Journal of Energy Storage 27 (2020) 101047

Contents lists available at ScienceDirect

Journal of Energy Storage

journal homepage: www.elsevier.com/locate/est

A review of energy storage types, applications and recent developments

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A B S T R A C T

Energy storage technologies, including storage types, categorizations and comparisons, are critically reviewed. Most energy storage technologies are considered, including electrochemical and battery energy storage, thermal energy storage, thermochemical energy storage, flywheel energy storage, compressed air energy storage, pumped energy storage, magnetic energy storage, chemical and hydrogen energy storage. Recent research on new energy storage types as well as important advances and developments in energy storage, are also included throughout.

ATES	aquifer thermal energy storage
CAES	compressed air energy storage
EES	electrical energy storage
PCM	phase change material
PHES	pumped hydro energy storage
PV	photovoltaic
RFB	redox flow battery
SMES	superconducting magnetic energy storage
TES	thermal energy storage
UC	ultracapacitor
VRB	vanadium redox battery
ZEB	zero energy building

1. Introduction

Energy systems play a key role in harvesting energy from various sources and converting it to the energy forms required for applications in various sectors, e.g., utility, industry, building and transportation. Energy sources like fossil fuels can be used to provide energy according to customer demand, i.e. they are readily storable when not required. But other sources such as solar and wind energy need to be harvested when available and stored until needed. Applying energy storage can provide several advantages for energy systems, such as permitting increased penetration of renewable energy and better economic performance. Also, energy storage is important to electrical systems, allowing for load leveling and peak shaving, frequency regulation, damping energy oscillations, and improving power quality and reliability.

Energy storage systems have been used for centuries and undergone continual improvements to reach their present levels of development, which for many storage types is mature. Many types of energy storage systems exist, and they can be categorized in various ways. For example, storage characteristics of electrochemical energy storage types, in terms of specific energy and specific power, are often presented in a 'Ragone plot' [1], which helps identify the potentials of each storage type and contrast them for applications requiring varying energy storage capacities and on-demand energy extraction rates. The plot also aids in selecting the most appropriate energy storage for specific applications or needs (Fig. 1). Storage energy density is the energy accumulated per unit volume or mass, and power density is the energy transfer rate per unit volume or mass. When generated energy is not available for a long duration, a high energy density device that can store large amounts of energy is required. When the discharge period is short, as for devices with charge/discharge fluctuations over short periods, a high power density device is needed. Energy storage systems also can be classified based on storage period. Short-term energy storage typically involves the storage of energy for hours to days, while long-term storage refers to storage of energy from a few months to a season (3–6 months). For instance, a long term thermal energy storage retains thermal energy in the ground over the summer for use in winter. Note that only a few energy storage types are shown in Fig. 1 as the Ragone plot is traditionally used only for batteries, capacitors and fuel cells. However, others have presented this chart for/including other storage types such as thermal energy storage [2] and flywheels [3, 4] as well as combustion engines [3] for comparison purposes. In the current article, a more comprehensive comparison of specific energy and power as well as other technical details of several energy storage types are provided in Table 3 for better comparison.

Guney and Tepe [5] present a description of energy storage systems with detailed classifications, features, advantages, environmental impacts, and implementation/application possibilities. Aneke and Wang [6] provide a detailed analysis of applications and performances of various energy storage technologies. Luo et al. [7] provide an overview of various types of electrical energy storage technologies and provide a detailed comparison based on technical and economic data. Scientific

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https://doi.org/10.1016/j.est.2019.101047
Received 11 July 2019; Received in revised form 21 October 2019; Accepted 28 October 2019
Available online 07 November 2019
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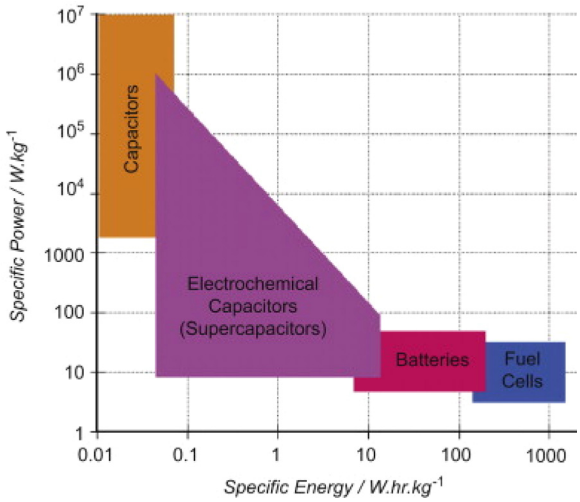

Fig. 1. Energy Storage Ragone plot (reproduced from [8]).

and engineering requirements of some storage technologies are reviewed by Hall and Bain [8], who describe the state of technologies in 2008 and anticipated developments for superconducting magnetic energy storage (SMES), flywheel energy storage and electrochemical energy storage. The previous reviews are often limited in terms of the types of energy storage covered. For example, some reviews focus only on energy storage types for a given application such as those for utility applications. Other reviews focus only on electrical energy storage systems without reporting thermal energy storage types or hydrogen energy systems and vice versa. It is important that more general reviews covering all energy storage types are performed to provide better insights on their differences, potential integration opportunities, and needed policy development. Furthermore, with the area of energy storage being very broad and numerous articles being published on them every year from technical and economical perspectives, the currency of reviews is particularly important for articles aiming to provide a review on a broad range of topics. In the current article, a broader and more recent review of each storage classification type is provided. More than 300 articles on various aspects of energy storage were considered and the most informative ones in terms of novelty of work or extent of scope have been selected and briefly reviewed. Several review articles in the literature provide a more detailed review of a single energy storage topic, such as reviews on thermal energy storage, whereas the current article aims to provide a more general review of various energy storage types to compare their characteristics. As a result, several noteworthy papers may not be included due to their high level of detail that does not serve the purpose of the current article.

This paper reviews energy storage types, focusing on operating principles and technological factors. In addition, a critical analysis of the various energy storage types is provided by reviewing and comparing the applications (Section 3) and technical and economic specifications of energy storage technologies (Section 4). Innovative energy storage advances, including new types of energy storage systems and recent developments, are covered throughout. This paper cites many articles on energy storage, selected based on factors such as level of currency, relevance and importance (as reflected by number of citations and other considerations). The manner in which the various energy storage topics are categorized in this article is summarized in Fig. 2.

2. Types of energy storage

The various types of energy storage can be divided into many categories, and here most energy storage types are categorized as electrochemical and battery energy storage, thermal energy storage, thermochemical energy storage, flywheel energy storage, compressed air energy storage, pumped energy storage, magnetic energy storage, chemical and hydrogen energy storage. Other types of energy storage such as biological energy storage are not focused on in this paper since they have not been the object of extensive research from a storage point of view. Note that the focus in the following sections is on the various energy storage types; details on technical and economical specifications as well as their applications are provided in Sections 4 and 3, respectively.

2.1. Electrochemical and battery energy storage

Electrical energy can be stored electrochemically in batteries and capacitors. Batteries are mature energy storage devices with high energy densities and high voltages. Various types exist including lithium-ion (Li-ion), sodium-sulphur (NaS), nickel-cadmium (NiCd), lead acid (Pb-acid), lead-carbon batteries, as well as zebra batteries ($Na\text{-}NiCl_2$) and flow batteries. Capacitors store and deliver energy electrochemically, and can be classified as electrostatic capacitors, electrolytic capacitors, and electrochemical capacitors. Among these three types, electrochemical capacitors, also called supercapacitors or ultracapacitors (UCs), have the greatest capacitance per unit volume due to having a porous electrode structure.

Several new electrode materials and electrolytes have been reviewed and suggested to improve the cost, energy density, power density, cycle life, and safety of batteries. Hall and Bain [8] provide a review of electrochemical energy storage technologies including flow batteries, lithium-ion batteries, sodium–sulphur and the related zebra batteries, nickel-cadmium and the related nickel-metal hydride batteries, lead acid batteries, and supercapacitors. Some of these electrochemical energy storage technologies are also reviewed by Baker [9], while performance information for supercapacitors and lithium-ion batteries are provided by Hou et al. [10]. Nitta et al. [11] review fundamental properties, opportunities, challenges, and recent progress of anode and cathode material research for lithium batteries. As strategies to improve the performance of Li-ion batteries, Nitta et al. suggest (a) reducing dimensions of active materials, (b) formation of composites, (c) doping and functionalization, (d) tuning particle morphology, (e) formation of coatings or shells around active materials, and (f) modification of the electrolyte.

Among the various battery types, lithium batteries are playing an increasingly important role in electrical energy storage because of their high specific energy (energy per unit weight) and energy density (energy per unit volume). A charged Li-air battery provides an energy source for electric vehicles rivalling that of gasoline in terms of usable energy density (Fig. 3). The fundamental battery chemistry during discharge is the electrochemical oxidation of lithium metal at the anode and the reduction of oxygen from air at the cathode. Before Li–air batteries can achieve high performance and become commercially viable, numerous technical challenges need to be addressed: designing cathode structures, optimizing electrolyte compositions and elucidating the complex chemical reactions during charge and discharge [11–13]. The most significant developments and the main limiting factors for Li–air batteries, as well as the current understanding of their chemistry, have been summarized in the literature [11, 12]. The Li-ion battery is a type of lithium battery that uses an intercalated lithium compound as an electrode material. Bruce et al. [14] examine the energy that can be stored in Li–air (based on aqueous or non-aqueous electrolytes) and lithium–sulfur (Li–S) batteries and compare it with that for Li-ion batteries, and discuss cell operation and development challenges. They suggest that both batteries offer improved energy density compared to Li-ion batteries and could also be more cost-competitive than Li-ion batteries. However, they suggest that more research on the fundamental chemistry involved in the $Li\text{–}O_2$ and Li–S cells is needed before they can reach markets. Thackeray et al. [15] provide a historical overview of lithium-ion batteries, the status of current ones, and a description of advances in lithium-air batteries. The performance of Li-ion batteries is

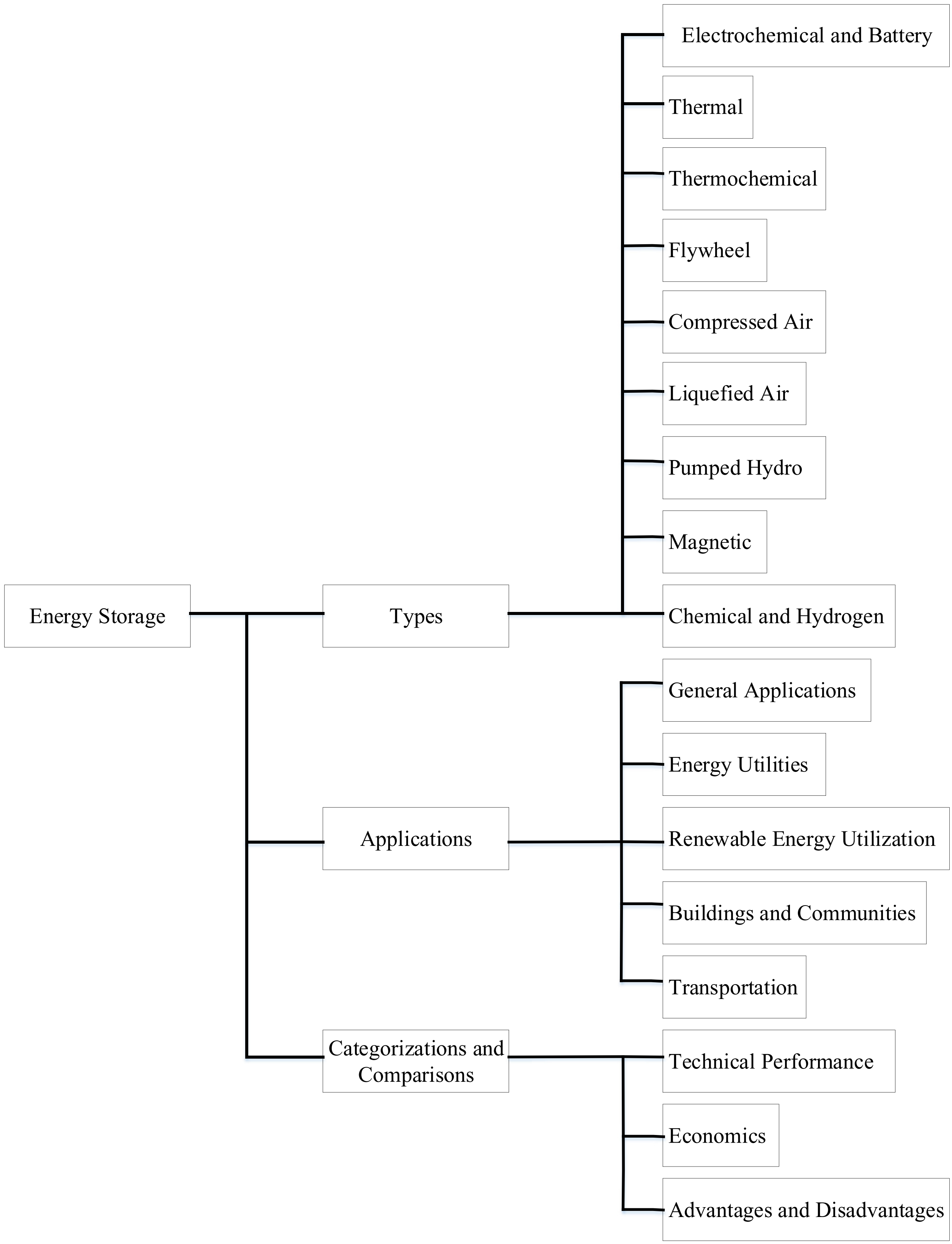

Fig. 2. Categorization of energy storage topics in the current article.

affected by the solid electrolyte interphase, a protecting layer formed on the negative electrode of the battery due to electrolyte decomposition during the first charge-discharge cycle. Factors that affect the solid electrolyte interphase and how they impact battery performance are discussed by Verma et al. [16]. Janek and Zeier [17] suggest that the energy density of conventional Li-ion batteries will soon reach a physicochemical limit and solid-state batteries that use solid electrolytes instead of liquid ones could meet the need for higher energy and power

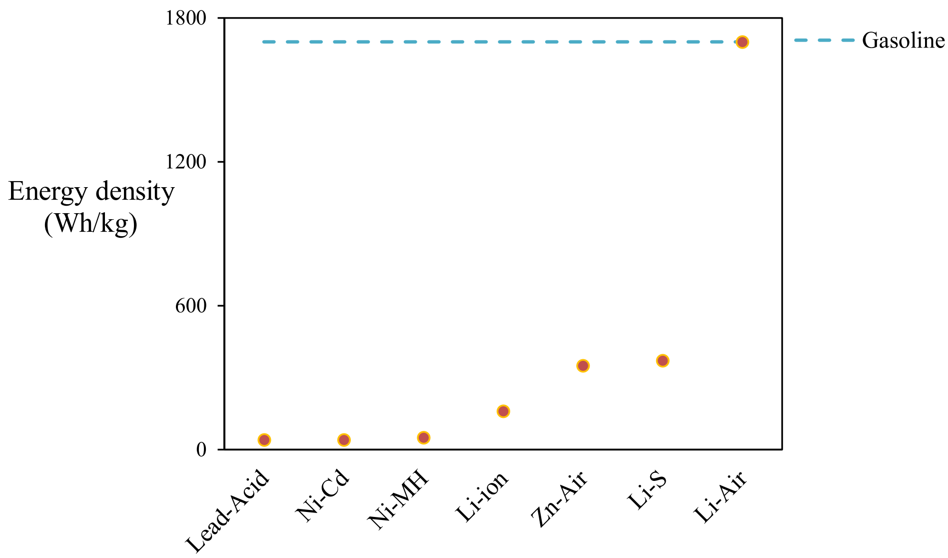

Fig. 3. Energy densities for various types of rechargeable batteries compared to gasoline (adapted from [11]). Note: NiCd: Nickel-Cadmium; Ni-MH: Nickel-metal hydride; Li-ion: Lithium-ion; Zn-Air: Zinc-air; LiS: Lithium-Sulphur; Li-Air: Lithium-air.

densities, although technical issues such as slow kinetics limit commercialization of solid-state systems.

Due to the widespread availability and low price of sodium, and the similarity of Li and Na insertion chemistries, Na-ion batteries could become the future low cost batteries for smart electric grids that integrate renewable energy sources. Much work has to be done in the Na-ion field to catch up with Li-ion technology. Cathodic and anodic materials must be optimized, and new electrolytes will be the key for Na-ion success. Palomares et al. [18] describe Na-ion battery materials, to provide a broad view of already explored systems and a platform for future research. Among the Na insertion cathodic materials, the authors suggest phosphates and fluorophosphates as promising options, but only after structural characteristics and Na insertion-extraction mechanisms are further studied and well understood. They also suggest a number of electrolytes as promising for Na-ion batteries, including sodium β”-alumina solid electrolyte and gel polymer electrolytes. Watanabe et al. [21] review various application of ionic liquids, i.e., liquids consisting entirely of ions, and focus on their use as electrolyte materials for Li/Na ion batteries, Li-sulfur batteries, and Li-oxygen batteries. They focus on the unique properties of ionic liquids such as non-volatility, high thermal stability, and high ionic conductivity and suggest that they could provide solutions to some of the current barriers to further development of batteries. Ru et al. [19] suggest aluminum-ion batteries as the most suitable candidate to replace Li-ion batteries due to their abundant resources, cost-effectiveness and eco-friendliness as well as their potential for fast charging speed and long life. Such advantages could make them suitable to support power generation from renewable energy sources. However, their energy density, cell capacity and cycle stability may still need to be improved before commercialization. Ru et al. review development challenges for such batteries, such as selection of the most suitable electrolyte and positive electrode materials; these challenges result in the batteries remaining in the conceptual stage. The authors suggest acidic $AlCl_3$-based electrolytes and transition metal oxides, metal sulfides, and carbonaceous materials for positive electrodes.

Electrochemical capacitors have high storage efficiencies ($>95\%$) and can be cycled hundreds of thousands of times without loss of energy storage capacity (Fig. 4). Energy efficiency for energy storage systems is defined as the ratio between energy delivery and input. The long life cycle of electrochemical capacitors is difficult to measure directly. Therefore, capacitance retention rate is used to estimate indirectly the cycle life by measuring and comparing the capacitance after a given number of cycles with that of the first cycle [20]. Although their efficiency and life cycle are very high, electrochemical capacitors are susceptible to self-discharge, and their operating voltages cannot exceed the potential at which the electrolyte undergoes chemical reactions. For high-voltage applications, they can be used in combination with batteries. Much research and development is focused on these energy storage options and their commercialization. Enhancing the kinetics of ion and electron transport within the electrochemical capacitor electrodes and increasing the rate of charge transfer at the interface of the electrode and the electrolyte help increase the storage capacity of electrochemical capacitors. They currently store 1–2 orders of magnitude less energy compared with batteries [21]. A recent development in electrochemical capacitor energy storage systems is the use of nanoscale research for improving energy and power densities. Kötz and Carlen [22] review fundamental principles, performance measures, characteristics, and present and future applications of electrochemical capacitors. Also, Lu et al. [23] examine recent progress in energy storage mechanisms and supercapacitor prototypes, the impacts of nanoscale research on the development of electrochemical capacitors in terms of improved capacitive performance for electrode materials, and significant advances in electrode and device configurations.

Electrochemical capacitors are classified according to the charge storage mechanism and the electrode materials used: electrochemical double-layer capacitors, pseudocapacitors and a combination of the two types. In electrochemical double-layer capacitors, the electrode material rapidly attracts solvated ions in the electrolyte which creates a double-layer acting as two capacitors, connected in series by the electrolyte, that remain charged after the circuit is opened. Since double-layer charge storage is a surface process, the electrochemically active surface area of the electrode greatly influences cell capacitance. Materials such as carbon, metal oxides, conducting polymers, hybrid and conducting polymers are used for the electrode. Various aspects of electrochemical double-layer capacitor technology including their historical background, classification, construction, modeling, testing, and voltage balancing are discussed by Sharma and Bhatti [24]. They suggest that manufacturing tolerances, the temperature gradient in the system, and cell aging are affected by unequal capacitance that is often observed within the cell series in double-layer capacitors. Voltage equalization circuits have to be employed to balance the voltage among cells. Several strategies to design the architecture of micro-supercapacitors are reviewed by Qi et al. [25]. Pseudocapacitors operate based on a Faradic charge transfer process on or near the

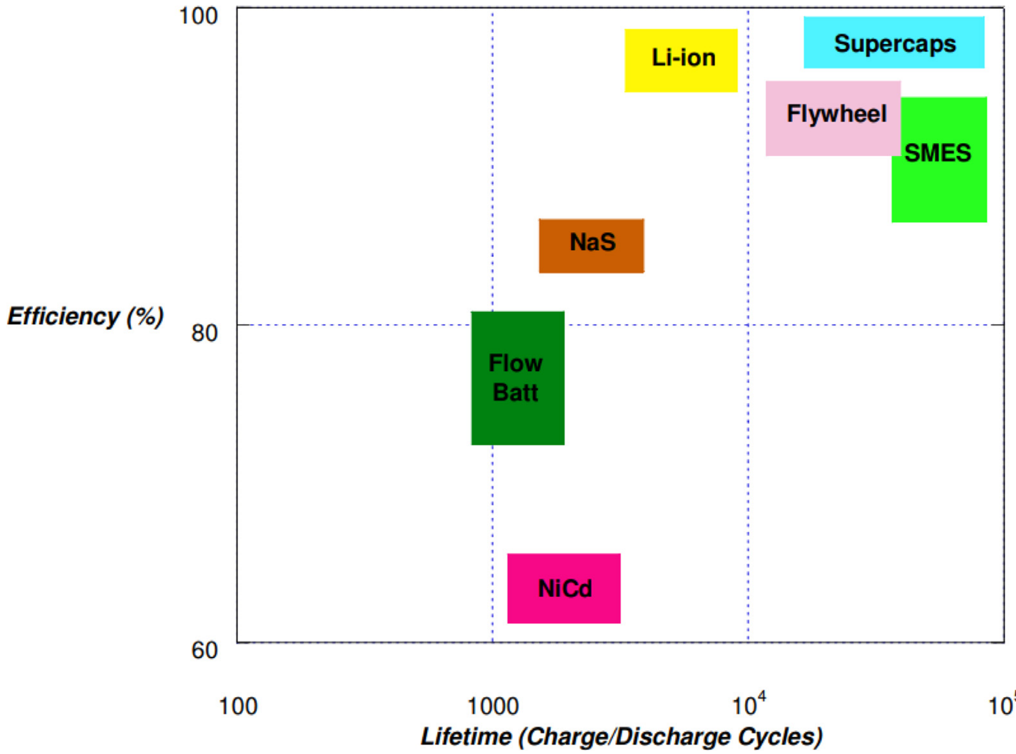

Fig. 4. Efficiency/lifetime properties of some energy storage technologies (reproduced from [8]). Note: SMES: superconducting magnetic energy storage; Li-ion: Lithium-ion battery; NaS: Sodium-Sulfur battery; Batt.: Flow battery; NiCd: Nickel-Cadmium battery.

electrode surface in which metal oxides transition. Electrically conducting polymers are often used as electrochemically active materials.

Batteries and supercapacitors are often compared for various storage applications. Batteries can store up to 30 times more charge per unit mass than supercapacitors. This high energy density is achieved by storing charge in the bulk of a material. However, supercapacitors can deliver up to thousands of times the power of a battery of the same mass as they only store energy by surface adsorption reactions of charged species on an electrode material. Electrochemical capacitors can be cycled more than batteries. The redox reactions in batteries usually produce volume changes that limit energy storage cycles in batteries. Batteries and supercapacitors are further compared by Miller and Simon [26]. Lukatskaya et al. [27] suggest that the utilization of multi-electron chemistries of both electrolyte and electrode materials can increase the amount of energy stored. They expect hybrid devices that combine the useful features of metal-ion batteries and electrochemical capacitors to provide the improved performance that is needed to meet future demands for electrical energy storage.

Solid-electrode batteries have a low energy density and can regulate wind or solar power output for only a short time. The flow battery, another type of electrochemical energy storage, can address this weakness. Flow batteries consist of two electrolyte reservoirs from which the electrolytes are circulated through an electrochemical cell comprising a cathode, an anode and a membrane separator. The energy density of such systems is mainly dependent on the stored electrolyte volume and is independent of the size and design of the electrochemical cell, which defines power density. The redox flow battery is suitable for utility-scale renewable energy storage applications. The main flow battery designs are polysulphide bromide (PSB), vanadium redox (VRB) and zinc bromide (ZnBr).

Since flow battery operation involves pump systems and flow control with external storage, its operation has increased capital and operating costs in comparison to batteries. Materials issues are a significant cause of the high costs of flow batteries, particularly those using redox-active metals and precious metal electrocatalysts. A class of energy storage materials that exploits the favourable chemical and electrochemical properties of a family of molecules known as quinones are described by Huskinson et al. [31]. This is a metal-free flow battery based on the redox chemistry that undergoes extremely rapid and reversible two-electron two-proton reduction on a glassy carbon electrode in sulphuric acid. Cycling of this quinone–bromide flow battery demonstrates a greater than 99% storage capacity retention per cycle. This flow battery may be able to provide large electrical energy storage at a greatly reduced cost.

Increasing the energy and power density of flow batteries is another challenge associated with the development of flow batteries. Developing monolithic electrodes with increased specific and volumetric surface areas, increasing electrode wetting by electrolytes and creating an open pore structure to allow increased mass transfer are some research topics for flow battery design aimed at overcoming some of these challenges. Studies on various redox flow battery (RFB) technologies focus on addressing issues regarding cell design, including cell-level components of electrolytes, electrodes, and membranes, and chemistry for both aqueous and non-aqueous systems [28, 29]. Wang et al. [30] highlight the importance of advancing the understanding of the complex charge transfer and redox reaction kinetics on the electrode surface, transport in membranes, and fluid mechanics through the electrode.

In another type of battery, the hybrid battery (HFB), features of conventional batteries and redox flow batteries are combined. One of the electrochemically active elements is stored within the electrochemical cell while the other is dissolved in the liquid electrolytes held in a tank. Novel redox flow battery concepts have been introduced including a solid oxide electrochemical cell integrated with a redox-cycle unit [32], a zinc hybrid-flow battery with a stable potential window of up to 2 V [33], hybrid membranes for VRB [34] and a trapezoid-shaped flow battery [35]. Such concepts introduce improvements in various aspects such as energy capacity, power density, cost, efficiency, self discharge time, electrolyte utilization, membrane structure stability against strong acidic and oxidizing conditions, utilization of non-toxic material, and utilization of less expensive heavy metals.

2.2. Thermal energy storage

Thermal energy storage refers to storage of heat or "cold" in a storage medium. Thermal storage systems typically consist of a storage medium and equipment for heat injection and extraction to/from the medium. The storage medium can be a naturally occurring structure or region (e.g., ground) or it can be artificially made using a container that prevents heat loss or gain from the surroundings (water tanks). There are three main thermal energy storage (TES) modes: sensible, latent and thermochemical. Traditionally, heat storage has been in the form of sensible heat, raising the temperature of a medium. Examples of such energy storage include hot water storage (hydro-accumulation), underground thermal energy storage (aquifer, borehole, cavern, ducts in soil, pit) [36], and rock filled storage (rock, pebble, gravel). Latent heat storage is a developing technology that involves changing the phase of a storage material, often between solid and liquid phases although solid-gas, liquid-gas and solid-solid phase changes are also available. Latent heat storage has attracted considerable attention recently, primarily due to the isothermal nature of the phase-change process, and its lower weight per unit of storage capacity and compactness. Its improved thermal properties compared to sensible heat storage materials, such as stable phase-change temperature and a high latent heat, are also factors that contribute to its emergence. Typical phase change materials (PCMs) used as the storage media include paraffin waxes, esters, fatty acids and salt hydrates, eutectic salts, and water [9]. PCMs are classified in Table 1.

Similar to other energy storage types, thermal energy is stored when the source of thermal energy does not provide energy at a continuous rate and/or a fixed cost. The fluctuations in thermal energy supply can occur seasonally or in shorter time periods. In seasonal energy storage, a larger energy storage system is required that is able to retain heat for its use after several months. An example is a ground heat storage system coupled to a building to store the heat that is removed from the building in the summer in the ground and use it in cooler seasons when heating is needed in the building. A similar concept can be applied by storing solar thermal energy over the summer for use in the winter. Short-term energy storage systems often have smaller capacities and retain heat for a period of a few hours to a few days. Such systems can also be used to store solar thermal energy during the day for use during cooler hours when heating is needed. In buildings where electrical heating and/cooling is used during the day, thermal energy storage systems can be used to reduce cost of electricity by storing thermal energy, produced using electricity during low-rate periods, and using it at peak times.

Research on thermal energy storage technologies is very extensive and several detailed reviews are available of various aspects of these technologies [37–41]. These include TES modes, material thermal properties, formulation and modeling approaches, thermal enhancement techniques for sensible and latent thermal storage systems and design configurations of heat storage facilities.

Research on latent heat storage is mostly focused on the development and introduction of new storage media and enhancing thermodynamic properties of the existing ones [42]. A recently investigated PCM is fatty acids derived from vegetable and animal oils [43]. Nazir et al. [44] focus on the application of various phase change materials based on their thermophysical properties such as the melting point, thermal energy storage density and thermal conductivity. They suggest that the application of PCMs in smart thermal grid systems along with intermittent renewable energy sources is promising.

Ground thermal storage is increasingly common method of sensible thermal energy storage. It often involves using a circulating medium (usually water or air) to extract heat from a building in summer and store it in the ground for winter use. Ground heat exchangers convey the circulating medium to the deeper ground. Models of ground heat exchangers and their applications are reviewed by Florides and Kalogirou [45]. Developments in using underground spaces for sensible heat storage include aquifer, borehole, cavern, pit and water tank thermal energy storages. Water tanks are suggested as the most favourable option from the thermodynamic point of view due to the high specific heat of water and their high capacity rates for energy charge and discharge [40, 46]. Aquifer thermal energy storage (ATES) systems (Fig. 5) use natural water in a saturated and permeable underground layer as the storage medium [46, 36]. Based on a country-by-country statistical analysis, Feluchaus et al. [36] identify market barriers for entering a commercialization level from the perspective of an emerging market phase, a growth phase, and a maturity phase. They suggest technical feasibility, lack of awareness and mistrust in technology some as of the barriers in the emerging market phase. As the technology moves towards the growth phase, high investment costs, policy and legislation, and lack of knowledge among national and local consultants become important barriers. In established energy markets, lower financial savings in smaller applications and a scarcity of subsurface space with an increasing number of implemented systems can be limiting factors.

Table 1
Classifications of solid-liquid phase change materials (adapted from [44] and [47]).

Type of phase change material	Operating temperatures (°C)	Compound groups	Examples
Organic	4–150	Paraffin compounds Non-paraffin compounds	Paraffin waxes Fatty acids Esters Alcohols Glycols
Inorganic	8–900	Salts Salt hydrates Metals	
Eutectic	12–600	Organic-organic Inorganic-inorganic Inorganic-organic	

2.3. Thermochemical energy storage

Thermochemical energy storage systems utilize chemical reactions that require or release thermal energy. They have three operating stages: endothermic dissociation, storage of reaction products, and exothermic reaction of the dissociated products (Fig. 7). The final step recreates the initial materials, allowing the process to be repeated. Thermochemical energy storage systems can be classified in various ways, one of which is illustrated in Fig. 6. Thermochemical energy storage systems exhibit higher storage densities than sensible and latent TES systems, making them more compact. This is a beneficial characteristic in applications where storage space is limited or expensive. Since energy losses during storage are smaller for thermochemical energy storage than for sensible or latent TES, thermochemical energy storage has good potential for long-term storage applications [48]. Thermochemical energy storage systems nonetheless face various challenges before they can achieve efficient operation. Suitable materials or combinations of materials are needed that store energy with low heat loss and release it readily when it is needed. Potential thermochemical storage materials include $MgSO_4{\bullet}7H_2O$ (for which the solid reactant is $MgSO_4$ and the working fluid is H_2O), $Ca(OH)_2$ (for which the solid reactant is CaO and the working fluid is H_2O), $CaSO_4{\bullet}2H_2O$ (for which the solid reactant is $CaSO_4$ and the working fluid is H_2O), and $FeCO_3$ (for which the solid reactant is FeO and the working fluid is CO_2). Lefevbre and Tezel [49] suggest composite materials and materials with salt impregnations as suitable for use in thermochemical storage systems. They suggest that ensuring the stability of the salt

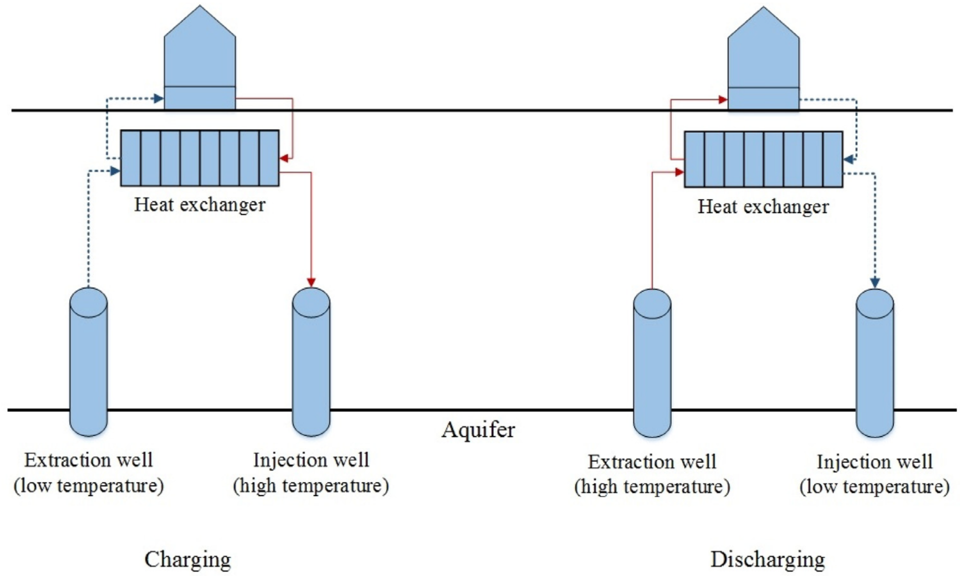

Fig. 5. Aquifer heat storage.

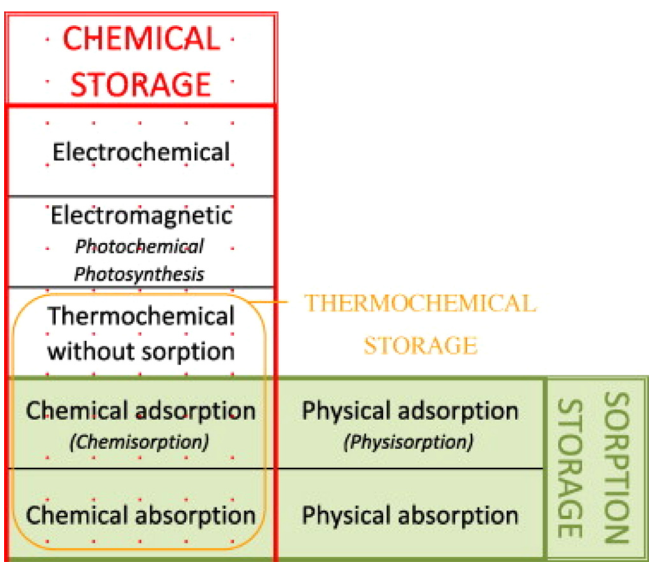

Fig. 6. Chemical storage and sorption storage classification (reproduced from [50]).

addition to the adsorbent material for repeated consistent long-term applications is one of the areas in which further research is needed.

Haji Abedin and Rosen [51] review principles of thermochemical energy storage and recent developments, and compare thermochemical storage systems with other TES systems. Due to the high cost of materials and operating problems, few long-term sorption or thermochemical energy storages are in operation. Several studies describe the physicochemical and thermodynamic properties of materials that are suitable for long-term storage of thermal energy [37, 50]. The feasibility of a solar-driven thermochemical cycle for dissociating H_2O and CO_2 using nonstoichiometric ceria (CeO_2), yielding CO and H_2, respectively, is demonstrated by Chueh et al. [52] in terms of materials, reaction rates, cyclability, reactor technology, and energy conversion efficiency.

A new technology for energy storage, based on microwave-induced CO_2 gasification of carbon materials, is proposed by Bermúdez et al. [53]. Various carbon materials are tested to examine the amount of energy consumed. Two microwave heating mechanisms, a single-mode oven and a multimode device, are evaluated to test their efficiencies in terms of energy consumption and recovery. The technology has achieved energy efficiencies of 45% at the laboratory scale, and seems improvable so that it becomes competitive with other energy storage technologies.

2.4. Flywheel energy storage

Flywheel energy storage, also known as kinetic energy storage, is a form of mechanical energy storage that is a suitable to achieve the smooth operation of machines and to provide high power and energy density. In flywheels, kinetic energy is transferred in and out of the flywheel with an electric machine acting as a motor or generator depending on the charge/discharge mode. Permanent magnet machines are commonly used for flywheels due to their high efficiencies, high power densities, and low rotor losses [54]. Other electrical machines such as induction, bearing-less and variable-reluctance machines vary in terms of limitations in application speed, idling losses, vibration, noise and cost. Charging energy is input to the rotating mass of a flywheel and stored as kinetic energy. This stored energy can be released as electric energy on demand. The rotating mass is supported by magnetic bearings which operate in a vacuum to eliminate frictional losses during long-term storage and safety issues [55]. The rotor bearing system can be mechanical or magnetic or a hybrid system of both to take advantage of the strengths of each type. The magnetic bearing has no lubrication requirements as it has no frictional loss, but it has complicated control systems and some types require energy to operate. Superconducting magnetic bearings (SMBs) are suitable for high-speed applications, but require energy to operate a cryogenic cooling system. Achieving high rotational velocity, with high power density, in flywheels is desirable since the energy stored is proportional to the square of the velocity but only linearly proportional to the mass. The key enabling technologies are in systems engineering and material science [9]. Steel, alloys (e.g., titanium or aluminum alloys) and more recently strong materials such as composites are used for the flywheel rotor and the housing that contains it. Much research is focused on rotor materials and design and speeds of up to 10,000 rpms can now be achieved [54]. The use of composite materials enables high rotational speeds with greater power densities than chemical batteries. High power density is desirable in vehicles where a large peak power is needed when accelerating and a large power becomes available for storage in a short time when braking. In addition to high energy and power density, high cycle

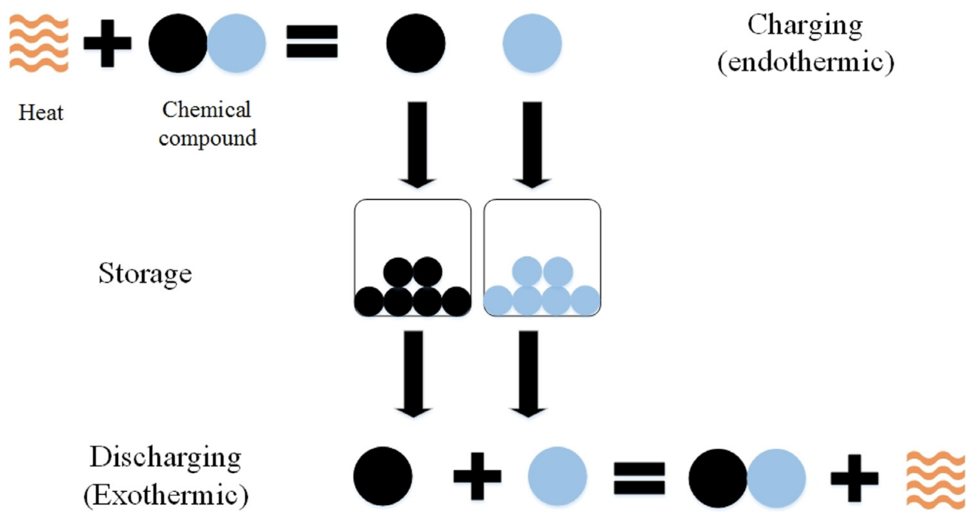

Fig. 7. Processes involved in a thermochemical energy storage cycle.

life (many tens of thousands), long operational life, high round-trip efficiency, and low environmental impacts are also attributed to flywheel energy storage systems [56]. Compared to batteries and supercapacitors, lower power density, cost, noise, maintenance effort and safety concerns are some of the disadvantages of flywheel energy storage systems [126, 127]. To improve their power density, Toodeji [127] proposes a novel design for a combined system in which supercapacitors are located inside the flywheel rotating disk. This allows exchanging pulsed power as well as storing large amounts of energy.

2.5. Compressed air energy storage

In compressed air energy storage (CAES) systems, air is compressed and stored in an underground cavern or an abandoned mine when excess energy is available. Upon energy demand, this pressurized air can be released to a turbine to generate electricity. Caverns can either be drilled in salt or rock formations, or existing cavities such as aquifer strata can be utilized. Such geological formations do not exist everywhere and large steel tanks that can maintain high pressures are sometimes installed under the ground at a higher system cost. Compressed air energy storage systems can be economically attractive due to their capacity to shift time of energy use, and more recently due to the need for balancing effects of intermittent renewable energy penetration in the grid [128]. Another option is to use available energy to store liquefied air at cryogenic temperatures in low-pressure insulated reservoirs. Compared to compressed air, liquid air has lower losses since it can be maintained at moderate pressures. Therefore, it may be a better option than compressed air for long-term storage. Liquid air also is denser and can be stored in smaller reservoirs. For a given amount of liquid air in a tank of 5000 m^3, it is shown in a case study that the CAES volume would be approximately 310,000 m^3 [129]. A comparison between compressed air and liquefied air energy storage systems indicates a higher efficiency for the latter [129].

To produce liquid air when additional energy is available, the simplest approach is based on the Linde–Hampson cycle in which a Joule-Thompson effect valve is used for expansion. Other variations of this cycle may also include cryogenic turbines for expansion (e.g., Claude and Collins cycles) which result in lower operating pressures, and higher liquid air production rates and efficiencies [130]. At discharge, liquid air is pumped to high pressure, evaporated and heated to provide high pressure air. Heat can be provided from any ambient-temperature medium such as air, but can additionally be provided from a higher-temperature medium such as gases from combustion of natural gas. Increasing the temperature of the air improves the specific work output and efficiency of the system, making it comparable to other energy storage technologies. Another option to increase the temperature is to use air directly for combustion. The air, or gas, from a liquefied container can be expanded in turbines to generate electricity.

Methods to reduce wastes of liquefaction and external energy requirements of regasification of liquefied air to improve the system efficiency have been proposed [131, 132, 135]. For example, the use of the waste cooling power from the liquid air evaporation stage in other cycles (e.g., Rankine) can generate additional work and improve the system efficiency to higher than 80% [131]. The cooled air can be used in a Brayton cycle or in a cryogenic organic Rankine cycle, as a heat sink. The waste heat that is generated when compressing the air before it is liquefied can be stored and used to reheat the air as it passes through turbines as well as to act as a heat source in a Brayton cycle. She et al. [132] propose a Brayton cycle that uses the heat from air liquefaction and releases heat to the evaporator of a liquefied natural gas storage system, thus coupling the two systems for improved efficiency. The authors show that system round-trip efficiency is approximately 70%. Peng et al. [133] suggest packed beds as direct contact heat exchangers to collect the excess heat in the compression stage of liquefaction and release it to the air in the expansion stage while discharging. Xie et al. [134] suggest that economical feasibility is unlikely for liquefied air energy storage systems without using waste heat, and that the feasibility is improved with larger plant installations.

Depending on how heat is handled during compression (i.e., heat discharge) and prior to the expansion stage (i.e., heat intake), there are three types of CAES: isothermal, diabatic and adiabatic. The thermal energy resulting from the charging compression process is dissipated in the diabatic type and needs to be provided during discharging, but is retained in a thermal storage in the adiabatic type for use during discharging. This results in lower efficiencies of diabatic CAES systems as they require a source of heat, often natural gas, to heat the compressed air before it is sent to the turbine for energy discharge. This also makes the economics of using diabatic CAES dependant on fossil fuel prices. The Huntorf gas turbine plant in Germany was the first utility-scale CAES plant and is of the diabatic type, using 1.6 kWh in terms of heating value of natural gas for every 1 kWh of electricity generation. In isothermal CAES systems, the temperature during compression and expansion is maintained close to ambient temperature, making the required power for compression the lowest that is thermodynamically possible and the generation power during expansion the highest. This makes the compression and expansion processes slow which can best be handled using piston machines. Further details on the three CAES types are described by Budt et al. [128].

Although CAES systems are mature technologies, they are still subject of studies that aim to identify how their current efficiencies

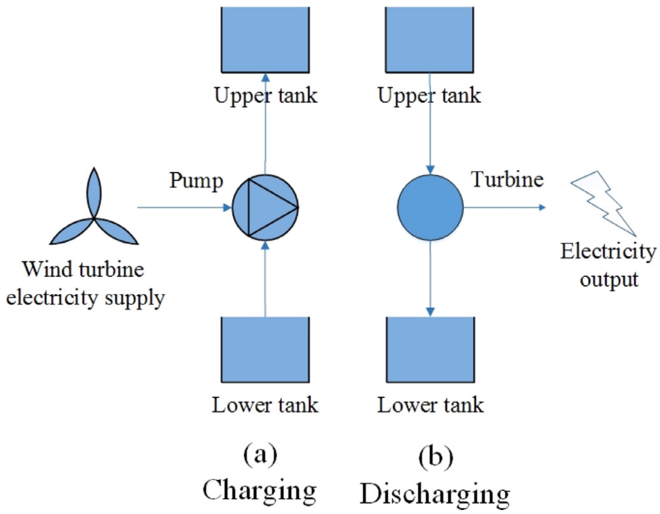

Fig. 8. Illustration of pumped hydro storage with the pumping energy supplied by wind turbines: (a) charging at off-peak hours, (b) discharging at peak hours.

(42–55%) can be improved [6, 128]. The efficiencies of a charging and discharging cycle for several adiabatic CAES configurations are analyzed using energy balances by Hartmann [57], who also examines the main factors affecting CAES efficiency. An accurate dynamic simulation model for diabatic CAES inside caverns, which involves formulating the mass and energy balances inside the storage, is developed by Raju and Khaitan [58]. A typical daily operation schedule of the Huntorf gas turbine plant and its CAES is used to validate the model. Further insights are provided by comparing the results obtained using adiabatic and isothermal assumptions inside the cavern.

2.6. Pumped energy storage

Pumped hydro energy storage (PHES) is a resource-driven facility that stores electric energy in the form of hydraulic potential energy by using an electric pump to move water from a water body at a low elevation through a pipe to a higher water reservoir (Fig. 8). The energy can be discharged by allowing the water to run through a hydro turbine from a high elevation to a lower elevation. The turbine is connected to a generator that can produce electricity as energy is discharged from the turbine. The inlet flow of water to the turbine can be controlled using gates to allow a variable power output. Variable-speed drives can also be used to provide regulation during charging. Pumped hydro energy storage systems require specific conditions such as availability of locations with a difference in elevation and access to water. If conditions are met, it is a suitable option for renewable energy storage as well as the grid. The energy efficiency of PHES systems varies between 70–80% and they are commonly sized at 1000–1500 MW [59]. Other characteristics of PHES systems are long asset life, i.e., 50 to 100 years, and low operation and maintenance costs. Some of the disadvantages of pumped hydro electricity are large unit sizes, high capital costs and topographic limitations, i.e., available elevation difference between both reservoirs, and environmental ones. Underground PHES systems are considered a technically feasible option to avoid some of these challenges by using underground reservoirs, e.g., abandoned mines [60]. Research is needed regarding methods and tools for identification and selection of feasible sites for PHES that are technically feasible, and commercially and socially acceptable [59]. Deane et al. [61] review locations and proposed timelines for new PHES development, and comprehensively review development trends. They suggest that the exploitable resources available for economically viable PHES are decreasing.

Deane et al. [61] review existing and proposed PHES plants and discuss their technical and economic drivers. To achieve greater operational flexibility and efficiencies than conventional PHES, variable speed PHES technologies and/or by-pass pump/turbine arrangements are being developed to increase the number of operation hours. Variable speed PHES technologies, while incurring slightly higher capital costs, offer a greater range of operation and efficiency than conventional PHES. At small capacities, PHES systems can vary design pumping capacity from 60% to full capacity and generation capacity from 20% to full capacity [62]. While single machines may be limited in efficiency when capacity is varied, options to use multiple machines in various configurations have also been explored. For example, various dynamic-response by-pass arrangements are analyzed by Beevers et al. [62] and their capacity flexibility and efficiency are compared. Various control strategies corresponding to different levels for variable speed operation of PHESs have also been developed [63]. The fast power response of variable-speed PHES systems was proved in a comparison that is made between the variable- and constant-speed PHES systems for wind power regulation [64]. The results are compared based on average and standard deviation of power difference between the two cases, penalty energy and power delay, and show improvements up to one order of magnitude in the variable-speed PHES case compared to the constant-speed case. The use of power converters also provides a quick response (i.e., within 2 s) in both pumping and generation modes of PHES systems, compared to the mechanically controlled, fixed speed system, allowing their application in micro-grids. To investigate the ability of power converters and controllers for the provision of stability within a PHES system and grid in several modes of operation as observed in practice, a prototyping environment is developed [65].

Yang and Jackson [66] review the historical development of pumped-hydro energy storage facilities in the United States, including new development activities and approaches in PHES technologies. To mitigate environmental issues of PHES systems, developers are proposing innovative ways of addressing the environmental impacts, including the potential use of waste water in PHES applications. With the increasing need for energy storage, these new methods can lead to increased use of PHES in coupling intermittent renewable energy sources such as wind and solar power.

New PHES designs are addressing the major challenges associated with conventional PHES. Vasel-Be-Hagh et al. [67] introduce a new design, which does not require tall water tank towers or long piping, and has scalable operation over a wide range of capacities depending on the electrical surpluses. The design provides constant-pressure and faster discharge, permitting quick response to instantaneous demand fluctuations.

2.7. Magnetic energy storage

Superconducting magnetic energy storage (SMES) can be accomplished using a large superconducting coil which has almost no electrical resistance near absolute zero temperature and is capable of storing electric energy in the magnetic field generated by dc current flowing through it. The superconducting coil is kept at a cryogenic temperature by using liquid helium or nitrogen vessels. Some energy losses are associated with the cooling system that maintains the cryogenic temperature, but energy losses in the coil are almost zero because superconductors offer no resistance to electron flow. SMES coils can discharge large amounts of power almost instantaneously, and can undergo an unlimited number of charging and discharging cycles at high efficiency. Coil configuration, energy capability, structure and operating temperature are some of the main parameters in SMES design that affect storage performance. Low temperature superconductor devices are currently available while high temperature ones are still in development due to their high costs. SMES applications include load leveling, system stability, voltage stability, frequency regulation, transmission capability enhancement, power quality improvement, automatic generation control, and uninterruptible power supplies. Configurations of thyristor-based, voltage-source-converter-based, and current-source-converter-based SMES are reviewed by Hassan Ali et al. [68]. They suggest categorizing the cost of SMES technologies based on the cost of the energy storage capacity (i.e., costs of conductor, coil structure components, cryogenic vessel, refrigeration, protection, and control equipment) and the cost of power handling capability. They suggest a wide cost variation exists in the latter, and that focussing research on it could considerably reduce the overall SMES cost. Sutanto and Cheng [69] review SMES systems for power systems. They emphasize the importance of the development of practical applications of SMES for power systems as opposed to several studies performed through computer simulations or in laboratories. They also suggest the development of efficient control strategies is needed to integrate small ratings of SMES systems at various locations to improve their power capacities.

2.8. Chemical and hydrogen energy storage

A reversible chemical reaction that consumes a large amount of energy may be considered for storing energy. Chemical energy storage systems are sometimes classified according to the energy they consume, e.g., as electrochemical energy storage when they consume electrical energy, and as thermochemical energy storage when they consume thermal energy.

In hydrogen energy storage, hydrogen is produced via direct (e.g., photoconversion) or electrolytic methods, stored for a period of time, and then oxidized or otherwise chemically reacted to recover the input energy (Fig. 9). The hydrogen results from a chemical reaction, but is not the source of energy. For many decades, electricity has been a primary energy carrier for many of society's energy technologies. Hydrogen energy exhibits characteristics complementary to those of electricity. Some have proposed a “hydrogen economy” involving all aspects of hydrogen energy systems, including production, storage, distribution and utilization [70]. Winter [71] describes the hydrogen economy, its environmental and climatic relevance, its positive influence on the energy quality of the system, its effect on decarbonizing fossil fueled power plants, and the novel non-heat-engine-related electrochemical energy converter fuel cell in portable electronics, in stationary and mobile applications. In this section, processes in which energy is stored by producing hydrogen and hydrogen storage techniques are both described.

One common method of hydrogen production is by splitting water. The energy required for this process can be provided from fossil fuels and renewable or other energy sources. Energy from renewable sources is often intermittent and needs to be stored before it is needed. Abbasi and Abbasi [72] discuss the production of hydrogen from solar energy with the following processes: (i) a combination of a solar cell with an electrolyser, (ii) a combination of a concentrated solar thermal system with a turbine and an electrolyser, (iii) a combination of a solar concentrating system with a thermochemical water-splitting cycle, and (iv) direct photoconversion (photocatalytic, photoelectrochemical, photobiological water splitting). Production of hydrogen from other renewable sources such as wind, hydroelectric, geothermal, ocean thermal energy conversion, anaerobic digestion of biomass and biowastes are also discussed in this work [72]. Since photosynthetic and photovoltaic processes harvest the energy in sunlight, they are sometimes compared. But the two processes operate differently and produce different products: biomass or chemical fuels in the case of natural photosynthesis and non-stored electrical current in the case of photovoltaics. Blankenship et al. [73] compare natural photosynthesis to present technologies for photovoltaic-driven electrolysis of water to produce hydrogen, and show photovoltaic-driven electrolysis is more efficient on an annual basis. Ways in which new developments in synthetic biology may be used to improve solar energy conversion efficiency of natural photosynthesis are discussed.

The storage of hydrogen is a substantial challenge, especially for automotive applications. Hydrogen has a low energy density on a volume basis compared to the other fuels, requiring a much larger fuel tank for a vehicle operating on hydrogen rather than petrol/diesel. Furthermore, hydrogen is the lightest of all elements and harder to liquefy than methane and propane. Due to its low density and also its small molecular size, it can leak from containment vessels. Hydrogen can be stored in its pure form as a compressed gas or as a cryogenic liquid or in a mixed-phase (hydrogen slush). Liquefaction of hydrogen and pressurization of a cryogenic liquid in order to achieve higher density in a liquid or mixed-phase state both require a large amount of energy and specialized infrastructure. In adsorptive storage, hydrogen is absorbed to and released from porous networks such as zeolites, metal – organic frameworks, clathrate hydrates, various carbon materials (e.g., nanotubes, fullerenes and graphene), and conventional organic polymers. This process can occur for several cycles without decomposition of the solid or loss of gas. In chemical storage, hydrogen is stored in chemical bonds with other elements in a hydrogen-rich material, in solid or liquid phases. Solid-phase systems include metal and non-metal hydrides, amines, amides, and ammonia-like complexes. Liquid carriers include N-ethylperhydrocarbazole, alcohols and formic acid. Details of specific storage types are compared by Pruestre et al. [74]. Lamb et al. [75] explore materials and technologies for hydrogen purification from decomposed ammonia gas streams, and suggest that energy-efficient decomposition of ammonia and subsequent separation and purification of the hydrogen product are two key challenges in using ammonia as a hydrogen storage intermediate. They show that defect-free dense-metal membranes can achieve satisfactory product purity. Various aspects of hydrogen storage methods have been reviewed [76–78]. These include various hydrogen storage methods, including high-pressure [78] and cryogenic-liquid storage, adsorptive storage on high-surface-area adsorbents, chemical storage in metal hydrides and complex hydrides and intermetallic compounds [79], and storage in boranes. Hosseini et al. [78] thermodynamically model the filling phase of compressed hydrogen storage and analyze it based on the second law of thermodynamics.

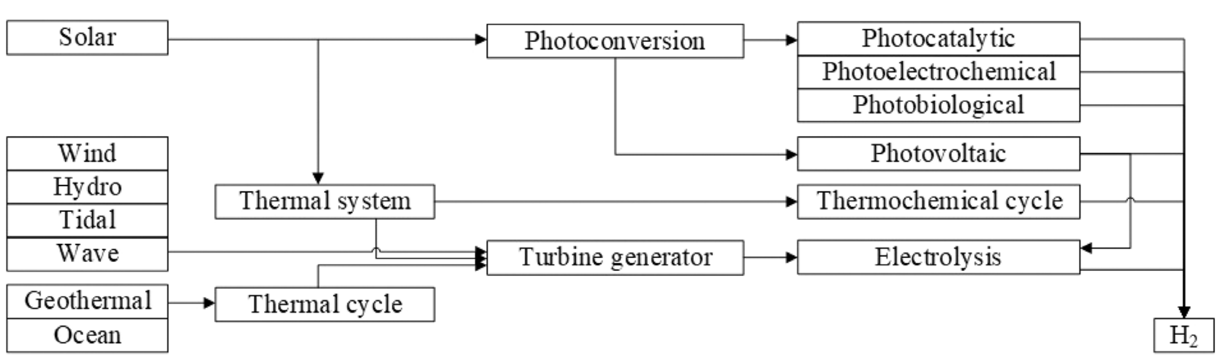

Fig. 9. Production of hydrogen using renewable energy sources (adapted from [72]).

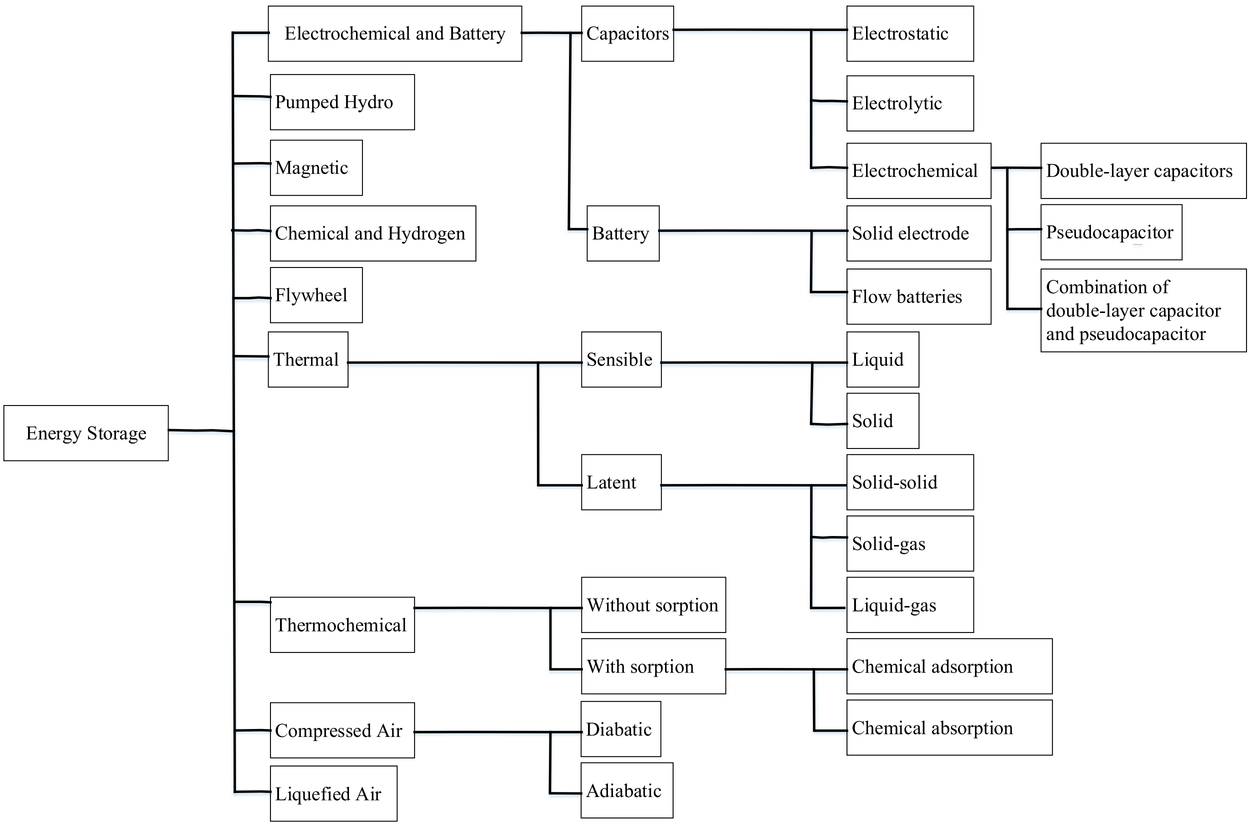

Fig. 10. A classification of energy storage types.

Fuel cells are low power-density devices like batteries that convert chemical energy to electricity. They exhibit energy efficiencies of approximately 70–80%, while some power plants (e.g., combined cycle units) can achieve efficiencies as high as 60%. Fuel cells use oxygen and a fuel such as hydrogen. They can be combined with supercapacitors to improve their power densities. Research to exploit unique features of graphene to produce supported catalysts with enhanced electrocatalytic activity, increased durability, and high performance electrode architectures in fuel cells is discussed by Hou et al. [10].

In summary, the energy storage types covered in this section are presented in Fig. 10. Note that other categorizations of energy storage types have also been used such as electrical energy storage vs thermal energy storage, and chemical vs mechanical energy storage types, including pumped hydro, flywheel and compressed air energy storage.

3. Applications of energy storage

Energy storage is an enabling technology for various applications such as power peak shaving, renewable energy utilization, enhanced building energy systems, and advanced transportation. Energy storage systems can be categorized according to application. Hybrid energy storage (combining two or more energy storage types) is sometimes used, usually when no single energy storage technology can satisfy all application requirements effectively. Storage mass is often an important parameter in applications due to weight and cost limitations, while storage volume is important when the system is in a space-restricted or costly area such as an urban core. Energy storage applications are continuously expanding, often necessitating the design of versatile energy storage and energy source systems with a wide range of energy and power densities. In this section, we focus on various applications of energy storage such as utilities, renewable energy utilization, buildings and communities and transportation. Table 2 provides examples of energy storage systems currently in operation or under construction and includes some of the features of such storage systems.

3.1. General applications

Some energy storage systems find broad and general applications. For instance, the fact that PCMs melt and solidify at a wide range of temperatures makes them attractive in numerous applications, including solar water heating, solar air heating, solar cooking, solar greenhouses, space heating and cooling in buildings, off-peak electricity storage, and waste heat recovery [47, 44]. Also, applications of flywheels, as discussed by Liu and Jiang [92], include uses in the International Space Station, Low Earth Orbits in earth observation missions, overall efficiency improvement and pulse power transfer for hybrid electric vehicles, and power quality assurance. Finally, asphalt concrete pavements have been considered for use as solar heat collectors and storage systems by Hall et al. [93]. Asphalt concrete pavements that incorporate aggregates and additives (e.g. limestone, quartzite, lightweight aggregate, copper slag, and copper fibre) are designed to become more conductive, or more insulating, or to store more thermal energy.

3.2. Energy utilities

The use of energy storage systems in utility networks has become increasingly important and focused on as more storage options become available. Energy storage deployed at any of the five major subsystems in the electric power systems, i.e., generation, transmission, substations, distribution, and final consumers, can help balance customer demand and generation. Intermittent power generation, such as that provided by many renewable energy sources, results in power instability which can damage grid equipment such as generators and motors. By combining renewable energy systems with energy storage technology, renewable energy penetration is increased and overall

Table 2
Examples of current energy storage systems in operation or under development.

Storage type	Example	Power capacity/ duration	Application	System specifications
Pumped hydro	Bath County Pumped Storage Station, US	3003 MW/10 h 18 min	Electric energy time shift	Consists of two large reservoirs with 385 m difference in height, a power house and the tunnels that connect them. At high demand, water is passed through the tunnel at a rate of up to 852 m^3/s to drive six generators [80].
	La Muela Pumped-Storage Plant, Spain	2000 MW	Renewable energy capacity firming	Provides 5000 GWh of energy storage.
Compressed air	Huntorf, Germany	290 MW/2 h	Arbitrage Spinning reserve Black start applications	Uses two cylindrical 150,000-m^3 salt caverns at a depth of 600–800 m. Pressure tolerance is 50–70 bar. With 42% efficiency [81], it uses 0.8 kWh electricity and 1.6 kWh in natural gas heating value for every 1 kWh of electricity generation.
	McIntosh, US	110 MW/26 h	Refine base-load electricity from a nuclear power plant, producing peak load electricity	Uses two cylindrical 538,000-m^3 salt caverns at depth of 450–750 m. Pressure tolerance is 45–76 bar [82]. Uses heat from turbine exhaust gases to preheat compressed air. With 54% efficiency [81], it uses 0.69 kWh electricity and 1.17 kWh in natural gas heating value for every 1 kWh of electricity generation.
Thermal	Planta Solar 20, Spain	20 MW/1 h	Renewable energy time shift Renewable energy capacity firming	Integrated with solar field of 210-acre containing 1255 heliostats. Provides 48 GWh of stored energy per year [83].
Thermal, molten salt	Solana Solar Generating Plant, US	280 MW/6 h	Renewable energy time shift Renewable energy capacity firming	Integrated with a parabolic-trough solar plant. Provides 944 GWh of stored energy per year [83].
Thermal, ice	University of Arizona, US	3 MW/6 h	Electricity use time shift	Utilizes nighttime-produced electricity to generate and store daytime cooling. Comprised of a total of 205 ice storage tanks [84].
Thermal, chilled water	University of Nebraska-Lincoln, US	100 MW/6.24 h	Electricity use time shift	A chilled water storage tank of 2.8 MG provides 314 MWh of cooling capacity at a maximum chilled water flow rate of 0.5 m^3/s [85, 86].
Flywheel	Hazle, Pennsylvania, US	20 MW/15 min	Frequency regulation Increase renewable energy use (wind and solar)	Plant comprises 200 flywheels rated at 0.1 MW and 25 kWh [87]. Flywheel spins at a rate of up to 15,500 rpm. Flywheels are able to operate at more than 100,000 full charge/discharge cycles.
	Railway Technical Research Institute (RTRI), Japan	0.3 MW/20 min	Increase renewable energy use (solar)	Uses superconducting magnetic rotor and bearing, the rotor being 2 m in diameter and weighing 4 tons [88].
Supercapacitor	Endesa STORE, Spain	4 MW/5 s	Frequency regulation [85]	
Battery, Li-ion	Endesa STORE, Spain	1 MW/3 h	Frequency regulation [85]	
Battery, lead acid	Kaheawa Wind Power Project II, US	10 MW/45 min	Frequency regulation [85] Ramping Renewable energy time shift Renewable energy capacity firming	Integrated with a 21 MW wind power plant.
Battery, Vanadium Redox flow	Hokkaido Electric Power, Japan	15 MW/4 hr	Renewable energy capacity firming [89]	
Chemical, hydrogen	140-MW wind Park, Germany	1 MW/27 hr	Renewable energy time shift	Can produce 210 Nm^3/hr of hydrogen. It is connected to a 140 MW wind farm [90].
Gravitational[1]	Advanced Rail Energy Storage, US	50 MW/15 min	Frequency regulation Electric supply reserve capacity Voltage support	Has an efficiency of 86% and ramps to full power in seconds [91].

[1] Utilizes a single uphill track with a central queue of loaded shuttle-trains that travel up and down grade in response to an independent system operator command to provide frequency adjustment.

system performance improves, while flexibility is provided for grid control and maintenance. Some of the applications of energy storage systems include [94]:

- reduction of congestion in the transmission system,
- storing energy during periods of low demand for use during periods of high demand,
- maintaining voltage and frequency within normal operating ranges,
- compensating for unexpected contingencies such as failure of a generating unit, and
- maintaining a real-time balance between generation and load.

Electricity can be stored in electric fields (capacitors) and magnetic fields (SMES), and via chemical reactions (batteries) and electric energy transfer to mechanical (flywheel) or potential (pumped energy storage) energy or pressure (compressed air energy storage) energy forms. Pumped energy storage has been the main storage technique for large-scale electrical energy storage (EES). Battery and electrochemical energy storage types are the more recently developed methods of storing electricity at times of low demand. Battery energy storage developments have mostly focused on transportation systems and smaller systems for portable power or intermittent backup power, although system size and volume are less critical for grid storage than portable or transportation applications. Future utility applications of batteries could be focused on providing peak distribution capacity deferral and peak shaving at the substation as well as reliability enhancement [95]. Research into reliable battery storage at the grid scale is focused on durability for large numbers of charge/discharge cycles and lifetime, high round-trip efficiency, ability to respond rapidly to changes in load or input, and reasonable capital costs.

Koohi-Kamali et al. [96] review various applications of electrical energy storage technologies in power systems that incorporate renewable energy, and discuss the roles of energy storage in power systems, which include increasing renewable energy penetration, load leveling, frequency regulation, providing operating reserve, and improving micro-intelligent power grids. Flywheel storage, electrochemical storage, pumped hydroelectric storage, and compressed air storage, as well as their operating principles and applications, are described. Vazquez et al. [97] review the main applications and the power converters used to operate some energy storage technologies, and describe various storage technologies, including batteries, electrochemical double-layer capacitors, regenerative fuels cells, CAES, flywheel, SMES, and thermoelectric energy storage, and their applications. Roberts and Sandberg [98] review new types of storage being utilized for grid support, and emphasize the growing importance of energy storage systems in smart grids with more dynamic loads and sources. Yang et al. [99] examine electrochemical storage technologies used in grids, such as redox flow batteries, Na-beta alumina membrane batteries, unique Li-ion chemistries, and lead-carbon technologies, and the needs to reduce costs and improve performance for these technologies to increase their market penetration. Dunn et al. [100] review sodium-sulfur batteries, redox-flow batteries and lithium-ion batteries for use in the grid and their potentials. Xue et al. [69] describe applications of SMES in improving power quality and system stability. Mousavi et al. [54] highlight the potential of flywheel energy storage systems compared to other energy storage technologies for power leveling, grid frequency support/control, and voltage sag mitigation based on their fast recharge time and high power density. Khodadoost et al. [101] suggest that future developments in increasing flywheel energy density and investigating the feasibility of its modular application, will improve the power system stability.

3.3. Renewable energy utilization

Renewable energy use is growing rapidly, helping provide electricity to satisfy the world's demand and mitigate environmental impacts, especially related to the electricity sector. However, the variability of these resources creates technical and economic challenges for their operation and use when integrated on a large scale. An important means of addressing the intermittency of renewable energy sources is energy storage. A higher penetration of renewable energy generation is typically achieved with storage, as it permits excess energy produced from renewable energy sources to be stored and dispatched later when needed. In addition to intermittency of renewable energy sources, storages are also distributed. Beaudin et al. [102] suggest that energy storage technologies that are scalable, modular, durable, and low maintenance may be suitable options for distributed renewable energy harvesting. Such technologies include flywheels, capacitors, SMES and most batteries (excluding lead-acid batteries).

Beaudin et al. [102] review the technology status and installations for a broad range of EES, focusing on advantages and disadvantages for integrating large-scale, variable renewable electricity sources, and discusses external factors affecting numerous EES applications, such as mineral availability and geographic limitations. The article indicates that addressing each challenge imposed by variable renewable electricity sources requires a different set of EES characteristics, and that no single EES technology consistently outperforms all others in all applications.

Technologies that couple a solar energy source with energy storage are discussed and/or reviewed by many researchers [20, 23, 105]. Examples include solar stills and solar dryers, which are used in drying agricultural food products [58–59]. Arjunan et al. [103] experimentally investigate various storage materials, such as black granite gravels, pebbles, blue metal stone, and paraffin wax, to examine the productivity of storing excess heat in solar stills during the day and releasing the stored heat to the basin at night. Agrawal and Sarviya [104] also review the use of various thermal storage materials in solar air heaters and dryers (e.g., rock, water, sand and granite, metal scrap, pure paraffin wax, and a mixture of aluminium power and paraffin wax). Due to their high heat storage capacity per unit volume, paraffin and salt hydrates have received considerable attention as storage materials for solar air dryers and heaters. Another way to store solar energy is to convert it directly into chemical fuels by methods such as photon-driven electrolysis of water to produce hydrogen and oxygen. Research on new metal oxide visible light-absorbing semiconductors could help improve this technology. Osterloh and Parkinson [106] review developments of semiconductor light absorbers and co-catalysts. They emphasize the importance of low cost and material stability of photoactive materials against photocorrosion to allow system technical and financial feasibility.

Díaz-González et al. [107] review several energy storage technologies for wind power applications, including gravitational potential energy with water reservoirs, compressed air, electrochemical energy in batteries and flow batteries, chemical energy in fuel cells, kinetic energy in flywheels, magnetic fields in inductors, and electric fields in capacitors. Mousavi et al. [54] suggest flywheel energy storage systems as the best systems for wind energy storage due to their quick response times and favorable dynamics. They provide several examples of wind-flywheel pairing studies and their control strategies to achieve smooth power control. Khodadoost et al. [101] suggest that flywheels are favorable options for integration with wind and PV systems compared to battery energy storage systems since variations in their output power occur in a short period of time.

Although the use of compressed air energy storage (CAES) has for some time been for grid management applications such as load shifting and regulation, CAES is expected to increase flexibility when integrating renewable energy sources such as wind, solar and tidal with the power grid. Succar and Williams [108] review CAES systems that are combined with wind turbines to produce electricity, including technical and geologic requirements for widespread CAES deployment and paying attention to relevant geologies in wind-rich regions of North America. Konrad et al. [109] investigate factors that affect site selection

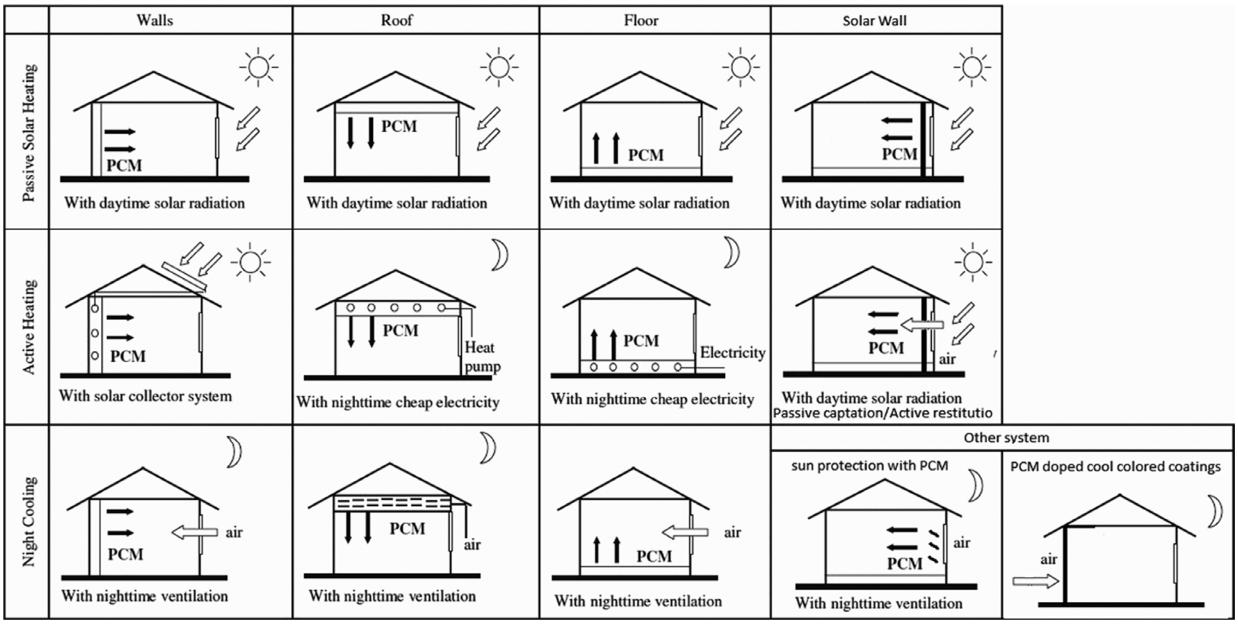

Fig. 11. Forms and effect of PCM applications in building (reproduced from [115]).

and planning of CAES facilities to assist in renewable energy harvesting in Ontario, Canada. The authors provide details of the groundwork needed for the feasibility study and identify and characterize influences such as mechanics of the ground rock and locations of renewable energy resources.

Rehman et al. [59] review several PHES hybrid systems such as wind-hydro, solar PV-hydro, and wind-PV-hydro. The importance, necessity and contribution of wind-hydro pumped storage systems in meeting Turkey's electric energy demand as well as the current status and potential of using pumped hydro in wind energy applications in Turkey are investigated by Dursun and Alboyaci [110]. They found that, in generating systems with limited flexibility, the application of PHES for providing standing reserve could significantly reduce the amount of wind curtailed and reduce the amount of energy produced by a conventional plant.

A question that arises when integrating energy storage with renewable energy systems is what configuration provides the most technically and economically viable method to supply electricity in stand-alone systems. To address this, Askari and Ameri [111] perform a feasibility analysis of renewable energy systems for supplying the electrical load requirements of a typical community in a remote location in Kerman, Iran, considering various combinations of PV modules and wind energy conversion systems supplemented with battery storage (e.g., photovoltaic/battery, wind/battery and hybrid photovoltaic/wind/battery). The assessment criterion is taken to be the total net present cost of each system configuration, and the results show that, because of the sudden decreases in wind speeds in Kerman, the total net present cost of the wind/battery and hybrid renewable energy systems is increased, making the PV/battery system the most advantageous for supplying the electrical load requirements.

Energy and exergy analyses are used to assess a hybrid solar hydrogen system with activated carbon storage for residential power generation in a novel study by Hacatoglu et al. [112]. Exergy flows and efficiencies are calculated for individual devices and the overall system, and show that solar photovoltaic-based sub-systems have the lowest exergy efficiencies and significant potential for improvement.

3.4. Buildings and communities

As research aimed at nearing or achieving net-zero energy buildings and communities intensifies, governments are promoting the adoption of renewable energy sources in buildings in the commercial, institutional, industrial and residential sectors. Energy storage is recognized as an important way to facilitate the integration of renewable energy into buildings (on the generation side), and as a buffer that permits the user-demand variability in buildings to be satisfied (on the demand side). Pero et al. [113] suggest a number of key performance indicators to facilitate the comparison of various storage technologies in the decision-making/design phase and the assessment of technical solutions. The indicators include storage capacity, maximum charge and discharge power, depth of charge, durability, specific cost of storage, maximum self discharge rate, storage weight, and generated energy/cost savings.

Thermal energy storage is a relatively common storage technology for buildings and communities and extensive research is available on storage materials and their classifications, recent developments, thermal storage usage conditions and performance, limitations and possible improvements for buildings uses [37, 47, 114, 116–120]. Buildings and communities can benefit from short-term (up to a few days) and long-term (up to a few months) storage. For example, thermal energy storage is capable of shifting electrical loads from peak to off-peak hours, providing a powerful tool in demand-side management programs [114]. Although this technology is a relatively mature type of energy storage, research and development is ongoing to overcome technical issues such as subcooling, segregation and materials compatibility [116], and to develop more efficient and economic TES systems in buildings, e.g., building thermal mass utilization, PCMs used to increase the thermal capacity of storage while operating at a fixed temperature (Fig. 11), underground thermal energy storage and storage tanks.

Pavlov et al. [117] review developments during the last four decades on seasonal TES in the ground, including aquifer, borehole, water tank and water gravel-pit thermal energy storage systems. They consider various storage concepts coupled with natural and renewable energy sources such as solar and waste thermal energy. They suggest that various parameters such as building peak thermal loads, thermal load profiles, availability of waste or excess thermal energy, availability of natural and renewable energy sources, type of thermal generating equipment, and building type and occupancy impact the feasibility of use of TES in buildings. Feluchaus et al. [36] suggest small system size as one of the barriers to market growth of ATES systems. They suggest a combination of district heating or cooling with ATES as a promising option for integration of ATES and building heating and cooling systems. Studies on the dynamic performance and control strategies of energy storage systems for various building types, weather conditions, and user behavior are needed to understand how TES systems can best support the development of low-energy and zero-emission buildings.

Among renewable energy sources, storage of solar thermal energy in building heating and cooling supply have been extensively reviewed [25, 21, 48]. A good example of systems utilizing thermal energy storage in solar buildings is the Drake Landing Solar Community in Okotoks, Alberta, Canada, which incorporates a borehole seasonal storage to supply space heating to 52 detached energy-efficient homes through a district heating network. Sibbitt et al. [118] describe the system and its operation and presents five years of performance data. Thermal analyses of PCM uses in building envelope (e.g., walls, floors, ceilings and windows) demonstrate that they can be effective in shifting heating and cooling loads from peak electrical demand periods to off-peak periods or in storing solar energy for use in hours when solar radiation is not available [120]. However, due to various PCM thermophysical properties and incorporation methods, investigations are needed to evaluate and compare cost, efficiency, environmental impact, life cycle, and practicability of various options under various weather and experimental conditions [119].

To store electricity in buildings, batteries are most commonly used. Examples include lead acid, molten salt (sodium sulphur, sodium metal hydride), lithium ion and flow batteries. Smolinski et al. [121] suggest that the use of flywheels in buildings that have solar PV panels installed significantly reduces the costs of the system, and they design and operate a prototype system. Other promising electrical energy storage technologies such as CAES and hydrogen storage technologies still face issues such as low efficiency, safety and cost for use in building-scale applications.

Zero Energy Buildings (ZEBs) are viewed by many as the future target for the design of buildings and have attracted considerable attention during the past decade. Thermal energy storage is a particularly attractive option for the development of zero energy buildings by reducing the energy consumption of the buildings, improving system efficiency, and reducing the peak load [122]. Reduction of building energy consumption can be achieved by increased renewable energy use which can be achieved by overcoming the time mismatch between demand and availability of solar and aero-thermal energy. The efficiencies of heating and cooling systems can be improved by avoiding partial-load operation. Lastly, the reduction of peak loads by the use of stored energy at peak times could result in smaller power capacity requirements for heating and cooling.

Applications in the built environment of fuel cells that utilize hydrogen from renewable sources are reviewed by Abdel-Wahab and Ali [123], based on information from the literature and industry experts. While they provide a structured approach for evaluation of such systems, Singh et al. [124] focus on the modelling and simulation of a hydrogen system for performance and cost feasibility estimation. Such analyses can be considered as preliminary steps towards more detailed analyses of the use of hydrogen fuel cells in buildings.

3.5. Transportation

The evolution of ground, water and air transportation technologies has resulted in the need for advanced energy storage systems. Compared to conventional transportation technologies that are driven by internal combustion engines and utilize gasoline tanks for energy storage, hybrid electric vehicles use onboard energy-storage systems such as flywheels, ultra-capacitors, batteries and hydrogen storage tanks for fuel cells. The requirements for the energy storage devices used in vehicles are high power density for fast discharge of power, especially when accelerating, large cycling capability, high efficiency, easy control and regenerative braking capacity.

The primary energy-storage devices used in electric ground vehicles are batteries. Electrochemical capacitors, which have higher power densities than batteries, are options for use in electric and fuel cell vehicles. In these applications, the electrochemical capacitor serves as a short-term energy storage with high power capability and can store energy from regenerative braking. A combination of a battery and an electrochemical capacitor can enhance the characteristics desired in land-based vehicles, aircraft and ships, including engine starting, high current for fast preheating of catalysts, electric power steering, and local power for actuators and distributed power systems. However, a system consisting of a battery of reduced size and an electrochemical capacitor has to be commercially competitive with battery-only systems to penetrate the market. Flywheels have also been used for a long time in transportation systems. They can be used for regenerative braking and load averaging or as the prime energy source for propulsion; the latter option is only a theoretical probability due to flywheel low energy density [54]. To improve energy storage energy density, hybrid systems using flywheels and batteries can also be attractive options in which flywheels, with their high power densities, can cope well with the fluctuating power consumption and the batteries, with their high energy densities, serve as the main source of energy for propulsion [101]. However, for large vehicles such as trains, a larger flywheel needs to be used to serve such a purpose and its weight becomes a disadvantage [54]. The need for a storage unit to recapture vehicular braking energy can be achieved in railway systems by installing an energy storage device at the supply substations, along the railway track or on board the train. Designing and optimizing a train timetable to allow the interchange of energy among accelerating and decelerating trains with energy storage options is another approach that is proving to be effective for high traffic conditions [125]. Wayside energy recovery systems store energy along the railway tracks from decelerating vehicles and discharge it to accelerating ones. This increases overall system efficiency and voltage stability within the grid, and lowers peak power demands, costs and potentially CO_2 emissions depending on the energy mix. Flywheels, batteries and supercapacitors are suitable options for wayside energy storage [126]. Pneumatic accumulators are also available options for regenerative braking energy storage, but often not considered due to their low energy density and efficiency [54]. Some additional benefits of such installations are load leveling and support of the mains voltage, lower energy costs, reduced investment costs since fewer substations are needed, and emergency supply in case of power failures. Several investigations have been made regarding energy storage applications in transportation [97, 136–138]. Hannan et al. suggest that, currently, limitations in electric vehicle energy storage and powering lies in raw material support and proper disposal, energy management, power electronics interface, sizing, safety measures. Khaligh and Li [136] suggest that hybrid energy storage systems with large capacity, fast charging/discharging, long lifetime, and low cost could be more feasible and increase competitiveness with conventional vehicles in the near future.

Several challenges and limitations exist in using lithium batteries in transportation. Methods for improving Li-ion batteries to meet demands for powering electric vehicles and storing renewable energy, including new ways to prepare electrode materials via eco-efficient processes and the use of organic rather than inorganic materials and new chemistries for Li-ion batteries, are suggested [140]. Thackeray et al. [15] suggest that while Lithium-based batteries have considerable potential for improved energy densities (e.g., factors of five or more may be possible for Li–oxygen systems), major breakthroughs, and not incremental advances, in materials and chemistries are required for their adoption in transportation systems to become widespread. Currently, most commercial electric and hybrid vehicles do not have hybrid energy storage systems on board. Since one type of energy storage systems cannot meet all electric vehicle requirements, a hybrid energy storage system composed of batteries, electrochemical capacitors, and/or fuel cells could be more advantageous for advanced vehicular energy storage systems. Such hybrid energy storage systems, with large capacity, fast charging/discharging, long lifetime, and low cost are currently being investigated for electric vehicles [136, 139]. Also, Yang et al. [138] describe the application of other energy storage candidates such as flywheels in automotive applications. Cao et al. [141] propose a new battery/ultracapacitor hybrid energy storage system for electric drive vehicles including electric, hybrid electric, and plug-in hybrid electric vehicles. This design can fully utilize the power capability of the UCs without requiring a matching power dc/dc converter to satisfy the real-time peak power demands. It uses a smaller dc/dc converter working as a controlled energy pump to keep the ultracapacitor voltage higher than the battery voltage for most city driving conditions, improving the battery load profile and vehicle drivability.

A global research effort focusing on the development of physical and chemical methods for storing hydrogen in condensed phases has recently emerged due to the need to store hydrogen onboard at high volumetric and gravimetric densities when using hydrogen as a vehicular fuel. Thus new materials with improved performance, or new approaches to the synthesis and/or processing of existing materials, are highly desirable. Desirable characteristics for hydrogen storage materials are investigated by Yang et al. [138] and Winter [71], accounting for fuel cell vehicle requirements. Yang et al. [138] also introduce candidate storage materials, such as conventional metal hydrides, chemical hydrides, complex hydrides and sorbent systems, and describe their performances and improvement prospects.

4. Categorizations and comparisons of energy storages

In this section several energy storage types are described and/or compared from technical and economic perspectives, rather than their classifications and principles. Similar analyses and comparisons have been reported in the past and shown to be of great interest [142–144]. The analysis in this section aims to provide an updated comparison.

4.1. Technical performance

Energy storage technologies are reviewed and compared in this section from a technical viewpoint, focusing on parameters that can improve the design and performance of energy storage systems, rather than their classifications and principles [140, 149, 150, 152–155]. Some comparisons are also made in previous sections of various energy storage technologies, for example, the advantages of electrochemical double-layer capacitors over other storage technologies as discussed by Sharma and Bhatti [24]. To assess the technical performance of various energy storage types, design parameters such as efficiency, energy capacity, energy density, run time, capital investment costs, response time, lifetime in years and cycles, self-discharge and maturity are often considered [149, 150, 152]. Here, technical characteristics of energy storage technologies are summarized in Table 3. Note that the values in this table are collected from references that are published over various years, since the literature on energy storage technologies lacks data for recent energy storage technologies in some cases. Differences that are noticed in technical information regarding a given energy storage technology may be due to various factors such as different applications or technical developments in a technology that have caused improvements to its technical characteristics. It is observed that energy storage systems with higher power density are often used for short-duration applications requiring fast response such as grid voltage maintenance. Storage systems with higher energy density are often used for long-duration applications such as renewable energy load shifting [145].

Raising power and energy densities of energy storage units significantly depends on advances in storage materials and the development of new materials for various energy storage types, including thermal, mechanical, electromagnetic, hydrogen and electrochemical [140, 153–155]. Strategies for developing advanced energy storage materials in electrochemical energy storage systems include nano-structuring, pore-structure control, configuration design, surface modification and composition optimization [153]. An example of surface modification to enhance storage performance in supercapacitors is the use of graphene as graphene anodes, graphene-based hybrid anodes and electrode additives. A single layer of graphene with little agglomeration is expected to exhibit high surface area and thus yield higher specific capacitance in a supercapacitor application. Graphene is also applied in other energy conversion and storage devices such as fuel cells and lithium-ion batteries [10]. Flexible electrodes based on carbonaceous nanomaterials can also improve such technologies as supercapacitors and Li-ion batteries [154]. Gogotsi and Simon [155] suggest that the most viable materials for electrochemical capacitors are biomass-derived and polymer-derived activated carbons. Hall et al. [156] discuss how the use of metal oxides can improve electrochemical capacitor performance. The use of a combination of pseudo-capacitive nanomaterials, including oxides, nitrides and polymers, with the latest generation of nanostructured lithium electrodes for enhancing the energy density of electrochemical capacitors, allows them to perform more like batteries [157]. The utilization of carbon nanotubes has further advanced micro-electrochemical capacitors, enabling flexible and adaptable devices [157]. Ways to enhance the power rate in batteries so they are more comparable to those of supercapacitors are also proposed using a material with high lithium bulk mobility ($LiFePO_4$) that can create a fast ion-conducting surface phase through controlled off-stoichiometry [158].

Various design aspects of latent thermal energy storage technologies such as material, encapsulation, heat transfer, applications and new PCM technology innovation have been extensively reviewed [159, 44, 42]. Experimental/computational efforts are made to enhance the thermal conductivity of PCMs [160]. These include the placement of fixed, stationary high conductivity inserts made from copper, aluminum, nickel, stainless steel and carbon fiber in various forms (fins, honeycomb, wool, brush, etc.). Various development possibilities also exist for high-temperature thermal storage including embedding metal foams within PCMs. Mathematical modelling need to be used to predict how such options affect the stability and energy flux through the composite at high temperatures [161]. Other TES techniques and their applications are discussed in Sections 2 and 3.

4.2. Economics

Various economic advantages and challenges exist regarding the use of energy storage technologies for the various applications included in Section 3. The cost of an energy storage system is often application-dependent. Carnegie et al. [94] identify applications that energy storage devices serve and compare costs of storage devices for the applications. In addition, costs of an energy storage system for a given application vary notably based on location, construction method and size, and the cost effectiveness depends on the price of the source of energy such as natural gas. For example, Marean [162] report capital costs of CAES systems for bulk energy storage applications based on various geologic formations: from $1/kWh for salt cavern (solution mined) to $30/kWh for hard rock (excavated and existing mines). For this reason, economic analyses comparing a wide range of energy technologies often have a degree of uncertainty, which needs to be taken into account. Nonetheless, estimated capital costs for various energy storage systems are listed in Table 4. Note that the costs listed are obtained from the literature that are published in different years. The costs of a number of energy storage technologies, that have not yet reached a mature development stage at the time of publication, are expected to be currently lower due to technology development and economies of scale. Examples of such technologies include hydrogen fuel cells, lithium-ion batteries for utility and residential applications, and vanadium-redox flow batteries. On the other hand, pumped hydro and lead-acid batteries have reached a mature status and have exhibited smaller variations in cost over the past two decades [163]. As a result, their current costs are not expected to vary much from the values listed in Table 4.

Table 3
Technical characteristics of energy storage technologies.

Storage type	Power density (volumetric) (kW/m^3)	Energy density (volumetric) (kWh/m^3)	Energy density (mass) (Wh/kg)	Cycle efficiency (%)	Lifetime (cycles)
Capacitor	>100,000 [148]	2–10 [148]	0.05–5 [148]	60–70 [148]	$>5 \times 10^4$ [148]
Supercapacitor	40,000–120,000 [151][1] >100,000 [148] 15–4500 [146]	10 [127] 10–20 [151][1] 10–30 [148, 126] 1–35 [146]	1–5 [126] 2–5 [127] 1–15 [151][1] 2.5–15 [148]	90–100 [126] 85–98 [151][1] 90–97 [148] 90–95 [1] 65–99 [146]	$<10^6$ [126] 10^4–10^5 [151][1] $>10^5$ [148] 10^4–10^6 [146]
Battery					
Li-ion	1300–10,000 [151] 1500–10,000 [148] 150–360 [126] 60–800 [146]	300–750 [126] 200–400 [151] 200–500 [148] 90–500 [146]	100–300 [126] 60–200 [151] 75–200 [148] 200 [102] 150–200 [5] 30–300 [146]	85–98 [151] 90–97 [148] 95 [5],[102] 85–95 [94] >95 [126] 70–100 [146]	500–10^4 [151] 1000–10^4 [148, 5] 3000 [102] 250–10^4 [146]
NiMH sealed	500–3000 [151] 8–600 [146]	80–200 [151] 40–300 [146]	40–80 [151] 30–90 [146]	65–75 [151] 50–80 [146]	600–1200 [151] 300–3000 [146]
Lead acid	90–700 [151] 10–400 [148, 146]	50–80 [151, 148] 25–90 [146]	30–45 [151] 30–50 [148] 35–50 [5] 10–50 [146]	65–80 [102] 75–90 [151, 94] 70–80 [148] 80 [5] 60–90 [146]	250–1500 [151] 500–1000 [148] 500–1500 [5] 100–2000 [146]
NiCd[2]	40–140 [146]	15–150 [146]	10–80 [146]	60–90 [146]	300–10^4 [146]
NiCd vented	75–700 [151]	15–80 [151]	15–40 [151]	60–80 [151]	1500–3000 [151]
NiCd sealed	80–600 [148]	80–110 [151] 60–150 [148]	30–45 [151] 50–75 [148] 75 [5]	60–70 [151, 148] 80 [5]	500–800 [151] 2500 [5]
NaNiCl	250–270 [151] 15–260 [146]	150–200 [151] 100–200 [146]	100–200 [151] 125 [5] 85–140 [146]	80–90 [151] 90 [5] 20–90 [146]	≈1000 [151] >2500 [5] 2000–3000 [146]
NaS	120–160 [151] 140–180 [148] 1–50 [146]	150–300 [151] 150–250 [148] 150–350 [146]	100–250 [151] 150–240 [148],[5] 100–240 [146]	70–85 [151] <90 [5] 65–90 [146]	2500–4500 [151, 102] 2500 [148, 5] 1000–4500 [146]
Zinc air	50–100 [151] 10–200 [146]	130–200 [151] 20–1700 [146]	130–200 [151] 10–500 [146]	50–70 [151] 30–50 [146]	>1000 [151] >500 [146]
HFB	1–25 [151]	65 [151]	75–85 [151]	65–75 [151]	1000–3650 [80]
VRB	0.5–2 [151] <2 [148]	20–70 [151] 16–33 [148] 10–30 [146]	15–50 [151] 10–30 [148] 10–50 [146]	60–75 [151] 75–85 [148] 60–90 [146]	$>10^4$ [151] $>1.2 \times 10^4$ [148] 800–1.6×10^4 [146]
Flywheel	5000 [151] 1000–2000 [148] 40–2000 [146]	20–80 [148],[151, 126] 0.3–400 [146]	5–100 [126] 5–30 [151] 10–30 [148] 5–200 [146]	80–90 [151] 90–95 [148, 102],[1, 126] 70–96 [146]	2×10^4–10^7 [151] $>2 \times 10^4$ [148] 10^4–10^5 [102, 146]
Magnetic	2600 [151] 300–4000 [146]	6 [151] 0.2–2.5 [148] 0.2–14 [146]	0.5–5 [148] 0.3–75 [146]	75–80 [151] 95–97 [148] 90–95 [1] 80–99 [146]	$>10^5$ [148] $>2 \times 10^4$ [102] 10^4–10^5 [146]
Compressed air	0.2–0.6 [151] 0.5–2 [148] 0.04–10 [146]	2–6 [151] 3–6 [148] 0.4–20 [146] 0.5–0.8 [147][3]	30–60 [148] 3–60 [146]	41–75 [151] 60–90 [146]	$>10^4$ [151] 10^4–3×10^4 [102, 146]
Pumped hydro	0.1–0.2 [151] 0.5–1.5 [148] 0.01–0.10 [146]	0.2–2 [151] 0.5–1.5 [148] 0.5–1.3 [146] 0.4–1.1 [147]	0.2–2 [151] 0.5–1.5 [148] 0.3–1.3 [146]	65–85 [102] 70–80 [151] 70–85 [148] 50–85 [1] 75–78 [94] 65–90 [146]	$>0.5 \times 10^4$ [151] 10^4–3×10^4 [102] 10^4–6×10^4 [146]
Hydrogen fuel cell	>500 [148]	500–3000 [148]	800–10,000 [148]	20–50 [148, 1]	>1000 [148]
Thermal		80–500 [148]	80–250 [148]	30–60 [148]	
Latent		100–370 [146]	150–250 [146]	75–90 [146]	
Sensible		25–120 [146]	10–120 [146]		

[1] Double-layer capacitor.
[2] Vented versus sealed is not specified in the reference.
[3] Energy density evaluated at 60 bars.

The capital costs are reported in terms of cost per unit power output ($/kW) and cost per unit energy stored ($/kWh). In applications where energy is to be stored and discharged frequently but at a high rate (e.g., frequency regulation), the cost per unit power output becomes an important factor when selecting the most suitable energy storage system. Similarly, in energy storage for longer durations (e.g., load shifting), the cost per unit energy stored becomes an important factor. Note that flywheels and capacitors (both types) are among the cheaper energy storage technologies when higher power outputs are required. These systems are often used in the transmission and distribution subsystems of electric power systems. Pumped hydro and compressed air systems that are often applied in generation subsystems have the lowest capital costs per unit energy stored.

The Energy Policy Council in North Carolina [95] recently published a report that reviewed the cost effectiveness of using various energy storage technologies for four categories of utility applications:

Table 4
Estimated capital cost ranges for various energy storage systems.

Storage type	Capital cost (power based) ($/kW)	Capital cost (energy based) ($/kWh)	Reference publication year
Pumped hydro	600–2000 [148] (2009)[1] 500–4600 [164]	5–100 [148] (2009) <300 [163] (2013)	2009 2014
Compressed air	400–800 [148, 102] 500–1500 [164]	2–50 [148] 1–30 [94] (2013)	2009–2014
Battery	300–3500 [164]	20,000 [102]	2010
Li-ion	1200–4000 [148] (2009)	100–2500 [126] 1200 [102] (2010) <300 [163][2] (2011) <500 [163][3]	2009–2019 2017
Lead-acid	300–600 [148], [102]	200–400 [148] <300 [163] (2012)	2009–2010
NiCd	5000–1500 [148]	800–1500 [148] 1000 [102]	2009–2010
NaS	1000–3000 [148]	300–500 [148] <500 [163]	2009 2017
VRB	600–1500 [148]	150–1000 [148]	2009
Capacitor	200–400 [148]	500–1000 [148]	2009
Supercapacitor	100–300 [148] 130–515 [164]	300–2000 [148] 10,000 [126]	2009 2014 2019
Magnetic	200–300 [148] 130–515 [164] 1000–10,000 [102]	1000–10,000 [148]	2009 2014
Flywheel	300–1000 [126] 250–350 [148] (2009) 130–500 [164] 1950–2200 [94] (2013)	3000–6000 [126] 1000–5000 [102] (2009) 7800–8800 [94] (2013)	2019 2009 2014
Hydrogen fuel cell	500–10,000 [102]		2009
Thermal	200–300 [148]	3–60 [148]	2009
Solid media (demand)	500–3000 [164]		2014
Underground	3400–4500 [164]		2014
Molten salts (supply)	400–700 [164]		2014
Pit (supply)	100–300 [164]		2014
Ice (demand)	6000–15,000 [164]		2014
Cold water (demand)	300–600 [164]		2014
Thermochemical (supply and demand)	1000–3000 [164]		2014

[1] Values in round brackets indicate the year in which the costs were determined. If the year is not mentioned in the reference, no value is included.
[2] For consumer electronics; above 100 GWh installed.
[3] For electric vehicles; between 1 and 100 GWh cumulative installed capacity.

end-user, distribution, transmission, and generation and resource adequacy. They concluded that use of Li-ion batteries are cost-effective at their current price for end-user applications and frequency regulation, but not for bulk energy storage time shifting and peak capacity deferrals. In addition, Li-ion batteries do not offer significant arbitrage opportunities due to the lower variation in marginal costs for electricity in North Carolina. For applications of energy storage in renewable energy systems, Beaudin et al. [102] suggest that large-scale integration of renewable energy systems to respond to larger load growth may become more economically feasible with the use of energy storage systems than the alternative option of construction of new transmission and generation capacity.

Various operating and maintenance (O&M) as well as capital cost components for energy storage systems need to be estimated in order to analyse the economics of energy storage systems for a given location. Capital costs for the application of electrical energy storage in utility systems include costs for grid connection interface and integration facilities (e.g., transformers), construction management costs (e.g., land and accessibility), power conversion systems (e.g., turbines and pumps in pumped hydro energy storage systems) and storage compartment (e.g., tanks) [162]. Such costs for a unit of energy storage often vary depending on the size of the energy storage technology. SNL [165] used available project costs to estimate construction costs of new pumped hydro facilities as a function of system capacity. In estimations of O&M costs, monetary values are often not assigned to CO_2 emission reductions that result from integrating energy storage technologies with energy systems. However, CO_2 emission reductions are often mentioned as a factor that could change the outcomes of economic analyses.

Life cycle costs of various grid-scale electrical energy storage technologies are also reported in the literature by taking into account various capital cost components. Zakeri and Syri [162] report inconsistencies among cost estimations of various references (by 5–17%) sometimes due to varying assumptions and scaling the size of the energy storage system. Adiabatic CAES and PHS systems are similar in that their costs are site-specific, and large in terms of capital costs but low in terms of variable O&M costs [166]. Zakeri and Syri [162] also report that the most cost-efficient energy storage systems are pumped hydro and compressed air energy systems for bulk energy storage, and flywheels for power quality and frequency regulation applications. However, costs for environmental approvals as well as those related to fuels and emissions over the lifetime of the energy storage application may increase the costs.

More site-specific studies have also been performed to provide more accurate estimates of energy storage economics. Lund and Salgi [167] analyse the economic potential of a CAES plant in the Danish electricity system and compare it with other technologies. Hour-by-hour simulations are performed to evaluate present and future economic feasibilities, and the business-economic potentials of CAES plants in Nordic electricity markets are analysed for both the spot market and the regulated power market. Peterson et al. [168] examine the potential economic benefits of using vehicle batteries to store electricity generated in the grid at off-peak hours for vehicle use during peak hours. Hourly electricity prices in three U.S. cities (Boston, Rochester NY and Philadelphia) are used to obtain daily profit values, and economic losses associated with battery degradation are accounted for. Their results show that it is unlikely for vehicle owners to receive sufficient incentives from electricity arbitrage to motivate large scale use of car batteries for grid energy storage in any of the three cities. Divya and Østergaard [169] describe how battery and electric vehicle technologies can improve operation reliability of future power systems by considering the Danish electricity grid, and discuss the present status of battery technology and methods of assessing its economic viability and impact on power system operation. They suggest that battery energy storage technologies, mainly lithium ion or nickel metal hydride, would play an important role to meet 50% of total electricity demand in Denmark by wind energy resources. Pruestre et al. [74] review the use of hydrogen from renewable electricity in both elemental and chemically bound forms as well as energy storage options as key components of such system. They suggest the cost of hydrogen as the main barrier to its use in the power market and suggest that applications of hydrogen at high pressure and high quality in small to medium quantities such as filling stations for hydrogen mobility applications or smaller industrial consumers may be a starting point to make an economic case for pursuing hydrogen. They also point out infrastructure requirements of a hydrogen economy in third world countries and suggest that operating sophisticated compressor equipment for hydrogen storage as a pressurized gas, handling liquid hydrogen, or developing pipelines is likely impracticable in such countries as opposed to transport of hydrogen bound to organic liquids via roads.

Benitez et al. [170] develop a nonlinear mathematical optimization program for investigating the economic and environmental implications of wind penetration in electrical grids. The use of thermal and hydropower plants in electrical grids fed by intermittent renewable sources such as wind power increases system variability and results in a need for additional peak load, gas-fired generators. When pumped hydro storage is introduced into the system or the capacity of the water reservoirs is enhanced, the hydropower facility can provide most of the peak load requirements obviating the need to build large peak-load gas generators.

A number of articles explore the future cost of energy storage technologies to determine the competitiveness of a given technology in the future as well as the required investments to become competitive. However, with a lack of knowledge regarding changes in technology, possible breakthroughs, knowledge spill-overs and commodity price shifts, such analyses are subject to a degree of uncertainty [163]. Schmidt et al. [163] use historic product prices and cumulative installed capacities based on actual price data from various sources to derive experience curves that can be used to project future prices for a number of electrical energy storage technologies. They show decreasing product prices with increasing cumulative installed capacities for several energy storage technologies and suggest that the technology that brings the most capacity to market is likely to become the most cost-competitive. For example, they indicate that once cumulative deployment of redox-flow and utility-scale Li-ion systems have reached 7 GWh and 33 GWh, respectively, electrical energy storage will be achieved competitively at $650/kWh. They suggest that such information can help quantify the required investment to achieve such cumulative capacities.

4.3. Advantages and disadvantages

The main features regarding technical performance and economics of various energy storage systems discussed in Section 4 lead to general advantages and disadvantages for each (see Table 5). Note that while some energy storage types seem to have more disadvantages than others, they may be the most suitable technology for some applications.

5. Conclusions and future directions

An overview and critical review is provided of available energy storage technologies, including electrochemical, battery, thermal, thermochemical, flywheel, compressed air, pumped, magnetic, chemical and hydrogen energy storage. Storage categorizations, comparisons, applications, recent developments and research directions are discussed. Significant performance parameters are described, such as energy density, power density, cycle efficiency, cycle life, charge/discharge characteristics and cost, making different storage technologies suitable for particular applications.

Among the energy storage types, much research is ongoing into various aspects of electrochemical energy storage, focused on introducing new storage materials and understanding their applicability to several energy storage needs. Batteries are likely to be the cheapest energy storage option for applications with relatively fewer numbers of cycles. Lithium batteries are playing an increasingly important role in portable electrochemical energy storage technologies. Performance and cost are expected to be the limiting factors in their expansion into a variety of energy storage applications. Among Li batteries, Li–air batteries seem to have the potential to achieve high performance and become commercially viable, although technical challenges still need to be addressed. Na-ion batteries are potential future low cost options, but much investigation is needed in the Na-ion field to achieve the technical maturity achieved for Li-ion technology. Replacement costs contribute a considerable part of life cycle cost of batteries and it is expected that the number of cycles, which significantly affects revenues for a given service, is an important factor that could expand the use of batteries. Batteries are often compared to supercapacitors for various storage applications and it is expected that exploiting their features (i.e., frequent energy storage capability without sacrificing their cycle) by integration could help address future electrical energy storage challenges. For large-scale electrical energy storage (e.g., energy from renewable energy sources) using batteries, flow batteries seem to be the most suitable options, although costs and electrolyte development remain challenges.

Other electrical energy storage types such as flywheel energy storage, used for very short storage periods and frequent use, and magnetic energy storage have received less attention. Key needs for flywheels are reductions in the mechanical, electrical and power-conversion losses. In addition, research is focused on material science to improve the strength of highly stressed rotors at high speeds. Pumped hydro and compressed air energy storage technologies are mature, cost effective and reliable technologies that are used for large scale storage with frequent cycling capabilities. However, research is still needed to improve their round-trip efficiencies. In PHES systems, advances in turbine design are needed to improve performance. Among CAES systems, isothermal CAES is still an emerging technology, but is ultimately likely to provide a better efficiency than the compressed air technology due to its more efficient compression operation.

Storage of heat is accomplished by sensible and to a lesser extent latent thermal energy storage in many applications, and less research is available on chemical and thermochemical heat storage. The key enabling technologies in most storage systems are in systems engineering and material science. Research on latent heat storage is mostly focused on the development and introduction of new storage media and enhancing thermodynamic properties of existing ones. Thermal energy storage using adsorption processes is currently not economically feasible. Further research on materials to avoid adsorbent instabilities and system optimization (e.g., optimization of temperatures during the charging and discharging processes) is needed to further develop this technology.

Among the various energy storage system categories, hydrogen energy storage systems appear to be the one that can result in large changes to the current energy system. Several technological, economic, social and political barriers need to be overcome before hydrogen technologies can be used in large scale applications.

Apart from the need to overcome technical and economic challenges that impede the growth of energy storage share in enhancing the performance of energy systems, policy support by governments is also needed. The impact of government mandates and targets in increasing the rate of growth of the energy storage market in 2018 was noticeable in Korea, China, the United States and Germany as well as in new markets such as South Africa [171].

Although renewable energy sources have long been considered important option for sustainable development, their intermittency and cost appear to be limiting factors preventing their rapid growth in some regions. With the expected rise in fossil fuel prices and perhaps larger CO_2 penalties in the future, it is expected that renewable energy sources will become more economic and their use will accelerate. However, their growth will still be limited due to their intermittent nature. Energy storage technologies are expected to serve as a catalyst to address intermittency issues of renewable energy sources, helping them realize their full economic benefits. Such expansion in generation of electricity from renewable energy sources would also assist growth in the use of other sustainable energy systems (e.g., hydrogen produced from electrolysis). It is expected that use of hydrogen and electricity as energy carriers in the future will both be improved as more renewable energy systems are integrated with energy storage systems.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to

Table 5
Advantages and disadvantages of various energy storages (adapted from Carnegie et al. [94]).

Energy storage type	Advantages	Disadvantages	Additional notes
Pumped hydro	Technical maturity High energy storage capacity* Long life cycle	Location constraints High cost Low power and energy density Potential environmental impacts (land and water footprints)	Most mature energy storage system Costs are site-specific Large upfront costs and variable operation and maintenance costs
Compressed air	Technical maturity High energy storage capacity	Variable efficiency Leakage Safety issues Location constraints	Costs are site-specific Large upfront costs and variable operation and maintenance costs
Battery			
Li-ion	High energy and power density compared to other batteries Short response time	Life cycle dependent on discharge levels High cost	
Lead-acid	Low cost Technical maturity	Low energy density Low power density Short response time Short life cycle High maintenance requirements Toxicity Material consumption	Most mature electrochemical energy storage system
NiCd	Technical maturity	High cost Low energy density Low power density Short response time Toxicity	Most common nickel electrode battery in the utility energy storage industry Popular for utility energy storage applications (e.g., substation batteries and bulk storage)
VRB	High energy storage capacity	Complex construction Low energy density Low power density	Useful for utility applications requiring long discharge durations (e.g., load shifting)
Supercapacitor	High power density	Interdependence of cells Life cycle dependent on voltage imbalances between cells and maximum voltage thresholds Safety issues Environmental implications	
Magnetic	Immediate response Life expectancy that is independent of duty cycle High efficiency High reliability	High cost Refrigeration energy requirements Requirement for large magnetic fields	No stand-by losses of the stored energy Cryogenic refrigeration is an integral part of the storage system.
Flywheel	High energy storage capacity No pollution Small area requirement Technical maturity	Noise issues Safety issues High cost per unit of energy stored	Common for uninterruptible power supply and power quality applications

* Large scale energy storage systems can be achieved.

influence the work reported in this paper.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.est.2019.101047.

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