and it can be combusted in gasoline engines [134].

In 2011, nearly 17 Mtonnes of methanol were used in fuel and energy applications. From 2012 to 2016, overall methanol consumption as a fuel almost doubled (from 20 Mtonnes in 2012 to 38 Mtonnes in 2016), translating to approximately 37% annual growth around the world [137].

Methanol is traditionally produced from syngas ($\text{CO}_2 + 3\text{H}_2 \rightarrow \text{CH}_3\text{OH} + \text{H}_2$). As the required ratio of CO_2 in the feed gas to the reactor is high, the methanol process is also viewed as a CO_2 utilization process opportunity for recycling CO_2 rather than direct emission. As such, methanol CO_2 utilization has received significant attention over recent years. When H_2 comes from renewable sources, a methanol process can be a double benefit with not only offering an intensified hydrogen carrier, but also reducing CO_2 emissions. Rihko-Struckmann, Peschel [138] investigated CO_2 utilization in membrane processes based on process simulations and assuming equilibrium conversion. They found that nearly 27% of CO_2 is converted in the reactor (250°C and 5 MPa), and the unreacted CO_2 is separated from the raw product gas and recycled to the reactor. As a result, a total conversion of CO_2 is reached ($\approx 96.8\%$).

Jadhav, Vaidya [139] found that the equilibrium conversion efficiency could be obtained with a copper catalyst. Methanol is synthesized from CO_2 at 300°C and around 70 bars in a reactor with a metallic catalyst (copper and zinc oxides on an alumina-based ceramic, $\text{Cu}/\text{ZnO}/\text{Al}_2\text{O}_3$). The ceramic is particularly adapted to this highly exothermic reaction.

Since 2009, a pilot plant of 100 tons per year has been built by Mitsui chemicals in Japan. In China, Wei and his coworkers have found a novel catalyst (ZrO_2 -doped CuZnO) for methanol synthesis from CO/CO_2 hydrogenation. The ZrO_2 -doped CuZnO catalyst showed high activity and high selectivity toward both CO and CO_2 hydrogenation [140].

6.4 Ammonia

As a hydrogen energy carrier, methane and methanol offer outward potentials; methane, because of an existing natural gas distribution infrastructure; and methanol, due to its liquid phase and ease of transportation. However, both of these options contribute to CO_2 emissions. Ammonia is, however, a carbon-free chemical energy carrier. It is not a greenhouse gas (GHG) and has a high hydrogen density, which leads to NH_3 being a favorable alternative to hydrogen. Ammonia is easy to store and deliver in large quantities. It is one of the most transported chemicals worldwide as gas, liquid, or solid form. The ability of ammonia gas to become a liquid at low pressures means that it is a good “carrier” of hydrogen. Liquid ammonia contains more hydrogen by volume than compressed hydrogen or liquid hydrogen. For example, ammonia is over 50% more energy dense per gallon than liquid hydrogen, so ammonia can be stored and distributed easier than elemental hydrogen.

The use of ammonia as an energy carrier has several advantages, such as mature technologies for production and transportation. The synthesis process of ammonia is well studied (the Haber-Bosch process). Although ammonia synthesis is exothermic, in practice the production of ammonia from hydrogen and nitrogen incurs a small energy loss of 1.5 GJ/ton compared to the 28.4 GJ/ton energy stored in the ammonia [141].

The storage of ammonia is more convenient than hydrogen; for example, up to 50,000 tons of ammonia stored in insulated tanks at 1 bar and -33°C . The temperature is kept down by slow vaporization, and the ammonia vapor is continually compressed back into a liquid. For small tanks, below 1500 ton, ammonia is stored under pressure in stainless steel spheres [141]. Ammonia can be stored as a liquid; a standard tank with a capacity of $60,000\text{m}^3$ filled with ammonia contains about 211 GWh of energy, equivalent to the annual production of roughly 30 wind turbines on land [142].

Ammonia has been already used in solid oxide fuel cells (SOFC), and it can also be used in polymer electrolyte membranes (PEMFCs) and alkaline fuel cells (AFCs). However, before feeding to the fuel cell, ammonia needs

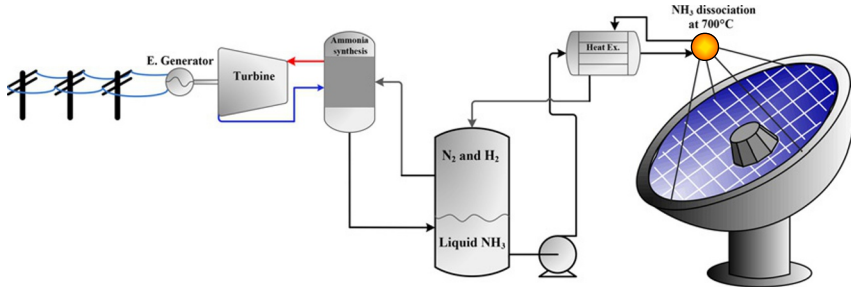


Fig. 14 Schematic of ammonia dissociation and storage [144].

to be split into hydrogen and nitrogen [143]. Dunn, Lovegrove [144] demonstrated that ammonia-based thermochemical storage with concentrating solar power systems are technically achievable (Fig. 14).

7 HYBRID ENERGY STORAGE (POLYSTORAGE)

The penetration of renewable energy sources (for example, wind and solar) into the electrical energy network is accelerating. The problem with these generation systems is that their energy sources are intermittent, and so the generated power is also intermittent, reducing stability, reliability, and power quality in the main electric grid. Energy storage is undoubtedly the best solution to address this challenge, along with demand-side management. However (as discussed in the earlier technology analysis sections), for most of the time, no single energy storage can address all techno-economic requirements. To overcome these problems, a hybrid energy storage system (HESS) or polystorage system is required [145].

A HESS or polystorage system is differentiated by a favorable combination of two or more EES systems with complementary operating features (such as energy and power density, self-discharge rate, efficiency, lifetime, and so on) to provide an optimal solution not achievable by any single technology. The HESS typically includes storage technologies that separately cover sprinter loads required for fast response, and marathon loads required for peak shaving and load shifting. Therefore, it should have a storage system with both high energy and power densities. However, none of the currently available EES system technologies satisfy these two features. Fig. 15 shows the basic structure of a HESS.

Khalilpour et al. [145, 146] have introduced an optimization algorithm for optimal screening, selection, sizing, and scheduling of multiple energy

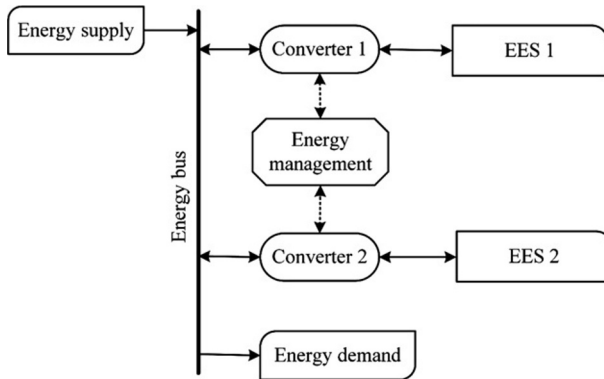


Fig. 15 Basic structure of a HESS.

storage systems along with multiple generator types for a given purpose. Generally, two complementary storage devices, one of high energy density and the other of high power density, form the HESS. The use of a unique EES system exhibiting high energy density but low power density creates problems with power control, since the response of these types of EES system is slow. In addition, a high-power supply may lessen the lifecycle of a storage system. Hence, by adding a short-storage system, the operating conditions of the main storage system are improved, prolonging its life cycle while simultaneously satisfying the power requirements. In addition, the use of a short-storage system in parallel with a long-storage one reduces the size and power losses of the main storage system [147].

Batteries, particularly lithium-ion, play a key role in many HESS-applications. They can be utilized both as “high energy” and as “high power” storage. Compared to batteries, supercapacitors and flywheels exhibit even higher power densities, efficiencies, and cycle lifetimes. For example, valve-regulated lead acid (VRLA) batteries suffer from flexibility in depth of charge and discharge. The mechanism of these batteries is based on the growth of lead sulfate crystals on the anode during discharging, and on dissolution during charging. If the battery is not fully charged and discharged then, over time, some crystals can stick to the electrode and resist dissolution. This mechanism is called *sulfation*, which reduces the life of a battery. On the other hand, a flexible battery is required to operate in various depths of charge and discharge, partial or full. To address this challenge, lead-acid batteries are integrated with supercapacitors to combine the benefits of both technologies, thus enabling a partial state of charge capability with an improved lifetime [148]. An example of such a technology is UltraBattery

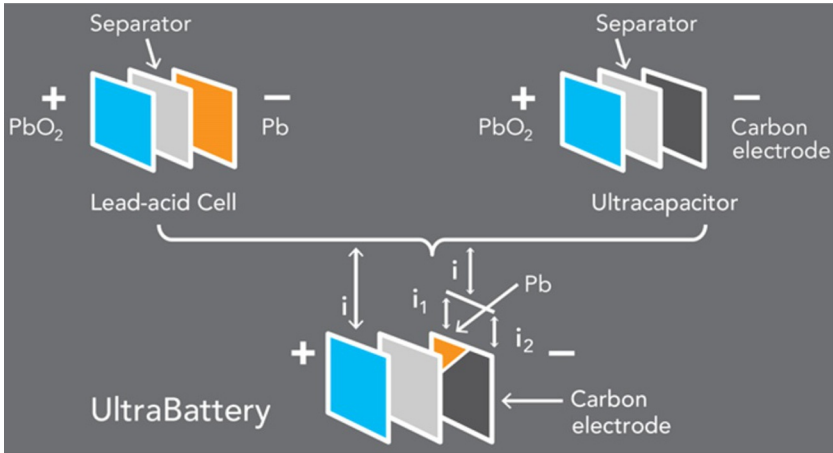


Fig. 16 Schematic of UltraBattery, a hybrid of lead-acid battery and supercapacitor [149].

[149] (see Fig. 16) with its potential use in various applications including hybrid vehicles [150].

Redox-flow batteries are also a promising technology due to their storage immanent decoupling of power and stored energy (similar to the hydrogen and power-to-gas storage path), and due to their good cycle lifetime and recyclability. Renewable hydrogen (H_2) and methane (CH_4) are both very promising options for long-term energy storage. In addition, heat storage and power-to-heat concepts will gain importance in the context of future HESS applications. The storage of heat produced from excessive renewable energy (via electric heating cartridges or heat pumps) and from power-to-gas conversion processes (for example, electrolyzers or fuel cells) will increase the overall utilization rate of renewable energies. Moreover, power-to-heat will enable HESS to perform peak shaving, and thereby significantly reduce the stress for the other storage components and for the public grid. Optimizing design, control, and energy management strategies for HESS at the interface between electricity, heat, and gas sectors will play an important role. It will unfold significant potentials for further improvements of cost, efficiency, and lifetimes of energy systems.

The shifting nature of wind and fluctuating load profiles are problematic for the operation of wind-based power systems, particularly when they operate in standalone mode. The random variation of wind speed leads to fluctuating torque of the wind turbine generator resulting in voltage and frequency excursions in the remote area power supply (RAPS) system. An ideal

ESS should be able to provide both high energy and power capacity to handle situations such as wind gusts or sudden load variations that may exist for a few seconds or even longer [151]. However, a single type of energy storage is not seen to satisfy both the power and energy requirements of the RAPS system; thus, there is a requirement to combine two or more energy storage systems to perform in a hybrid manner. In general, batteries and supercapacitors are perceived to provide high energy and power requirements, respectively. Therefore, the integration of a supercapacitor ensures a healthy operation of the battery storage by preventing it from operating in high depth of discharge (DOD) regions and allowing it to operate in low-frequency power regions (Fig. 17) [151].

Duke Energy recently installed a HESS that combines high-capacity batteries with fast-responding supercapacitors. The pilot project will provide peak demand response, load shifting, and support for a utility-owned 1.2-MW photovoltaic array [152]. Another HESS is ADELE at Saxony-Anhalt in Germany, which uses CAES and TES technologies to enhance efficiency and avoid fossil fuel consumption [9].

Zhao, Dai [153] proposed a HESS, which consists of an adiabatic compressed air energy storage system (A-CAES) and a FESS (Fig. 18). The A-CAES system is the high-power rating, high-energy rating, and slow ramp rate device. The FESS is the low-power rating, low-energy rating, and fast ramp rate device. The power generated from a windfarm is used to meet the system load. If the wind power supply exceeds the load demand, the surplus power will be divided into two branches through an energy dispatch system. One branch is stored in the FESS by accelerating the flywheel rotor via a motor. The electrical energy is converted from the kinetic energy

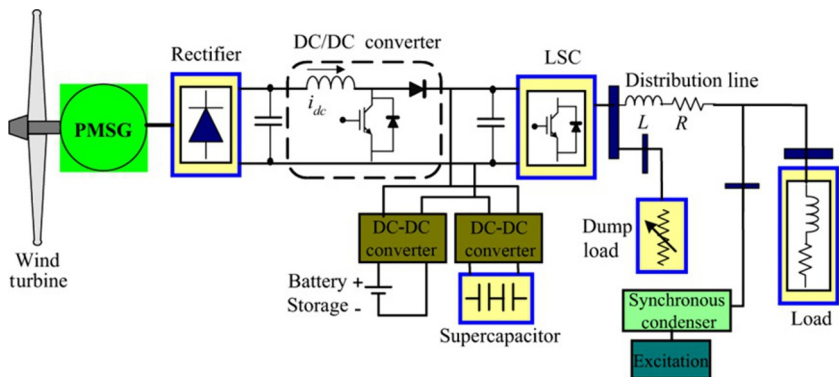
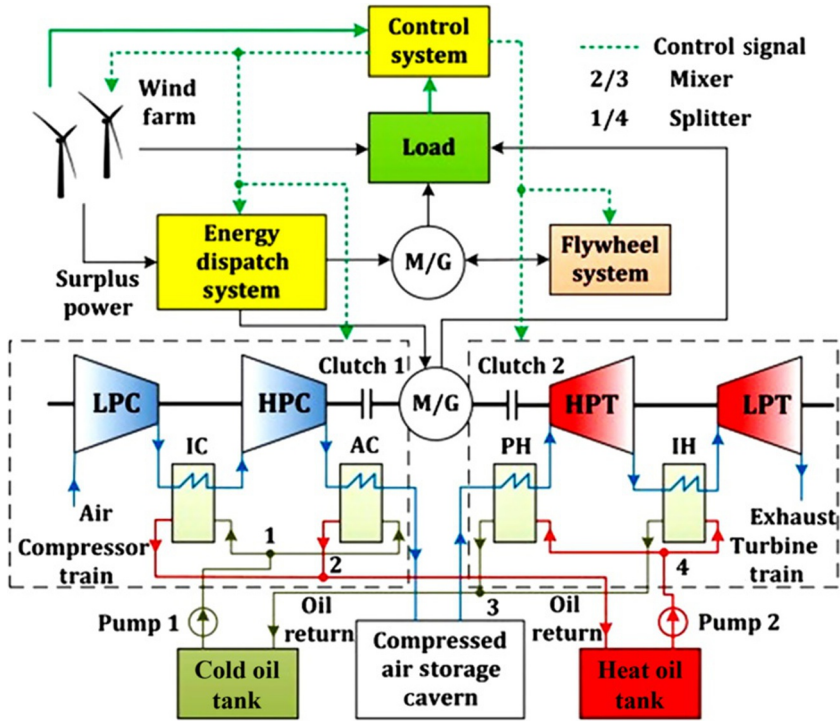


Fig. 17 Wind-based hybrid RAPS system with a hybrid energy storage [151].



C: Compressor M: Motor G: Generator LP: Low pressure HP: High pressure T: Turbine IC: Intercooler AC: Aftercooler PH: Preheater IH: Interheater
 Fig. 18 A hybrid energy storage system with A-CAES and FESS [153].

of the flywheel rotor. The other branch is stored in the A-CAES system. In this situation, clutch 1 meshes whereas clutch 2 separates. The compressor train, driven by electrical energy, compresses the air from ambient pressure to a high-pressure level, and is then stored in the compressed air storage cavern. Meanwhile, the heat released from the compression process is absorbed in the intercooler (IC) and aftercooler (AC) by the thermal oil circulatory system to store in the hot oil tank.

On the other hand, if the wind power cannot match the load demand, the hybrid energy storage system will be discharged to compensate the electricity gap. For the FESS, the flywheel rotor will drive the generator to convert its kinetic energy into electrical energy, and the speed of the flywheel rotor decreases. For the A-CAES system, the compressed air is drawn from the storage cavern, and is heated in the preheater (pH) and interheater (IH)

through heat transferring with the thermal oil from the thermal oil circulatory system. Then, the heated air is expanded in the HP turbine and LP turbine successively for converting most of the energy of compressed air into electrical energy.

As obvious from the name, the concept of the CAES technology is formed around the integration of air storage system with a gas-fired power generator. In a different approach, Khalilpour et al. [154] have further integrated the CAES system with inclusion of natural gas storage. Through this hybrid storage arrangement, a gas-power-generating plant installs both air and natural gas storage system to utilize their stored energy as well as the real economic value of natural gas following market dynamics (Fig. 19).

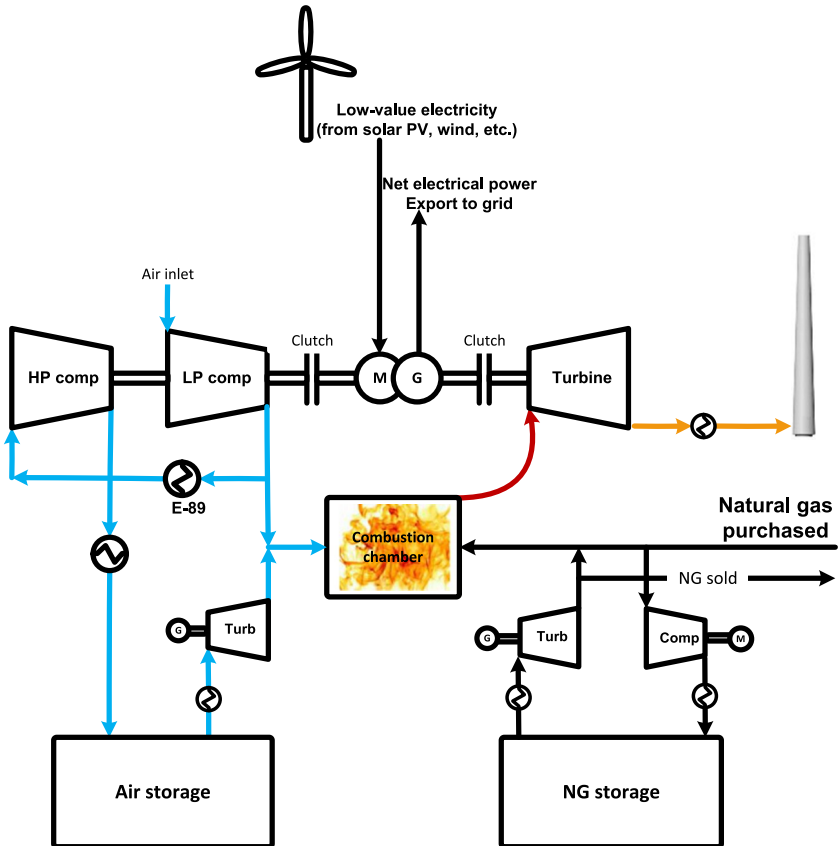


Fig. 19 Schematic of a gas-fired power plant integrated with air and natural gas storage systems [154].

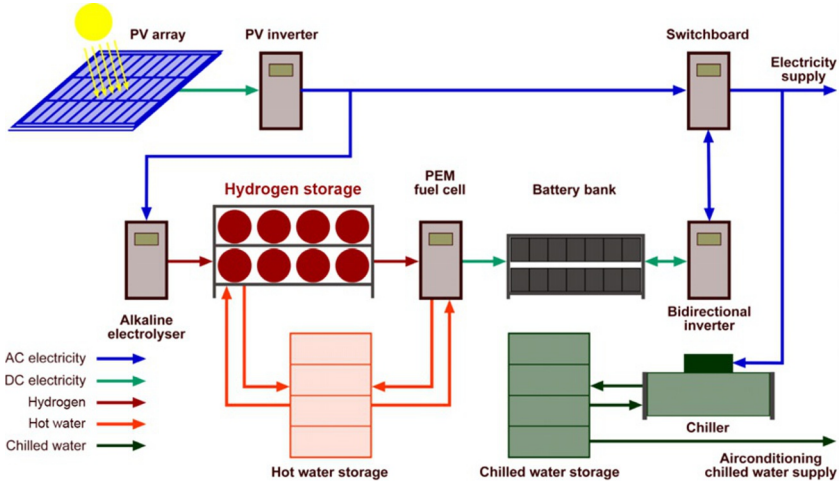


Fig. 20 Installed hydrogen-based energy system: Sir Samuel Griffith Centre, Griffith University, Brisbane, Australia [155].

A renewable and sustainable energy system based on hybrid energy storage (for example, hydrogen and Li-ion batteries) has been installed in the Sir Samuel Griffith Centre [155], Griffith University, Brisbane, Australia (Fig. 20). The goal of the system is to demonstrate an autonomous energy system, with long-term storage of energy in the form of hydrogen ensuring that the building will be operated off-grid as much as possible. The primary energy source is 330 kW of PV modules installed on the building itself. Surplus solar energy is first used to charge a bank of Li-ion batteries, with a capacity of 1.31 MWh electricity, to provide short-term energy storage. Once the batteries are fully charged, the surplus solar energy is used to generate hydrogen using alkaline water electrolyzers. Hydrogen storage is in a proprietary metal-hydride storage system with a total capacity of 120 kg H₂, equivalent to approximately 2.3 MWh electricity. Should the solar generation drop below the building requirements—that is, at night and in dull weather—then the batteries initially supply the building's energy requirements. When the batteries reach a set level of discharge, fuel cells power the building using stored hydrogen.

Recently, Toshiba Corporation installed a solar hydrogen autonomous energy system (Fig. 21) named H₂One at the Henn-na Hotel near Nagasaki, Japan [156]. The installed solar capacity is 62 kW, fuel cell output is up to 54 kW (depending on the number of installed modules), and the hydrogen storage capacity is approx. 1.3 MWh electric equivalent.

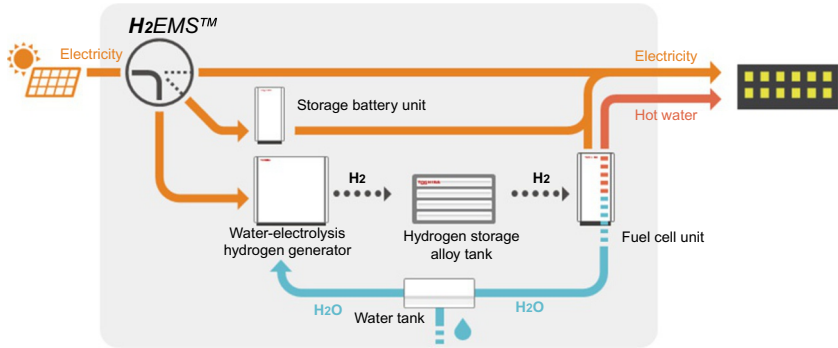


Fig. 21 Installed hydrogen-based energy system: Henn-na Hotel, at the Huis Ten Bosch theme park near Nagasaki, Kyushu, Japan [156].

8 SUMMARY AND CONCLUSIONS

This chapter gives an outline of various current state-of-the-art EES technologies. From this overview, it is apparent that existing EES technologies exhibit a wide range of technological characteristics. Hence, it might be helpful to combine different EES technologies to meet the different requirements of power system and network operations. Fig. 22 [12] illustrates a comparison of power ratings and rated energy capacities of EES technologies. From Fig. 20, EES technologies can be categorized by the nominal discharge time at rated power such as *discharge time < 1h* (flywheel, supercapacitors and SMES); *discharge time up to around 10h* (aboveground, small-scale CAES,

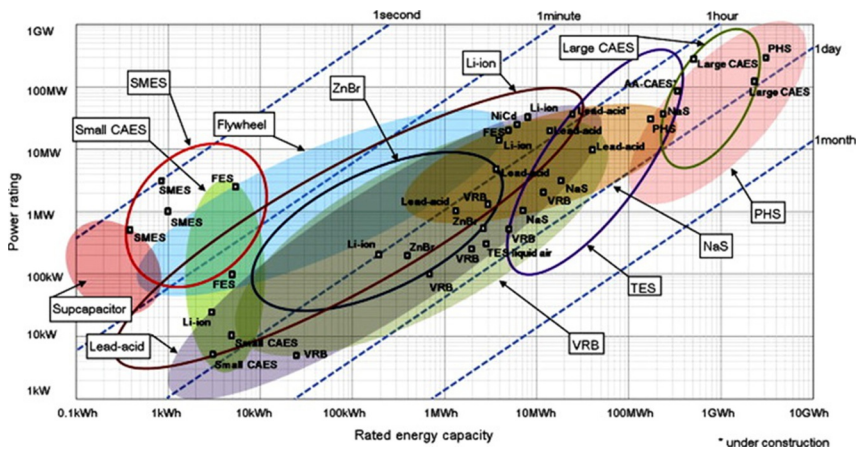


Fig. 22 Comparison between power rating and rated energy capacity with discharge times of EES technologies [12].

lead-acid, Li-ion, NiCd, ZnBr, and PSB); *discharge time longer than 10h* (PHS, underground large-scale CAES, VRB, hydrogen, and TES).

The level of self-discharge of an EES system is one of the major factors in understanding the exact storage duration. Usually, PHS, CAES, NaS batteries, flow batteries, and hydrogen have small daily self-discharge ratios, which lead to energy that can be stored in long-term duration—possibly up to months. Secondary batteries (except NaS) have daily self-discharge ratios ranging from 0.03% to 5%, which can be used for medium-term storage durations—possibly up to days. Flywheel, SMES and supercapacitors have very high daily self-charge ratios, ranging from 10% to 100%; hence, they can only be used for short-term storage durations—perhaps up to hours. TES includes a variety of technologies, and thus it may be suitable for medium-term and/or long-term storage durations.

A comprehensive economic analysis of EES technologies is necessary to optimize the system output by considering the capital cost, operation cost, maintenance cost, and the impact of the equipment lifetime. Lifetime and cycling times are two factors that affect the overall investment cost. Low lifetime and low cycling times will increase the cost of maintenance and replacement. Besides which, EES plays an important role in energy management for optimizing energy uses and decoupling the timing of generation and consumption of electric energy. Time shifting and peak shaving are typical applications in energy management; hence, dynamic power management systems need to develop power systems and network operations to maximize the availability of power and minimize outages. However, many EES-based projects have been installed globally, but the wide-ranging deployment of such kinds of power system will depend on the advancement of EES technologies and the competitive benefits brought by EES.

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