

Review

Progress in electrical energy storage system: A critical review

Haisheng Chen^{a,b}, Thang Ngoc Cong^a, Wei Yang^a, Chunqing Tan^b, Yongliang Li^a,
Yulong Ding^{a,*}

^a *Institute of Particle Science and Engineering, University of Leeds, Leeds, LS2 9JT, UK*

^b *Institute of Engineering Thermophysics, Chinese Academy of Sciences, Beijing 100190, China*

Received 15 April 2008; received in revised form 2 July 2008; accepted 2 July 2008

Abstract

Electrical energy storage technologies for stationary applications are reviewed. Particular attention is paid to pumped hydroelectric storage, compressed air energy storage, battery, flow battery, fuel cell, solar fuel, superconducting magnetic energy storage, flywheel, capacitor/supercapacitor, and thermal energy storage. Comparison is made among these technologies in terms of technical characteristics, applications and deployment status.

© 2008 National Natural Science Foundation of China and Chinese Academy of Sciences. Published by Elsevier Limited and Science in China Press. All rights reserved.

Keywords: Progress; Electrical energy storage

1. Introduction

Electrical Energy Storage (EES) refers to a process of converting electrical energy from a power network into a form that can be stored for converting back to electrical energy when needed [1–3]. Such a process enables electricity to be produced at times of either low demand, low generation cost or from intermittent energy sources and to be used at times of high demand, high generation cost or when no other generation means is available [1–5]. EES has numerous applications including portable devices, transport vehicles and stationary energy resources [1–9]. This paper will concentrate on EES systems for stationary applications such as power generation, distribution and transition network, distributed energy resource, renewable energy and local industrial and commercial customers.

The history of the stationary EES dates back to the turn of the 20th century, when power stations were often shut down overnight, with lead-acid accumulators supplying the residual loads on the direct current networks [2–4].

Utility companies eventually recognised the importance of the flexibility that energy storage provides in networks and the first central station for energy storage, a Pumped Hydroelectric Storage (PHS), was put to use in 1929 [2,10,11]. The subsequent development of the electricity supply industry, with the pursuit of economy of scale, at large central generating stations, with their complementary and extensive transmission and distribution networks, essentially consigned interest in storage systems up until relatively recent years. Up to 2005, more than 200 PHS systems were in use all over the world providing a total of more than 100 GW of generation capacity [10–12]. However, pressures from deregulation and environmental concerns lead to investment in major PHS facilities falling off, and interest in the practical application of EES systems is currently enjoying somewhat of a renaissance, for a variety of reasons including changes in the worldwide utility regulatory environment, an ever-increasing reliance on electricity in industry, commerce and the home, power quality/quality-of-supply issues, the growth of renewable as a major new source of electricity supply, and all combined with ever more stringent environmental requirements [3,4,6]. These factors, combined with the rapidly accelerat-

* Corresponding author. Tel.: +44 113 343 2747; fax: +44 113 343 2405.
E-mail address: y.ding@leeds.ac.uk (Y. Ding).

ing rate of technological development in many of the emerging EESs, with anticipated unit cost reductions, now make their practical applications look very attractive on future timescales of only a few years. The governments of the USA [1,2,9,13–15], the EU [3,6,10], Japan [10,16] and Australia [4] all have granted their national programmes on EES recently. The anticipated storage level is expected to increase by 10–15% the delivered inventory for the USA and European countries, and even higher for Japan in the near future [4,10].

This paper aims to review the state-of-the-art development of EES technologies including PHS [11,12,17], Compressed Air Energy Storage system (CAES) [18–22], Battery [23–27], Flow Battery [3,4,6,13], Fuel Cell [24,28], Solar Fuel [4,29], Superconducting Magnetic Energy Storage system (SMES) [30–32], Flywheel [13,16,33,34], Capacitor and Supercapacitor [4,16], and Thermal Energy Storage system (TES) [35–43]. Some of them are currently available and some are still under development. The imperativeness and applications, classification, technical characteristics, research and development (R&D) progress and deployment status of these EES technologies will be discussed.

2. Imperativeness and applications

2.1. Imperativeness

EESs are urgently needed by the conventional electricity generating industry [2–7]. Unlike any other successful commodities markets, the conventional electricity generating industries have little or no storage facility. The electricity transmission and distribution systems are operated for the simple one-way transportation from remote and large power plants to consumers. This means that electricity must always be used precisely when produced. However, the demand for electricity varies considerably emergently, daily and seasonally, the maximum demand may only last for a few hours each year. This leads to inefficient, over-designed and expensive plants. EES allows energy production to be de-coupled from its supply, self generated or purchased. By having large-scale electricity storage capacity available over any time, as shown in Fig. 1, system planners would need to build only sufficient generating capacity to meet average electrical demand rather than peak demands [13]. This is particularly important to large utility generation systems, e.g. nuclear power plants, which must operate near full capacity for economic reasons [1,44]. Therefore, EES can provide substantial benefits including load following, peaking power and standby reserve. Also by providing spinning reserve and a dispatched load, EES can increase the net efficiency of thermal power sources while reducing harmful emissions [43–46].

Furthermore, EES is regarded as an imperative technology for the distributed energy resource (DER) systems [2–7,25,32,47,48]. Deferred from the conventional power system which has large, centralized units, DERs are usually

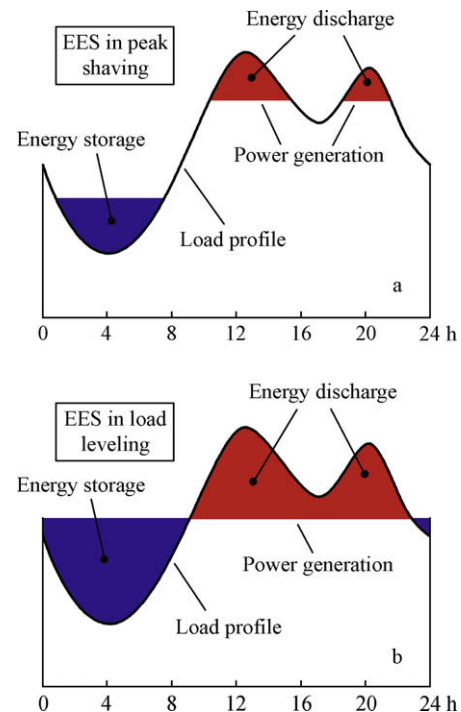


Fig. 1. Load profile of a large-scale electricity storage system. (a) EES in Peak Shaving; (b) EES in load levelling.

installed at the distribution level, close to the place of utilisation, and generate power typically in the small range of a few kW to a few MW [25]. A DER is regarded as a sustainable, efficient, reliable and environmentally friendly alternative to the conventional energy system [25,47]. The energy resource system is undergoing the change to be a mixture of centralized and distributed sub-systems with higher and higher penetration of DERs [47]. However, more drastic load fluctuations and emergent voltage drops are anticipated in DER systems due to smaller capacity and higher possibility of line fault than the conventional power system. EES is identified as a key solution to compensate the power flexibility and provide uninterruptible power supply (UPS) in cases of instantaneous voltage drop for such a distributed energy network.

More urgently, EES systems are critically important to intermittent renewable energy supply systems [2–7,48–58] such as solar photovoltaic, wind turbine and wave. The penetration of renewable resources may displace significant amounts of energy produced by large conventional plants (15% of the UK by 2015 and 16% of China by 2020 in their national energy plans). However, intermittency and non-controllability are inherent characteristics of renewable energy-based electricity generation systems [52]. Such disadvantages have become major hurdles to the extensive utility of the renewable energies and the green electricity industry. A suitable EES could obviously provide an important (even crucial) approach [51] to dealing with the intermittency of renewable sources and the unpredictability of their output as the surplus could be stored during the periods when intermittent generation exceeds the demand

and then be used to cover periods when the load is greater than the generation.

2.2. Application

The traditional electricity value chain has been considered to consist of five links: fuel/energy source, generation, transmission, distribution and customer-side energy service as shown in Fig. 2. By supplying power when and where needed, EES is on the brink of becoming the “sixth link” by integrating the existing segments and creating a more responsive market [14]. Stored energy integration into the generation-grid system is illustrated in Fig. 3 [13]. It can be seen that potential applications of EES are numerous and various and could cover the full spectrum ranging from larger scale, generation and transmission-related systems, to those primarily related to the distribution network and even ‘beyond the meter’, into the customer/end-user site [2]. Some important applications have been summarised in Refs. [2–4,7,13,14,58–61]:

- (1) *Generation:* (i) Commodity storage: Storing bulk energy generated at night for use during peak demand periods during the day allows for arbitraging the production price of the two periods and a more uniform load factor for the generation, transmission, and distribution systems. (ii) Contingency service: Contingency reserve refers to the power capacity capable of providing power to serve customer demand should a power facility fall off-line. Spinning reserves are ready instantaneously, with non-spinning and long-term reserves ready in 10 min or longer. (iii) Area control: This is to prevent unplanned transfer of power between one utility and another. (iv) Frequency regulation: This would enable maintaining a state of frequency equilibrium during regular and irregular grid conditions. Large and rapid changes in the electrical load of a system can damage the generator and customers’ electrical equipment. (v) Black-Start: This refers to units with a capability to start-up

on their own in order to energise the transmission system and to assist other facilities to start-up and synchronise to the grid.

- (2) *Transmission and distribution:* (i) System stability: The ability to maintain all system components on a transmission line in synchronous operation with each other to prevent collapse of a system. (ii) Voltage regulation: Stable voltage between each end of all power lines can be maintained through voltage regulation. (iii) Asset deferral: This refers to deferring of the need for additional transmission facilities by supplementing the existing transmission facilities to save capital that otherwise goes underutilised for years.
- (3) *Energy service:* (i) Energy Management allows customers to peak shave by shifting energy demand from one time of the day to another thus reducing their time-of-use (demand) charges. (ii) Power quality provides electrical service to customers without any secondary oscillations or disruptions to the electricity “waveform” such as swells/sags, spikes, or harmonics. (iii) Power Reliability provides bridging power (UPS) for consumers to ‘ride-through’ a power disruption. Coupled with energy management storage, this allows remote power operation.
- (4) *Renewable energy:* Future development of renewable energy technologies will drive the cost down. This has already been evidenced in wind and photovoltaic power generation. Nonetheless, the widespread deployment of solar, wind and wave power in the future will face the fundamental difficulty of intermittent supplies, which requires demand flexibility, backup power sources, and enough electricity storage for hours to days and perhaps a week. Applications of energy storage to enhance wind generation are reported in Ref. [59], where single-function applications were identified as (i) Transmission curtailment: mitigation of power delivery constraint imposed by insufficient transmission capacity. (ii) Time-Shifting: firming and shaping of wind-generated energy by storing it during the off-peak interval (supplemented by power purchased from the grid when wind gener-

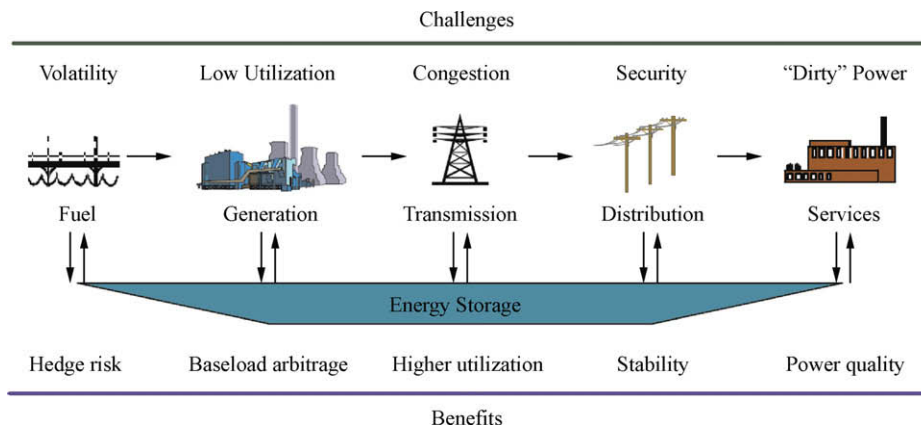


Fig. 2. Benefits of EES along the electricity value chain [14].

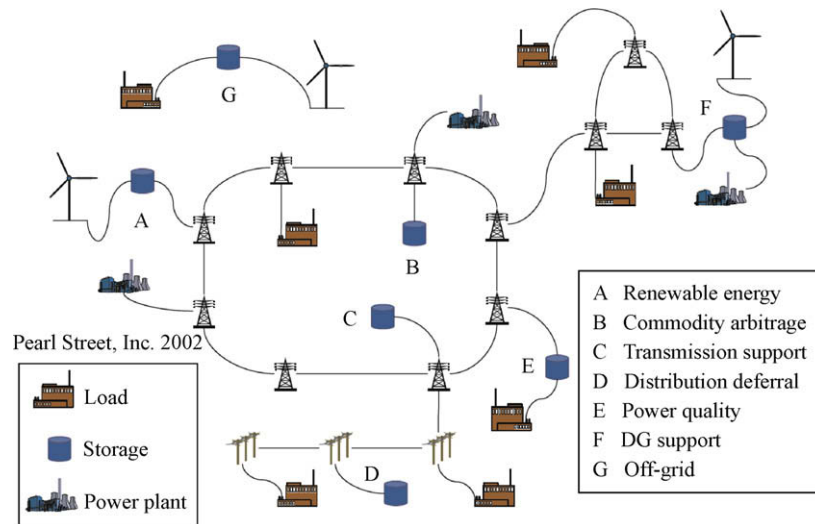


Fig. 3. Energy storage applications into grid [13].

ation is inadequate) and discharging during the on-peak interval. (iii) Forecast Hedge: mitigation of errors (shortfalls) in wind energy bids into the market prior to required delivery, thus reducing volatility of spot prices and mitigating risk exposure of consumers to this volatility. (iv) Grid Frequency Support: Energy storage supports grid frequency during sudden, large decreases in wind generation over a short discharge interval. (v) Fluctuation suppression: Wind farm generation frequency can be stabilised by suppressing fluctuations (absorbing and discharging energy during short duration variations in output). Although the work reported in Ref. [58] focuses on wind energy, these key applications for storing the renewable electricity should be equally relevant to solar and wave power generation as well as other intermittent renewables.

3. Classification

There are two criteria to categorise the various EES: function and form. In terms of the function, EES technologies can be categorised into those that are intended firstly for high power ratings with a relatively small energy content making them suitable for power quality or UPS; and those designed for energy management, as shown in Fig. 4. PHS, CAES, TES, large-scale batteries, flow batteries, fuel cells, solar fuel and TES fall into the category of energy management, whereas capacitors/supercapacitors, SMES, flywheels and batteries are in the category of power quality and reliability. This simple classification glosses over the wide range of technical parameters of energy storage devices. For example, several flywheel manufacturers are developing flywheels with higher energy to power ratios, and advanced batteries often show good characteristics for pulse power; see Section 5 for more data and further discussion.

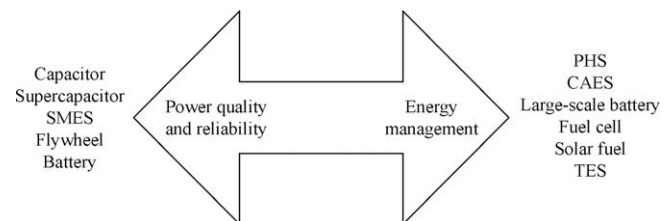


Fig. 4. Energy storage classification with respect to function.

Although electricity is not easy to be directly stored cheaply, it can be easily stored in other forms and converted back to electricity when needed. Storage technologies for electricity can also be classified by the form of storage into the following:

- (1) *Electrical energy storage*: (i) Electrostatic energy storage including capacitors and supercapacitors; (ii) Magnetic/current energy storage including SMES.
- (2) *Mechanical energy storage*: (i) Kinetic energy storage (flywheels); (ii) Potential energy storage (PHS and CAES).
- (3) *Chemical energy storage*: (i) Electrochemical energy storage (conventional batteries such as lead-acid, nickel metal hydride, lithium ion and flow-cell batteries such as zinc bromine and vanadium redox); (ii) chemical energy storage (fuel cells, molten-carbonate fuel cells – MCFCs and Metal-Air batteries); (iii) thermochemical energy storage (solar hydrogen, solar metal, solar ammonia dissociation–recombination and solar methane dissociation–recombination).
- (4) *Thermal energy storage*: (i) Low temperature energy storage (Aquiferous cold energy storage, cryogenic energy storage); (ii) High temperature energy storage (sensible heat systems such as steam or hot water accumulators, graphite, hot rocks and concrete, latent heat systems such as phase change materials).

4. Description of EES

4.1. Pumped hydroelectric storage

PHS is the most widely implemented large-scale EES. As shown schematically in Fig. 5, such a system normally consists of (1) two reservoirs located at different elevations, (2) a unit to pump water to the high elevation (to store electricity in the form of hydraulic potential energy during off-peak hours), and (3) a turbine to generate electricity with the water returning to the low elevation (converting the potential energy to electricity during peak hours). Clearly, the amount of stored energy is proportional to the height difference between the two reservoirs and the volume of water stored. Some high dam hydro plants have a storage capability and can be dispatched as a PHS. Underground pumped storage, using flooded mine shafts or other cavities, is also technically possible. Open sea can also be used as the lower reservoir [10].

PHS is a mature technology with large volume, long storage period, high efficiency and relatively low capital cost per unit of energy. Owing to the small evaporation and penetration, the storage period of PHS can be varied from typically hours to days and even years. Taking into account the evaporation and conversion losses, ~71% to ~85% of the electrical energy used to pump the water into the elevated reservoir can be regained. The typical rating of PHS is about 1000 MW (100 MW–3000 MW) and facilities continue to be installed worldwide at a rate of up to 5 GW per year. The rating of PHS is the highest all over the available EESs, hence it is generally applied for energy management, frequency control and provision of reserve. Since first use in Italy and Switzerland in the 1890s and the first large-scale commercial application in the USA in 1929 (Rocky River PHS plant, Hartford), there are over 200 U and 100 GW of PHS in operation worldwide [10–12] (~32 GW installed in Europe, ~21 GW in Japan, ~19.5 GW in the USA and others in Asia and Latin America), which is about 3% of global generation capacity.

The major drawback of PHS lies in the scarcity of available sites for two large reservoirs and one or two dams. A long lead time (typically ~10 years) and a high cost (typi-

cally hundreds to thousands of million US dollars) for construction and environmental issues (e.g. removing trees and vegetation from the large amounts of land prior to the reservoir being flooded) [45,46] are the other three major constraints in the deployment of PHS.

4.2. Compressed air energy storage

CAES is the only other commercially available technology (besides the PHS) capable of providing very large energy storage deliverability (above 100 MW with single unit). Fig. 6 shows a schematic diagram of a CAES system [62]. It consists of five major components: (1) A motor/generator that employs clutches to provide alternate engagement to the compressor or turbine trains. (2) An air compressor of two or more stages with intercoolers and after-coolers, to achieve economy of compression and reduce the moisture content of the compressed air. (3) A turbine train, containing both high- and low pressure turbines. (4) A cavity/container for storing compressed air, which can be underground rock caverns created by excavating comparatively hard and impervious rock formations, salt caverns created by solution- or dry-mining of salt formations, and porous media reservoirs made by water-bearing aquifers or depleted gas or oil fields, e.g. sandstone and fissured lime. (5) Equipment controls and auxiliaries such as fuel storage and heat exchanger units.

CAES works on the basis of conventional gas turbine generation. It decouples the compression and expansion cycles of a conventional gas turbine into two separated processes and stores the energy in the form of elastic potential energy of compressed air. During low demand, energy is stored by compressing air into an air tight space, typically 4.0–8.0 MPa. To extract the stored energy, compressed air is drawn from the storage vessel, heated and then expanded through a high pressure turbine, which captures some of the energy in the compressed air. The air is then mixed with fuel and combusted with the exhaust expanded through a low pressure turbine. Both the high and low pressure turbines are connected to a generator to produce electricity. The waste heat of the exhaust is potentially captured via a recuperator before being released.

CAES systems are designed to cycle on a daily basis and to operate efficiently during partial load conditions. This design approach allows CAES units to swing quickly from generation to compression modes. Utility systems that benefit from the CAES include those with load varying significantly during the daily cycle and with costs varying significantly with the generation level or time of day. In addition, CAES plants can respond to load changes to provide load following because they are designed to sustain frequent start-up/shut-down cycles. CAES systems also have improved environmental characteristics in comparison with conventional intermediate generating units. CAES has a relatively long storage period, low capital costs and high efficiency. The typical rating for a CAES system is in the range of 50–300 MW. This is much higher than other stor-

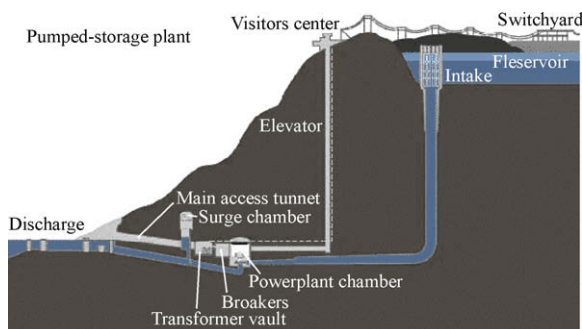


Fig. 5. Schematic diagram of PHS [11].

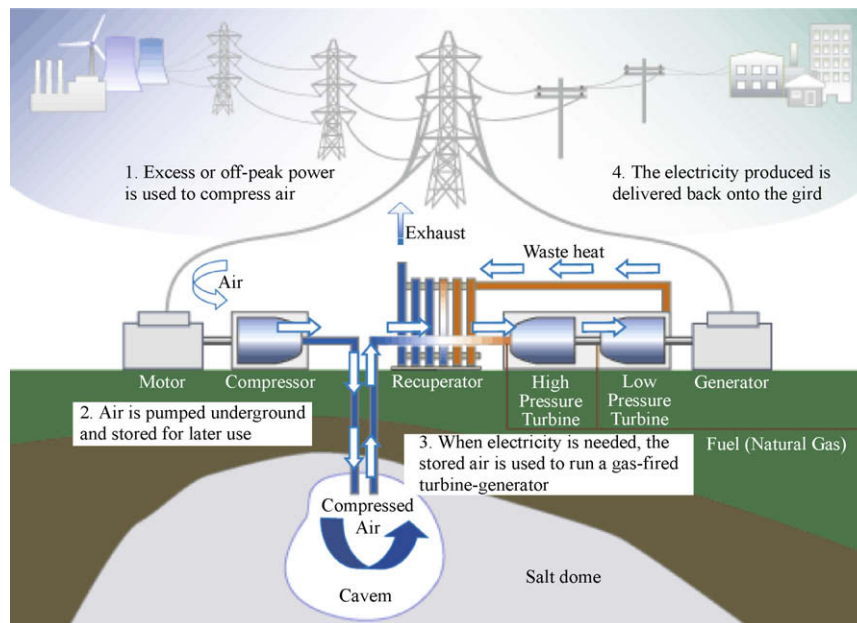


Fig. 6. Schematic diagram of CAES [63].

age technologies except for the PHS. The storage period can be over a year, longer than other storage methods except for the PHS due to very small losses. The storage efficiency of the CAES is in the range of 70–89%. Capital costs for CAES facilities depend on the underground storage conditions, ranging typically between \$400 and \$800 per kW.

There are two CAES units in the world. The first CAES plant is in Huntorf, Germany, and has been in operation since 1978. The unit has a cavern of $\sim 310,000 \text{ m}^3$, converted from a solution mined salt dome located $\sim 600 \text{ m}$ underground, coupled with 60 MW compressors providing a maximum pressure of 10 MPa. It runs on a daily cycle with 8 h of charging and can generate 290 MW for 2 h. The plant has shown an excellent performance with 90% availability and 99% starting reliability. The second CAES plant in McIntosh, Alabama, USA, has been in operation since 1991. The unit compresses air to up to $\sim 7.5 \text{ MPa}$ in an underground cavern of a solution mined salt dome 450 m below the surface. The storage capacity is over $500,000 \text{ m}^3$ with a generating capacity of 110 MW and up to 26 h' working duration. The McIntosh system utilises a recuperator to reuse the heat from the gas turbine, which reduces fuel consumption by $\sim 25\%$ in comparison with the Huntorf CAES plant. There are also several CAES units being planned or under construction [10,12] such as the Norton, Ohio Project ($9 \times 300 \text{ MW}$) developed by Haddington Ventures Inc., Markham, Texas Project ($4 \times 135 \text{ MW}$) developed jointly by Ridege Energy Services and EI Paso Energy, Iowa Project (200 MW) developed by the Iowa Association of Municipal Utilities in the United States, and some other projects, e.g. Chubu Electric Project in Japan and Eskom Project in South Africa.

Similar to the PHS, the major barrier to the implementation of the CAES is also the reliance on favourable geog-

raphy, hence it is only economically feasible for power plants that have nearby rock mines, salt caverns, aquifers or depleted gas fields. In addition, CAES is not an independent system and has to be associated with a gas turbine plant. It cannot be used in other types of power plants such as coal-fired, nuclear, wind turbine or solar photovoltaic plants. More importantly, the requirement of combusting fossil fuels and the contaminating emission render the CAES less attractive [19,45,46]. As a result of this, some improved CAES systems are proposed or under investigation, including the Small-Scale CAES with fabricated small vessels, Advanced Adiabatic CAES (AACAES) with Thermal Energy Storage (TES) [19,21] and Compressed Air Storage with Humidification (CASH) [13,20] etc.

4.3. Battery

Rechargeable/secondary battery is the oldest form of electricity storage [1,2] which stores electricity in the form of chemical energy. A battery comprised of one or more electrochemical cells and each cell consists of a liquid, paste, or solid electrolyte together with a positive electrode (anode) and a negative electrode (cathode). During discharge, electrochemical reactions occur at the two electrodes generating a flow of electrons through an external circuit. The reactions are reversible, allowing the battery to be recharged by applying an external voltage across the electrodes.

Batteries are in some ways ideally suited for electrical energy storage applications. They not only provide fuel flexibility and environmental benefits, but also offer a number of important operating benefits to the electricity utility. They can respond very rapidly to load changes and accept co-generated and/or third-party power, thus enhancing the

system stability. Batteries usually have very low standby losses and can have a high energy efficiency (60–95%). The construction of a secondary battery is facilitated by the short lead times, potentially convenient sitting, and the technology's modularity [16,26]. However, large-scale utility battery storage has been rare up until fairly recently because of low energy densities, small power capacity, high maintenance costs, a short cycle life and a limited discharge capability. In addition, most batteries contain toxic materials. Hence the ecological impact from uncontrolled disposal of batteries must always be considered [6]. Batteries that are either in use and/or potentially suitable for utility scale battery energy storage applications include lead acid, nickel cadmium, sodium sulphur, sodium nickel chloride and lithium ion [27].

4.3.1. Lead acid batteries

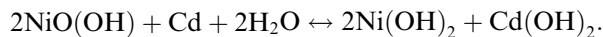
Lead acid batteries, invented in 1859, are the oldest and most widely used rechargeable electrochemical devices. A lead acid battery consists of (in the charged state) electrodes of lead metal and lead oxide in an electrolyte of about 37% (5.99 Molar) sulphuric acid. In the discharged state both electrodes turn into lead sulphate and the electrolyte loses its dissolved sulphuric acid and becomes primarily water. The chemical reactions are (i) Anode: $\text{Pb} + \text{SO}_4^{2-} \leftrightarrow \text{PbSO}_4 + 2\text{e}^-$; and (ii) Cathode: $\text{PbO}_2 + \text{SO}_4^{2-} + 4\text{H}^+ + 2\text{e}^- \leftrightarrow \text{PbSO}_4 + 2\text{H}_2\text{O}$. There are several types of lead acid batteries including the flooded battery requiring regular topping up with distilled water, the sealed maintenance free battery having a gelled/absorbed electrolyte, and the valve regulated battery.

Lead acid battery has a low cost (\$300–600/kWh), and a high reliability and efficiency (70–90%). It is a popular storage choice for power quality, UPS and some spinning reserve applications. Its application for energy management, however, has been very limited due to its short cycle life (500–1000 cycles) and low energy density (30–50 Wh/kg) due to the inherent high density of lead. Lead acid batteries also have a poor low temperature performance and therefore require a thermal management system. Nevertheless, lead acid batteries have been used in a few commercial and large-scale energy management applications such as the 8.5 MWh/1 h system in BEWAG Plant (Berlin, Germany), the 4 MWh/1 h system at the Iberdrola Technology Demonstration Centre (Madrid, Spain), and the 14 MWh/1.5 h system in PREPA (Puerto Rico). The largest one is a 40 MWh system in Chino, California (USA), which works with a rated power of 10 MW for 4 h [58].

4.3.2. Nickel cadmium batteries

Nickel cadmium batteries (NiCd) rank alongside lead-acid systems in terms of their maturity (~100 years) and popularity. NiCd batteries contain a nickel hydroxide positive electrode plate, a cadmium hydroxide negative electrode plate, a separator, and an alkaline electrolyte. NiCd batteries usually have a metal case with a sealing plate equipped with a self-sealing safety valve. The positive and

negative electrode plates, isolated from each other by the separator, are rolled in a spiral shape inside the case. The chemical reaction is



NiCd batteries have a high energy density (50–75 Wh/kg), a robust reliability and very low maintenance requirements, but relatively low cycle life (2000–2500). These advantages over lead acid batteries make them favoured for power tools, portable devices, emergency lighting, UPS, telecoms, and generator starting. However, portable devices such as mobile telephones and laptops have effectively been displaced from these markets by other electrochemistries over the past decade.

The main drawback of NiCd batteries is the relatively high cost (~\$1000/kWh) due to the expensive manufacturing process. Cadmium is a toxic heavy metal hence posing issues associated with the disposal of NiCd batteries. NiCd batteries also suffer from “memory effect”, where the batteries will only take full charge after a series of full discharges. Proper battery management procedures can help to mitigate this effect.

The NiCd system has also achieved significant prominence in terms of its application in the “world's largest (most powerful) battery”, at Golden Valley, Fairbanks, Alaska, USA [57,63]. It comprises four battery strings, each of 3440 cells, with a string voltage of 5200 V. The system is rated at 27 MW for 15 min, 40 MW for 7 min and with an ultimate 46 MVA limitation imposed by the power converter. The batteries are expected to perform 100 complete and 500 partial discharges in the system's 20-year design life. The system here provides critical spinning reserve functionality in what is effectively an “electrical island”.

4.3.3. Sodium sulphur

A NaS battery, as shown in Fig. 7, consists of liquid (molten) sulphur at the positive electrode and liquid (molten) sodium at the negative electrode as active materials separated by a solid beta alumina ceramic electrolyte [64,65]. The electrolyte allows only the positive sodium ions to go through it and combines with sulphur to form sodium polysulphides: $2\text{Na} + 4\text{S} \leftrightarrow \text{Na}_2\text{S}_4$. During discharge positive Na^+ ions flow through the electrolyte and electrons flow in the external circuit of the battery producing ~2.0 V. This process is reversible as charging causes sodium polysulphides to release the positive sodium ions back through the electrolyte to recombine as elemental sodium. The battery is kept at 300–350 °C.

NaS batteries have a typical cycle life of ~2500 cycles. Their typical energy and power density are in the range of 150–240 and 150–230 W/kg, respectively. NaS battery cells are efficient (75–90%) and have a pulse power capability over six times their continuous rating (for 30 s). This attribute enables NaS batteries to be economically used in combined power quality and peak shaving applications. The NaS battery technology has been demonstrated at over

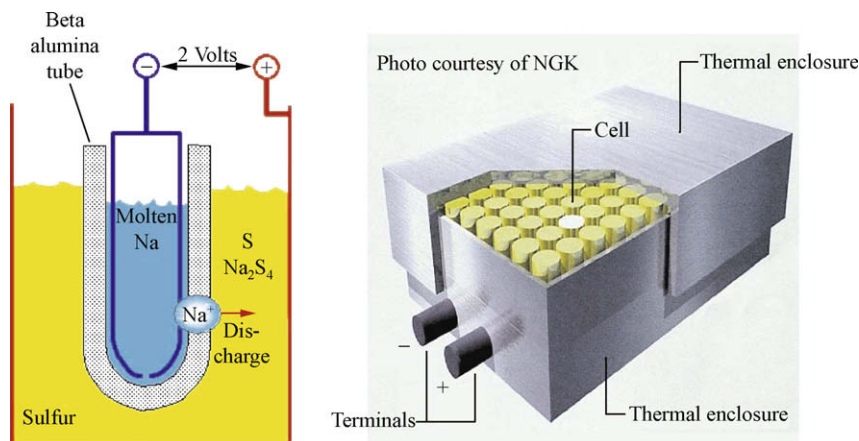


Fig. 7. NaS battery [65,66].

30 sites in Japan totalling more than 20 MW with stored energy suitable for 8 h daily peak shaving, such as the 6 MW/8 h unit in the Tokyo Electric Power Company and the 8 MW/7.25 h at a Hitachi Plant. Such applications of NaS in the U.S. market are under evaluation. American Electric Powers have launched the first demonstration of the NaS system in Ohio with a capacity up to 1.2 MW.

The major drawback is that a heat source is required which uses the battery's own stored energy, partially reducing the battery performance, as the NaS battery needs to operate at a high temperature (300~350 °C) as mentioned above. Initial capital cost is another issue (~\$2000/kWh and ~\$350/kWh), but it is expected to fall as the manufacturing capacity is expanding.

4.3.4. Sodium nickel chloride

The sodium nickel chloride battery [66,67] is better known as the ZEBRA battery. It is a high temperature (~300 °C) system that uses nickel chloride as its positive electrode and has the ability to operate across a broad temperature range (-40 ~ +70 °C) without cooling. The chemical reaction occurring in a ZEBRA battery is: $2\text{NaCl} + \text{Ni} \leftrightarrow \text{NiCl}_2 + 2\text{Na}$.

Compared to NaS batteries, ZEBRA batteries can withstand limited overcharge and discharge and have potentially better safety characteristics and a high cell voltage (2.58 V). The disadvantages with respect to NaS batteries are their low energy density (~120 Wh/kg) and power density (~150 W/kg), although the former still represents a considerable improvement over the lead acid battery technology. Another disadvantage is that only one company, the Beta R&D (UK), in the world produces this kind of battery and the technology was acquired by MES (Swiss) in 1999. Beta R&D became an independent company in 2003 following a management buy out. At present Beta R&D is developing a high power version of the ZEBRA battery for hybrid electric vehicles, a high energy version for storing renewable energy and a load-levelling battery for industrial applications [66,67]. The application of the

ZEBRA batteries in the new NATO Submarine Rescue System (NSRS) has also been announced recently.

4.3.5. Lithium ion batteries

The cathode in this kind of battery is a lithiated metal oxide (LiCoO₂, LiMO₂, LiNiO₂ etc.) and the anode is made of graphitic carbon with a layering structure [64,68]. The electrolyte is made up of lithium salts (such as LiPF₆) dissolved in organic carbonates. When the battery is charged, the lithium atoms in the cathode become ions and migrate through the electrolyte toward the carbon anode where they combine with external electrons and are deposited between the carbon layers as lithium atoms. This process is reversed during the discharge process.

Lithium ion batteries, first proposed in the 1960s, came into reality when Bell Labs developed a workable graphite anode to provide an alternative to lithium metal (lithium battery). The first commercial lithium ion batteries were produced by Sony in 1990. Since then, improved material developments have led to vast improvements in terms of the energy density (increased from 75 to 200 Wh/kg) and cycle life (increased to as high as 10,000 cycles). The efficiency of Li-ion batteries is almost 100% – another important advantage over other batteries.

Although Li-ion batteries take over 50% of the small portable devices market, there are some challenges for making large-scale Li-ion batteries. The main hurdle is the high cost (>\$600/kWh) due to special packaging and internal overcharge protection circuits. Several companies are working to reduce the manufacturing cost of Li-ion batteries to capture large energy markets such the Lithium Battery Energy Storage Technology Association (LIBES), Kyushu Electric Power and Mitsubishi Heavy Industries in Japan who have produced 3 kW demonstration modules. In the United States, the Department of Energy has sponsored a project by SAFT and SatCon Power Systems to design and construct two 100 kW/1-min lithium ion battery energy storage system for use in providing power quality for grid-connected micro-turbines. Both units are being tested at utility partner sites.

4.4. Fuel cell

A fuel cell is an electrochemical energy conversion device. It produces electricity from external supplies of fuel (anode side) and oxidant (cathode side). These react in the presence of an electrolyte. Generally, the reactants flow in and reaction products flow out, while the electrolyte remains in the cell [6,24,28,69]. Fuel cells can operate virtually continuously as long as the necessary flows are maintained. A reversible fuel cell is a fuel cell that is designed to consume chemical A to produce electricity and chemical B, and be reversed to consume electricity and chemical B to produce chemical A. Fuel cells differ from batteries in that they consume reactants, which must be replenished, while batteries store electrical energy chemically in a closed system. Additionally, the electrodes within a battery react and change when a battery is charged or discharged, while a fuel cell's electrodes are catalytic and relatively stable. Many combinations of fuel and oxidant are possible. A hydrogen cell uses hydrogen as fuel and oxygen as oxidant. Other fuels include hydrocarbons, alcohols and even metal. Other oxidants include air, chlorine and chlorine dioxide.

4.4.1. Hydrogen fuel cell

A hydrogen fuel cell uses hydrogen and oxygen to produce electricity and water, as shown in Fig. 8, and a reversible hydrogen fuel cell could also use electricity and water to produce hydrogen and oxygen. Hydrogen-based energy storage systems are receiving increasing attention at the present time, particularly in relation to their integration with renewable power sources. The essential elements comprise an electrolyser unit, to convert the electrical energy input into hydrogen, the hydrogen storage system itself and a hydrogen energy conversion system, to convert the stored chemical energy in the hydrogen back to electrical energy. In addition, there are a range of approaches to producing hydrogen directly from thermo-chemical or photo-chemical processes using concentrated solar energy, although they are at earlier stages of development and will be addressed in Section 4.6. There is a strong technical preference for the generator element to be a fuel cell system, in order to capitalise on its high energy conversion efficiency, although this does not preclude the use of hydrogen burning internal combustion engines. There are a num-

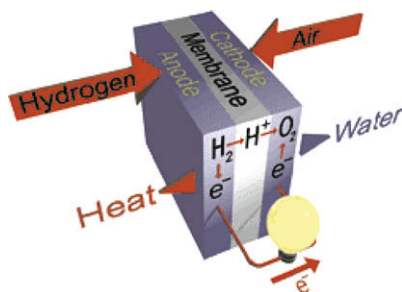


Fig. 8. Hydrogen fuel cell [6,70].

ber of concepts of hydrogen fuel cells, the typical examples include Proton Exchange Membrane Fuel Cells (PEMFCs), Alkaline Fuel Cells (AFCs), Phosphoric Acid Fuel Cells (PAFCs) and Regenerative Fuel Cells (RFCs).

Hydrogen fuel cells possess a number of inherent advantages, including high energy density (0.6–1.2 kWh/kg), ability to implement systems over a wide range of scales, from kW scale to multi-MW capacity, independent system charge rate, discharge rate and storage capacity, modular construction with ability to add further modules and/or re-configuration at a later date, and potential to provide surplus hydrogen off-gas supplies for road transport applications – environmentally benign operating characteristics.

Notwithstanding these advantages, hydrogen fuel cells are generally somewhat at a cost disadvantage (\$6–20/kWh) at the present time and also suffer from a relatively low round-trip efficiency (20–50%), particularly if gas engines are used as the power generation means [24]. This latter aspect may, however, not be a totally limiting aspect, e.g. in a system providing significant added value to an essentially low cost input resource.

4.4.2. Direct-methanol fuel cells

Direct-methanol fuel cell (DMFC) is a subcategory of PEMFC, where, the fuel, methanol (CH_3OH), is not reformed, but fed directly to the fuel cell. Because methanol is fed directly into the fuel cell, complicated catalytic reforming is unnecessary, and storage of methanol is much easier than that of hydrogen, as high pressure or low temperature storage is not needed (methanol is a liquid at -97.0 – 64.7 °C). The DMFC relies upon the oxidation of methanol on a catalyst layer to form carbon dioxide. Water is consumed at the anode and is produced at the cathode. Positive ions (H^+) are transported across the proton exchange membrane (often Nafion) to the cathode where they react with oxygen to produce water. Electrons are transported via an external circuit from anode to cathode providing power to external devices. The half reaction at the anode is $\text{CH}_3\text{OH} + \text{H}_2\text{O} \rightarrow \text{CO}_2 + 6\text{H}^+ + 6\text{e}^-$, whereas that at the cathode is $1.5\text{O}_2 + 6\text{H}^+ + 6\text{e}^- \rightarrow 3\text{H}_2\text{O}$. These give the net reaction of $\text{CH}_3\text{OH} + 1.5\text{O}_2 \rightarrow \text{CO}_2 + 2\text{H}_2\text{O}$.

Because water is consumed at the anode in the reaction, pure methanol cannot be used without provision of water via either passive transport such as back diffusion (osmosis), or via active transport such as pumping. Although the need for water limits the energy density of the fuel cell, the energy density of methanol is orders of magnitude higher than highly compressed hydrogen. However, the efficiency of DMFC is low due to the high permeation of methanol through the membrane (methanol crossover), and the dynamic behaviour is sluggish. Other problems include the management of CO_2 evolved at the anode. Currently, DMFC is limited by the power it can produce, but it can still store a lot of energy in a small space. This means that it can produce a small amount of power over a long period of time. Samsung recently announced a new break-

through in this technology, which is expected to have commercial sales for laptop batteries in the near future. Other issues are associated with the chemical properties of methanol – toxic and flammable.

4.4.3. Molten carbonate fuel cell

Molten carbonate fuel cells (MCFCs) work quite differently from those discussed above [69]. These cells use either molten lithium potassium or lithium sodium carbonate salts as the electrolyte. When heated to a temperature of around 650 °C, these salts melt and generate carbonate ions which flow from the cathode to the anode where they combine with hydrogen to give water, carbon dioxide and electrons. These electrons are routed through an external circuit back to the cathode, generating power. Chemical reactions for this type of fuel cell are $\text{CO}_3^{2-} + \text{H}_2 \rightarrow \text{H}_2\text{O} + \text{CO}_2 + 2\text{e}^-$ at the anode and $\text{CO}_2 + 0.5\text{O}_2 + 2\text{e}^- \rightarrow \text{CO}_3^{2-}$ at the cathode.

The high temperature at which these cells operate means that they are able to internally reform hydrocarbons, such as natural gas and petroleum, to generate hydrogen within the fuel cell structure. At these elevated temperatures there is no problem with carbon monoxide poisoning, although sulphur remains a problem, and the platinum catalysts can be substituted by less expensive nickel species. The excess heat generated can also be harnessed and used in combined heat and power plants. The high temperatures do, however, present some problems. The cells take a considerable time to reach the operating temperature, making them unsuitable for transport applications, and the temperature and corrosive nature of the electrolyte probably mean that they are unsafe for home power generation. The high power generating efficiencies mean that they are attractive for use in large-scale industrial processes and electricity generating turbines. Current demonstration cells have produced up to 2 MW, but designs up to 50 and 100 MW capacities are still on the drawing board [69].

4.4.4. Solid oxide fuel cells

Solid oxide fuel cells (SOFCs) work at even higher temperatures than the MCFCs. They use a solid ceramic electrolyte, such as zirconium oxide stabilised with yttrium oxide, instead of a liquid, and operate at 800–1000 °C. In these fuel cells, energy is generated by the migration of oxygen anions from the cathode to the anode to oxidise the gaseous fuel, which is typically a mixture of hydrogen and carbon monoxide. The electrons generated at the anode move via an external circuit back to the cathode where they reduce the incoming oxygen, thereby completing the cycle. The reactions taking place in the anode are $\text{H}_2 + \text{O}^{2-} \rightarrow \text{H}_2\text{O} + 2\text{e}^-$ and $\text{CO} + \text{O}^{2-} \rightarrow \text{CO}_2 + 2\text{e}^-$, whereas the reaction at the cathode is $\text{O}_2 + 4\text{e}^- \rightarrow 2\text{O}^{2-}$.

With the MCFC, the high temperature means that these cells are resistant to poisoning by carbon monoxide as it is readily oxidised to give carbon dioxide. This removes the need for external reforming to extract hydrogen from the fuel and these cells can again use petroleum or natural

gas directly. SOFCs also exhibit the highest tolerance to sulphur contamination among all the fuel cell technologies so far. These cells are more stable than MCFCs due to the solid electrolyte but the construction materials needed to contain the high temperatures tend to be more expensive. The SOFCs can have an efficiency of around 60% and are expected to be used for generating electricity and heat in industry and potentially for providing auxiliary power in vehicles.

4.4.5. Metal-Air battery

Metal-Air battery can be regarded [64,70] as a special type of fuel cell using metal as the fuel and air as the oxidant as is shown in Fig. 9. Metal-Air batteries are the most compact and, potentially, the least expensive batteries. They are also environmentally benign. The main disadvantage, however, is that electrical recharging of these batteries is very difficult and inefficient. Although many manufacturers offer refuel units, where the consumed metal is mechanically replaced and processed separately, few developers offer an electrically rechargeable battery. Rechargeable metal-air batteries that are under development have a life of only a few hundred cycles and the efficiency is below 50%.

The anodes in these batteries are commonly available metals with a high energy density such as aluminium or zinc that release electrons when oxidised. The cathodes or air electrodes are often made of a porous carbon structure or of a metal mesh covered with proper catalysts. The electrolytes are often a good OH-ion conductor such as KOH. The electrolyte may be in the liquid form or a solid polymer membrane saturated with KOH. For example, reactions of Zinc-Air battery are $\text{Zn} + 4\text{OH}^- \rightarrow \text{Zn}(\text{OH})_4^{2-} + 2\text{e}^-$ at the anode, $\text{Zn}(\text{OH})_4^{2-} \rightarrow \text{ZnO} + \text{H}_2\text{O} + 2\text{OH}^-$ in the fluid and $\text{O}_2 + 2\text{H}_2\text{O} + 4\text{e}^- \rightarrow 4\text{OH}^-$ at the cathode, with the overall reaction given as $2\text{Zn} + \text{O}_2 \rightarrow 2\text{ZnO}$. While the high energy density and low cost of Metal-Air batteries may make them ideal for many primary battery applica-

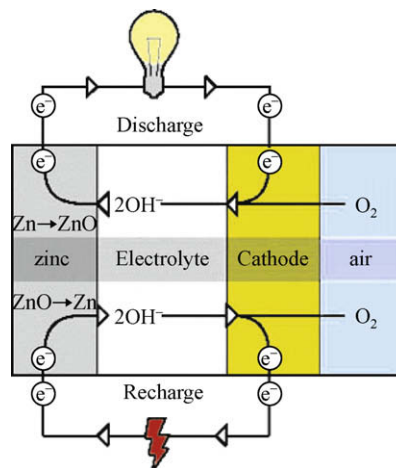


Photo Courtesy of EVonyx Inc.

Fig. 9. Metal-Air battery [65,71].

tions, the electrical rechargeability of the batteries needs to be developed further.

4.5. Flow battery

A flow battery, as shown in Fig. 10, is a form of a battery in which the electrolyte contains one or more dissolved electroactive species flowing through a power cell/reactor in which the chemical energy is converted to electricity. Additional electrolyte is stored externally, generally in tanks, and is usually pumped through the cell (or cells) of the reactor. The reaction is reversible allowing the battery to be charged, discharged and recharged. In contrast to conventional batteries, flow batteries store energy in the electrolyte solutions. The power and energy ratings are independent of the storage capacity determined by the quantity of electrolyte used and the power rating by the active area of the cell stack. Flow batteries can release energy continuously at a high rate of discharge for up to 10 h. In contrast to fuel cells in which only the electroactive chemicals (e.g. hydrogen, methanol, and oxygen) flow through the reactor, and the electrolyte remains at all times within the reactor, flow batteries drive the electrolyte (generally the majority in weight and volume terms) flows through the reactor. Flow batteries are also distinguished from fuel cells by the fact that the chemical reaction involved is often reversible, i.e. they are generally of the secondary battery type and so they can be recharged without replacing the electroactive material.

There are three different electrolytes that form the basis of the existing designs of flow batteries currently in demonstration or in large-scale project development.

4.5.1. Vanadium redox battery (VRB)

VRB stores energy by employing vanadium redox couples (V^{2+}/V^{3+} in the negative and V^{4+}/V^{5+} in the positive half-cells) [64]. These are stored in mild sulphuric acid solutions (electrolytes). During the charge/discharge cycles, H^+ ions are exchanged between the two electrolyte tanks

through the hydrogen-ion permeable polymer membrane. The reactions can be expressed simply by $V^{4+} \leftrightarrow V^{5+} + e^-$ at the positive electrode and $V^{3+} + e^- \leftrightarrow V^{2+}$ at the negative electrode. The cell voltage is 1.4–1.6 V and the efficiency can be as high as 85%.

VRB is suitable for a wide range of energy storage applications for electricity utilities and industrial end-users. These include enhanced power quality, UPSs, peak shaving, increased security of supply and integration with renewable energy systems. The majority of development work has focused on stationary applications due to the relatively low energy density.

VRB was pioneered in the University of New South Wales (UNSW), Australia, in the early 1980s. The Australian Pinnacle VRB bought the basic patents in 1998 and licensed them to Sumitomo Electric Industries (SEI) and VRB Power Systems. VRB storages of up to 500 kW, 10 h (5 MWh) have been installed in Japan by SEI for Kwansai Gakuin University, etc. VRB has also been applied for power quality applications (3 MW, 1.5 s, SEI) for Tottori Sanyo Electric.

4.5.2. Zinc bromine battery (ZnBr battery)

In each cell of a ZnBr battery [64,71], two different electrolytes flow past carbon-plastic composite electrodes in two compartments separated by a microporous polyolefin membrane. During discharge, Zn and Br combine into zinc bromide, generating 1.8 V across each cell. This will increase the Zn^{2+} and Br-ion density in both electrolyte tanks. During charge, metallic zinc will be deposited (plated) as a thin film on one side of the carbon-plastic composite electrode. Meanwhile, bromine evolves as a dilute solution on the other side of the membrane, reacting with other agents (organic amines) to make thick bromine oil that sinks down to the bottom of the electrolytic tank. It is allowed to mix with the rest of the electrolyte during discharge. The net efficiency of this battery is about 75%. The reactions are (i) Positive electrode: $2Br^- \leftrightarrow Br_2(aq) + 2e^-$; (ii) Negative electrode: $Zn^{2+} + 2e^- \leftrightarrow Zn$.

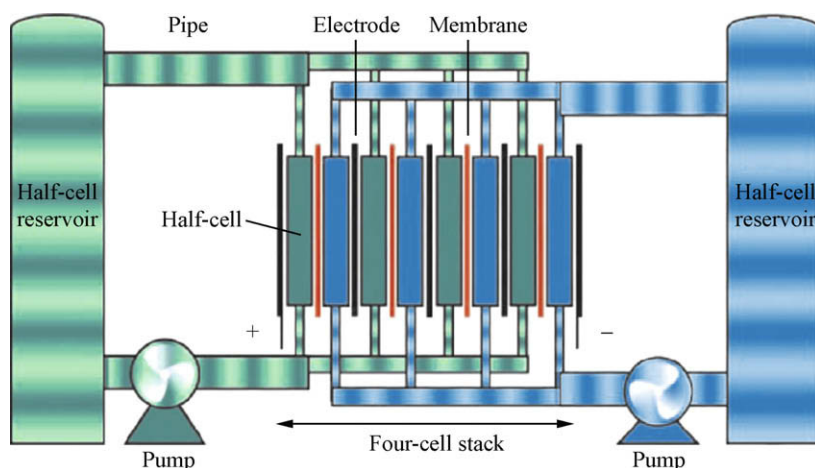


Fig. 10. Schematic of flow battery [13].

The ZnBr battery was developed by Exxon in the early 1970s. Over the years, many kWh ZnBr batteries have been built and tested. Meidisha demonstrated a 1 MW/4 MWh ZnBr battery in 1991 at the Kyushu Electric Power Company. Currently the major companies that develop and supply ZnBr batteries are the ZBB Energy Corporation and the Premium Power Corporation. Some kWh units are now available pre-assembled, complete with plumbing and power electronics. And ZBB can provide the baseline turnkey product F2500, a fully containerised 500 kWh (250 kW × 2 h) grid-interactive storage system. In addition, it can supply individual 50 kWh modules for renewable energy applications as well.

4.5.3. Polysulphide bromide battery (PSB)

PSB [4,64] provides a reversible electrochemical reaction between two salt solution electrolytes (sodium bromide and sodium polysulfide): $3\text{NaBr} + \text{Na}_2\text{S}_4 \leftrightarrow 2\text{Na}_2\text{S}_2 + \text{NaBr}_3$. PSB electrolytes are brought close together in the battery cells where they are separated by a polymer membrane that only allows positive sodium ions to go through, producing about 1.5 V across the membrane. Cells are electrically connected in series and parallel to obtain the desired voltage and current levels. The net efficiency of this battery is about 75%. This battery works at room temperature. It has been verified in the laboratory and demonstrated at multi-kWh scale in the UK.

Regenesys Technologies is building a 120 MWh, 15 MW energy storage plant at Innogy's Little Barford Power Station in the UK. The second demonstration plant is located at Tennessee Valley Authority (TVA) in Columbus, Mississippi (USA) with a 12 MW, 120 MWh capacity.

4.6. Solar fuels

Solar fuels are at an earlier stage of development but have attracted more attention recently. The principle of solar fuels is shown in Fig. 11. By concentrating the diluted sunlight over a small area with the help of parabolic mirrors and then capturing the radiative energy using suitable receivers and reactors, one is able to obtain heat at high temperatures for carrying out an endothermic chemical transformation and producing a storable and transportable fuel [72–75]. The fuels can be stored and/or transported to the customer site for electricity generation.

In principle the energy input to a solar fuel could be provided with electricity; however, re-conversion of recovered heat to electricity via a steam Rankine cycle or other “heat engine” processes would result in a relatively low round trip efficiency. The major competitive advantages of the solar fuel approach are that the change in solar to electric conversion efficiency of a solar energy system with and without storage can be close to zero. The storage becomes an integrated part of the system and replaces components that would have some energy losses anyway. The result is a “virtual” electricity storage system of close to 100% “virtual storage efficiency”. Furthermore, the substitution of

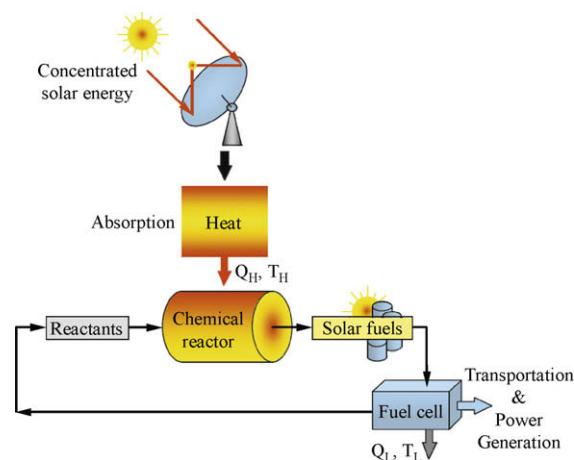


Fig. 11. Solar energy conversion into solar fuels [29].

components plus the ability to downsize the heat engine to run at a higher capacity factor mean that it is conceivable that the cost increment can also be very small [4].

A number of fuels can be produced by solar energy. The following are the three key examples:

- (1) *Solar hydrogen*: Five thermo-chemical routes for solar hydrogen production are depicted in Fig. 12. The figure shows the chemical sources for hydrogen production, including water for the solar thermolysis and solar thermo-chemical cycles, fossil fuels for the solar cracking, and a combination of fossil fuels and H₂O for the solar reforming and solar gasification. All of these routes make use of concentrated solar radiation as the energy source of high-temperature process heat [72–75].
- (2) *Solar metal*: Metals are attractive candidates for storage and transport of energy. They may be used to generate either high-temperature heat via combustion or electricity via fuel cells (batteries) as mentioned in Section 4.4. The chemical products from these power generating processes are metal oxides which, in turn, need to be reduced and recycled. The conventional extraction of metals from their oxides by carbothermic and electrolytic processes is characterized by high energy consumption and concomitant environmental pollution. Both the issues can be substantially reduced by using concentrated solar energy as the source of high temperature process heat [29]. The solar thermal dissociation of ZnO is among the most promising metal oxide processes because of relatively low reaction temperature [75,76].
- (3) *Solar chemical heat pipe*: High temperature solar process heat is used for driving an endothermic reversible reaction in a solar chemical reactor. The products can be stored for a long term and transported over a long range to the customer site where the energy is needed. At that site, the exothermic reverse reaction is effected, yielding process heat in an amount equal

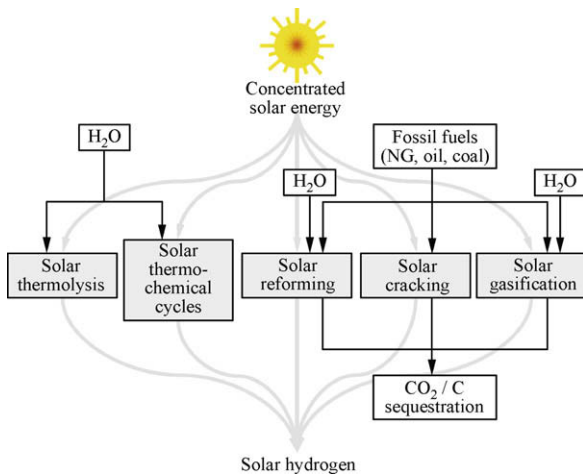


Fig. 12. Routes for solar hydrogen [29].

to the stored solar energy $\Delta H_{A \rightarrow B}$. This high-temperature heat may be applied, for example, to generate electricity. The chemical products for the reverse reaction are the original chemicals; they are returned to the solar reactor and the process is repeated. Two reverse reactions that have been extensively investigated for application in chemical heat pipes are the CH₄ reforming methanation and the NH₃ dissociation synthesis [76,77].

4.7. Superconducting magnetic energy storage

SMES is the only known technology to store electrical energy directly into electric current [78]. It stores electric energy as direct electric current passing through an inductor (coil) made from a superconducting material and circular so that current can circulate indefinitely with almost zero loss. SMES can also be used for storing energy as the magnetic field created by the flow of electric current. To maintain the inductor in its superconducting state, it is immersed in liquid helium contained in a vacuum-insulated cryostat. Typically, the conductor is made of niobium-titanium, and the coolant can be liquid helium at 4.2 K, or super fluid helium at 1.8 K. The SMES system normally consists of three major components, as shown in Fig. 13, a superconducting unit, a cryostat system (a cryogenic refrigerator and a vacuum-insulated vessel), and a power conversion system. The energy stored in the SMES coil can be calculated by $E = 0.5LI^2$, where L is the inductance of the coil and I is the current passing through it.

SMES exhibits a very high energy storage efficiency (typically $> \sim 97\%$) and a rapid response (within a few milliseconds) in comparison with other energy storage systems, but only for short periods of time. The energy output of an SMES system is much less dependent on the discharge rate compared with batteries. SMES also has a high cycle life and, as a result, is suitable for applications

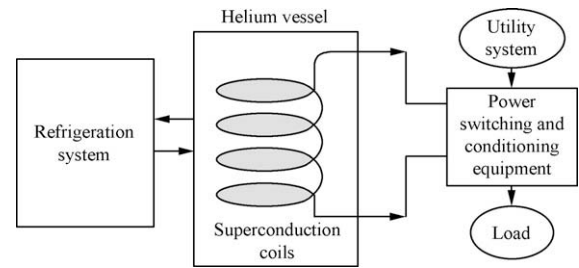


Fig. 13. SMES system [79].

that require constant, full cycling and a continuous mode of operation. These features make SMES suitable for use in solving voltage stability and power quality problems for large industrial customers. The typical rating is 1–10 MW a storage time of seconds although research is being conducted on larger SMES systems in the range of 10–100 MW and with a storage time of minutes [31].

The initial proposal of an SMES was brought up by Ferrier in 1969 in France. In 1971 research began in the US by the University of Wisconsin, which led to construction of the first SMES device. Afterward the development of SMES was rapid. Many companies developed their SMES systems (Hitachi, 1986, ISTECH, 1998, Wisconsin Public Service Corporation, 2000, ACCEL Instruments GmbH, 2005, etc.) and over 100 MW of SMES units are now in operation worldwide.

The major problems confronting the implementation of SMES units are the high cost and environmental issues associated with strong magnetic field [31].

4.8. Flywheel

Flywheels have been used to store energy for thousands of years [9,78–80]. They store energy in the angular momentum of a spinning mass. During charge, the flywheel is spun up by a motor; during discharge, the same motor acts as a generator producing electricity from the rotational energy of the flywheel. The total energy of a flywheel system is dependent on the size and speed of the rotor, and the power rating is dependent on the motor-generator.

Fig. 14 shows a typical flywheel storage device which consists of a flywheel that spins at a very high velocity to achieve maximum storage of rotational kinetic energy within the given constraints, a containment system that provides a high vacuum environment (10^{-6} – 10^{-8} atmospheric pressure) to minimise windage losses and to protect the rotor assembly from external disturbances, a bearing assembly providing a very low loss support mechanism for the flywheel rotor, and a power conversion and control system for operating the flywheel to store energy or generate the electricity on demand [78–80].

The major advantage of flywheel over batteries is that they have a long life capable of providing several hundreds of thousands of full charge–discharge cycles [80]. The efficiency of flywheels is high and typically in the range of

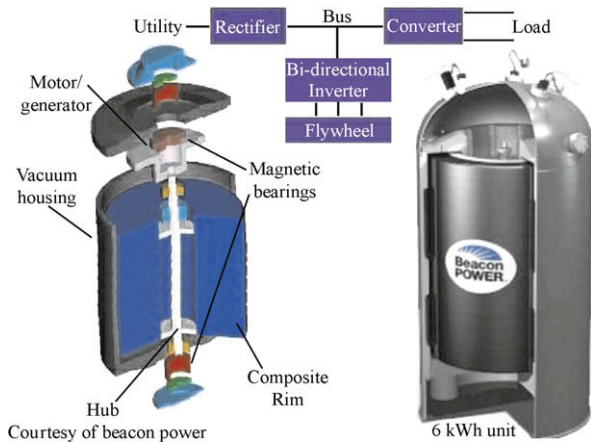


Fig. 14. Flywheel system [80].

90–95%. The applications of flywheels are principally on high power/short duration applications (e.g. 100 s of kW/10 s of seconds). The most common application is to act as a power quality device to provide ride-through of interruptions up to 15 s long or to bridge the shift from one power source to another. Such systems may be implemented in a hybrid configuration with stand-by generators (e.g. diesel generators). Flywheels have also been used for demand reduction and energy recovery in electrically powered mass transit systems. MW scale flywheels can also be used for reactive power support, spinning reserve and voltage regulation by power-quality-sensitive customers such as communications facilities and computer server centres, the duration could be up to tens of minutes with a magnetic levitation bearing. Ureco Power Technologies (UPT) has recently demonstrated the application of flywheel to the smoothing of the output of wind turbine systems and the associated stabilisation of small-scale island power supply networks [79,80]. The rail traction industry represents another significant and high added value application for flywheel storage, particularly for trackside voltage support [9,33]. Compared with other EESs, the relatively short duration, high frictional loss (windage) and low energy density restrain the flywheel systems from the application in energy management.

The flywheel systems can be categorised into two groups, conventional metal rotor systems and high speed composite systems. The conventional metal rotor systems, with low speed metal rotor, lack the necessary energy and have relatively large standby losses. They are therefore typically used for short-term (~10–100 s) and medium/high load applications. The leading commercial suppliers of such flywheels are Piller (Germany), Active Power (US), Satcon (US) and Caterpillar (US). Much of the current R&D on flywheel EES is directed towards high speed composite machines, running at 10,000s RPM and utilising fabric composite materials [33]. The high directional strength properties of such composites, in combination with their relatively low density, allow the designers freedom in optimising the overall configuration hence specific energy and

specific power. Units have already been supplied on a commercial basis by UPT and with further systems being developed by AFS-Trinity, Beacon Power, Piller, etc. Typical products are rated at 100–250 kWe with 3.3–25 kWh stored energy [79].

4.9. Capacitor

The most direct and literal way of storing electrical energy is with a capacitor. In its simplest form, a capacitor consists of two metal plates separated by a nonconducting layer called a dielectric. When one plate is charged with electricity from a direct-current source, the other plate will have induced in it a charge of the opposite sign as shown in Fig. 15 [4,64].

Capacitors can be charged substantially faster than conventional batteries and cycled tens of thousands of times with a high efficiency. Conventional capacitors have been developed for daily peak load in summer for less than 1 h with small capacities (~kW). However, the main problem presented by conventional capacitors is the low energy density. If a large capacity is required, the area of the dielectric must be very large. This fact makes the use of large capacitors uneconomical and often cumbersome. This is particularly true in stationary EES applications [41,43].

Recent progress in the electrochemical capacitors/supercapacitors could lead to much greater capacitance and energy density than conventional capacitors, thus enabling compact designs. The supercapacitors store energy by means of an electrolyte solution between two solid conductors rather than the more common arrangement of a solid dielectric between the electrodes. The electrodes are often made from porous carbon or another high surface area material as the conductor with an aqueous or non-aqueous electrolyte. Since the surface area of activated carbons is very high, i.e. up to 2000 m² per gram, and since the distance between the plates is very small (less than 1 nm), very large capacitances and stored energy are possible using supercapacitors. The energy storage capabilities of supercapacitors are substantially greater than that of conventional

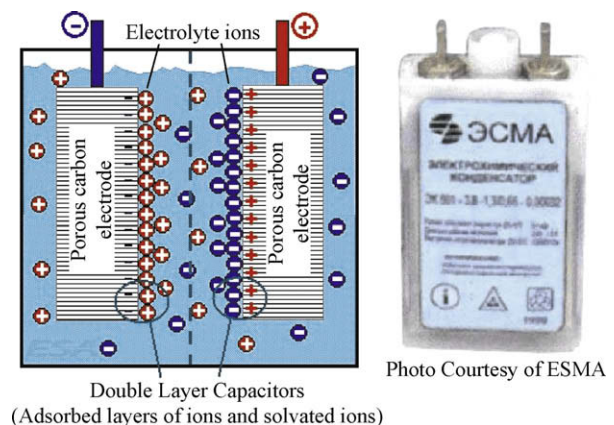


Fig. 15. Capacitor/supercapacitor [65].

capacitors, by approximately two orders of magnitude (10–100 s kW) [41,43].

The major problems with capacitors, similar to flywheels, are the short durations and high energy dissipations due to self-discharge loss. Therefore, similar to flywheel, capacitors are mainly used in power quality applications such as ride-through and bridging, as well as for energy recovery in mass transit systems [4]. On the other hand, although the small electrochemical capacitors are well developed, large units with energy densities over 20 kWh/m³ are still in the development stage.

There are a large number of developers of capacitors/supercapacitors. The leading companies include SAFT (France), NESS (Korea), ESMA (Russia), PowerCache (Maxwell, USA), ELIT (Russia), PowerSystem Co. (Japan) and Chubu Electric Power (Japan), etc. [64].

4.10. Thermal energy storage

TES already exists in a wide spectrum of applications. It uses materials that can be kept at high/low temperatures in insulated containments. Heat/cold recovered can then be applied for electricity generation using heat engine cycles. Energy input can, in principle, be provided by electrical resistance heating or refrigeration/cryogenic procedures, hence the overall round trip efficiency of TES is low (30–60%) although the heat cycle efficiency could be high (70–90%), but it is benign to the environment and may have particular advantages for renewable and commercial buildings.

TES systems can be classified into low-temperature TES and high-temperature TES depending on whether the operating temperature of the energy storage material is higher than the room temperature. More precisely, TES can be categorised into industrial cooling (below –18 °C), building cooling (at 0–12 °C), building heating (at 25–50 °C) and industrial heat storage (higher than 175 °C).

4.10.1. Low-temperature TES

The low-temperature TES technologies currently in use and under development are briefly described as follows:

- (1) *Aquiferous low-temperature TES (AL-TES)*: Water is cooled/iced by a refrigerator in off-peak hours and stored for later use to meet the cooling needs during the peak time. The amount of stored cooling energy depends on the temperature difference (plus fusion heat for iced water) between the chilled/iced water stored in the tank and the warm return water from the heat exchanger. Aquiferous energy storage is particularly suitable for peak shaving commercial and industrial cooling loads during the daytime, especially for large commercial buildings, allowing for smaller chillers and substantially lower air conditioning operating costs, particularly peak demand charges.

- (2) *Cryogenic Energy Storage (CES)*: CES is a new electricity energy storage system [41–43,81,82]. The principle of such a technology is shown in Fig. 16. Cryogen (e.g. liquid nitrogen or liquid air) is generated by off-peak power or renewable generated electricity or even through direct mechanical work from a hydro or wind turbines (electricity is stored). During the peak time, heat from the surrounding environment boils the liquid, the heated cryogen is used to generate electricity using a cryogenic heat engine (electricity is released). At the same time, the waste heat from the flue gas of the power plant, if available, can be used by the CES. CES can also provide direct cooling and refrigeration, air conditioning units and act as the power for vehicles [42,81,82]. CES could have a relatively high energy density (100–200 Wh/kg), low capital cost per unit energy, be benign to the environment and have a relatively long storage period. However, CES has a relatively low efficiency (40~50%) according to the current energy consumption for air liquefaction. CES is still under development by the University of North Texas (USA) and the University of Washington (USA) [81–85], Mitsubishi (Japan) [40], the University of Leeds (UK) and the Chinese Academy of Sciences (China) [41–43].

4.10.2. High-temperature TES

The high-temperature TES technologies in use and under development include [1,86]:

- (1) *Molten salt storage and Room Temperature Ionic Liquids (RTILs)*: RTILs are organic salts with negligible vapour pressure in the relevant temperature range and a melting temperature below 25 °C. Such liquids have been proposed for energy storage, which have the potential to be stored at temperatures of many 100s of degrees without decomposing. The state of the art use of RTILs for energy storage is the so-called 2-tank molten salt storage tested in the “Solar

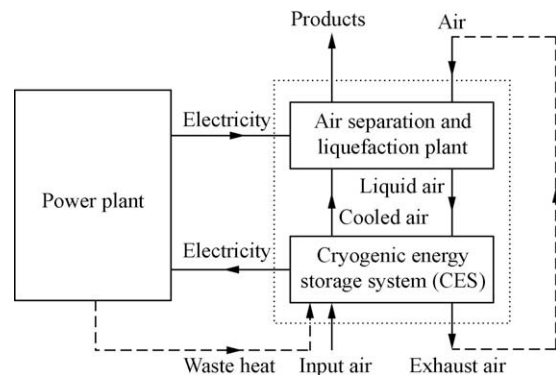


Fig. 16. Schematic diagram of CES [41].

Two” Central Receiver Solar Power Plant demonstration project in California, combined with using molten salt as the heat transfer fluid.

- (2) *Concrete storage*: The concept of using concrete or castable ceramics to store energy at high temperatures for parabolic trough power plants with synthetic oil as the heat transfer fluid (HTF) has been investigated in European projects. The implementation of a concrete storage system is claimed to be realisable within less than 5 years.
- (3) *Phase Change Materials (PCMs)*: PCMs are materials selected to have a phase change (usually solid to liquid) at a temperature matching the thermal input source. The high “latent heat” in a phase change offers the potential for higher energy storage densities than storage of non phase change high temperature materials. Because a solid/liquid phase change is involved, a heat transfer mean is needed to move heat from the source to PCM. At present, two principle approaches are being investigated: encapsulation of small amounts of PCM and embedding of PCM in a matrix made of another solid material with high heat conduction. Storage based on PCM is still in an early stage of development.

Other high-temperature TES technologies under development include air receivers using solid materials, saturated water/steam, high-purity graphite, [1,86] etc.

5. Assessment and comparison of the energy storage technologies

5.1. Technical maturity

The technical maturity of the EES systems is shown in Fig. 17. The EES technologies can be classified into three categories in terms of their maturity:

- (1) *Mature technologies*: PHS and lead-acid battery are mature and have been used for over 100 years.
- (2) *Developed technologies*: CAES, NiCd, NaS, ZEBRA Li-ion, Flow Batteries, SMES, flywheel, capacitor, supercapacitor, AL-TES and HT-TES are developed

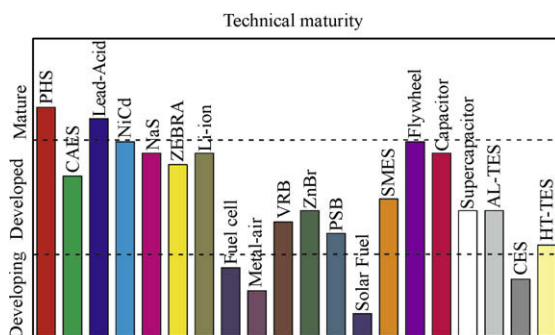


Fig. 17. Technical maturity of EES systems.

technologies. All these EES systems are technically developed and commercially available; however, the actual applications, especially for large-scale utility, are still not widespread. Their competitiveness and reliability still need more trials by the electricity industry and the market.

- (3) *Developing technologies*: Fuel cell, Metal-Air battery, Solar Fuel and CES are still under development. They are not commercially mature although technically possible and have been investigated by various institutions. On the other hand, these developing technologies have great potential for industrial take-up in the near future. Energy costs and environmental concerns are the main drivers.

5.2. Power rating and discharge time

The power ratings of various EESs are compared in Table 1. Broadly, the EESs fall into three types according to their applications:

- (1) *Energy management*: PHS, CAES and CES are suitable for applications in scales above 100 MW with hourly to daily output durations. They can be used for energy management for large-scale generations such as load leveling, ramping/load following, and spinning reserve. Large-scale batteries, flow batteries, fuel cells, solar fuels, CES and TES are suitable for medium-scale energy management with a capacity of 10–100 MW.
- (2) *Power quality*: Flywheel, batteries, SMES, capacitor and supercapacitor have a fast response (\sim milliseconds) and therefore can be utilized for power quality such as the instantaneous voltage drop, flicker mitigation and short duration UPS. The typical power rating for this kind of application is lower than 1 MW.
- (3) *Bridging power*: Batteries, flow batteries, fuel cells and Metal-Air cells not only have a relatively fast response ($< \sim 1$ s) but also have relatively long discharge time (hours), therefore they are more suitable for bridging power. The typical power rating for these types of applications is about 100 kW–10 MW.

5.3. Storage duration

Table 1 also illustrates the self-discharge (energy dissipation) per day for EES systems. One can see that PHS, CAES, Fuel Cells, Metal-Air Cells, solar fuels and flow batteries have a very small self-discharge ratio so are suitable for a long storage period. Lead-Acid, NiCd, Li-ion, TESs and CES have a medium self-discharge ratio and are suitable for a storage period not longer than tens of days.

NaS, ZEBRA, SMES, capacitor and supercapacitor have a very high self-charge ratio of 10–40% per day. They

Table 1
Comparison of technical characteristics of EES systems.

Systems	Power rating and discharge time		Storage duration		Capital cost		
	Power rating	Discharge time	Self discharge per day	Suitable storage duration	\$/kW	\$/kWh	¢/kWh-Per cycle
PHS	100–5000 MW	1–24 h+	Very small	Hours–months	600–2000	5–100	0.1–1.4
CAES	5–300 MW	1–24 h+	Small	Hours–months	400–800	2–50	2–4
Lead-acid	0–20 MW	Seconds–hours	0.1–0.3%	Minutes–days	300–600	200–400	20–100
NiCd	0–40 MW	Seconds–hours	0.2–0.6%	Minutes–days	500–1500	800–1500	20–100
NaS	50 kW–8 MW	Seconds–hours	~20%	Seconds–hours	1000–3000	300–500	8–20
ZEBRA	0–300 kW	Seconds–hours	~15%	Seconds–hours	150–300	100–200	5–10
Li-ion	0–100 kW	Minutes–hours	0.1–0.3%	Minutes–days	1200–4000	600–2500	15–100
Fuel cells	0–50 MW	Seconds–24 h+	Almost zero	Hours–months	10,000+		6000–20,000
Metal-Air	0–10 kW	Seconds–24 h+	Very small	Hours–months	100–250	10–60	
VRB	30 kW–3 MW	Seconds–10 h	Small	Hours–months	600–1500	150–1000	5–80
ZnBr	50 kW–2 MW	Seconds–10 h	Small	Hours–months	700–2500	150–1000	5–80
PSB	1–15 MW	Seconds–10 h	Small	Hours–months	700–2500	150–1000	5–80
Solar fuel	0–10 MW	1–24 h+	Almost zero	Hours–months	–	–	–
SMES	100 kW–10 MW	Milliseconds–8 s	10–15%	Minutes–hours	200–300	1000–10,000	
Flywheel	0–250 kW	Milliseconds–15 min	100%	Seconds–minutes	250–350	1000–5000	3–25
Capacitor	0–50 kW	Milliseconds – 60 min	40%	Seconds–hours	200–400	500–1000	
Super-capacitor	0–300 kW	Milliseconds – 60 min	20–40%	Seconds–hours	100–300	300–2000	2–20
AL-TES	0–5 MW	1–8 h	0.5%	Minutes–days		20–50	
CES	100 kW–300 MW	1–8 h	0.5–1.0%	Minutes–days	200–300	3–30	2–4
HT-TES	0–60 MW	1–24 h+	0.05–1.0%	Minutes–months		30–60	

can only be implemented for short cyclic periods of a maximum of several hours. The high self-discharge ratios of NaS and ZEBRA are from the high working temperature which needs to be self-heating to maintain the use of the storage energy.

Flywheels will discharge 100% of the stored energy if the storage period is longer than about 1 day. The proper storage period should be within tens of minutes.

5.4. Capital cost

Capital cost is one of the most important factors for the industrial take-up of the EES. They are expressed in the forms shown in Table 2, cost per kWh, per kW and per kWh per cycle. All the costs per unit energy shown in the table have been divided by the storage efficiency to obtain the cost per output (useful) energy. The per cycle cost is defined as the cost per unit energy divided by the cycle life which is one of the best ways to evaluate the cost of energy storage in a frequent charge/discharge application, such as load levelling. For example, while the capital cost of lead-acid batteries is relatively low, they may not necessarily be the least expensive option for energy management (load levelling) due to their relatively short life for this type of application. The costs of operation and maintenance, disposal, replacement and other ownership expenses are not

considered, because they are not available for some emerging technologies.

CAES, Metal-Air battery, PHS, TESs and CES are in the low range in terms of the capital cost per kWh. The Metal-Air batteries may appear to be the best choice based on their high energy density and low cost, but they have a very limited life cycle and are still under development. Among the developed techniques, CAES has the lowest capital cost compared to all the other systems. The capital cost of batteries and flow batteries is slightly higher than the break even cost against the PHS although the gap is gradually closing. The SMES, flywheel, capacitor and supercapacitor are suitable for high power and short duration applications, since they are cheap on the output power basis but expensive in terms of the storage energy capacity.

The costs per cycle kWh of PHS and CAES are among the lowest among all the EES technologies, the per cycle cost of batteries and flow batteries are still much higher than PHS and CAES although a great decrease has occurred in recent years. CES is also a promising technology for low cycle cost. However, there are currently no commercial products available. Fuel cells have the highest per cycle cost and it will take a long time for them to be economically competitive. No data have been found for the solar fuels as they are in the early stage of development.

It should also be noted that the capital cost of energy storage systems can be significantly different from the esti-

Table 2
Comparison of technical characteristics of EES systems.

Systems	Energy and power density				Life time and cycle life		Influence on environment	
	Wh/kg	W/kg	Wh/L	W/L	Life time (years)	Cycle life (cycles)	Influence	Description
PHS	0.5–1.5		0.5–1.5		40–60		Negative	Destruction of trees and green land for building the reservoirs
CAES	30–60		3–6	0.5–2.0	20–40		Negative	Emissions from combustion of natural gas
Lead-acid	30–50	75–300	50–80	10–400	5–15	500–1000	Negative	Toxic remains
NiCd	50–75	150–300	60–150		10–20	2000–2500		
NaS	150–240	150–230	150–250		10–15	2500		
ZEBRA	100–120	150–200	150–180	220–300	10–14	2500+		
Li-ion	75–200	150–315	200–500		5–15	1000–10,000+		
Fuel cell	800–10,000	500+	500–3000	500+	5–15	1000+	Negative	Remains and/or combustion of fossil fuel
Metal-Air	150–3000		500–10,000			100–300	Small	Little amount of remains
VRB	10–30		16–33		5–10	12,000+	Negative	Toxic remains
ZnBr	30–50		30–60		5–10	2000+		
PSB	–	–	–	–	10–15			
Solar fuel	800–100,000		500–10,000		–	–	Benign	Usage and storage of solar energy
SMES	0.5–5	500–2000	0.2–2.5	1000–4000	20+	100,000+	Negative	Strong magnetic fields
Flywheel	10–30	400–1500	20–80	1000–2000	~15	20,000+	Almost none	
Capacitor Super-	0.05–5	~100,000	2–10 capacitor	100,000+ 2.5–15	~5 500–5000	50,000+ 10–30	Small	Little amount of remains 100,000+
20+		100,000+	Small	Little amount of remains				
AL-TES	80–120		80–120		10–20		Small	
CES	150–250	10–30	120–200		20–40		Positive	Removing contaminates during air liquefaction (Charge)
HT-TES	80–200		120–500		5–15		Small	

mations given here due to, for example, breakthroughs in technologies, time of construction, location of plants, and size of the system. The information summarised here should only be regarded as being preliminary.

5.5. Cycle efficiency

The cycle efficiency of EES systems during one charge-discharge cycle is illustrated in Fig. 18. The cycle efficiency is the “round-trip” efficiency defined as $\eta = E_{out}/E_{in}$, with η , E_{out} and E_{in} being the cycle efficiency, electricity input and electricity output, respectively. The self-discharge loss during the storage is not considered and has been addressed in Section 5.3. One can see that the EES systems can be broadly divided into three groups:

- (1) *Very high efficiency*: SMES, flywheel, supercapacity and Li-ion battery have a very high cycle efficiency of > 90%.
- (2) *High efficiency*: PHS, CAES, batteries (except for Li-ion), flow batteries and conventional capacitor have a cycle efficiency of 60–90%. It can also be seen that

storing electricity by compression and expansion of air using the CAES is usually less efficient than pumping and discharging water with PHSs, since rapid compression heats up a gas, increasing its pressure thus making further compression more energy-consuming.

- (3) *Low efficiency*: Hydrogen, DMFC, Metal-Air, solar fuel, TESs and CES have an efficiency lower than ~60% mainly due to large losses during the conver-

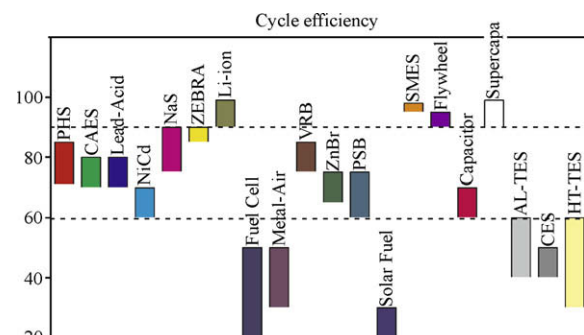


Fig. 18. Cycle efficiency of EES systems.

sion from the commercial AC side to the storage system side. For example, hydrogen storage of electricity has relatively low round-trip energy efficiency (~20–50%) due to the combination of electrolyser efficiency and the efficiency of re-conversion back to electricity.

It must be noted that there is a trade-off between the capital cost and round-trip efficiency, at least to some extent. For example, a storage technology with a low capital cost but a low round-trip efficiency may well be competitive with a high cost, high round-trip efficiency technology.

5.6. Energy and power density

The power density (W/kg or W/litre) is the rated output power divided by the volume of the storage device. The energy density is calculated as a stored energy divided by the volume. The volume of the storage device is the volume of the whole energy storage system including the energy storing element, accessories and supporting structures, and the inverter system. As can be seen from Table 1, the Fuel Cells, Metal-Air battery, and Solar fuels have an extremely high energy density (typically ~1000 Wh/kg), although, as mentioned above, their cycle efficiencies are very low. Batteries, TESs, CES and CAES have medium energy density. The energy density of PHS, SMES, Capacitor/supercapacitor and flywheel are among the lowest below ~30 Wh/kg. However, the power densities of SMES, capacitor/supercapacitor and flywheel are very high which are, again, suitable for applications for power quality with large discharge currents and fast responses. NaS and Li-ion have a higher energy density than other conventional batteries. The energy densities of flow batteries are slightly lower than those of conventional batteries. It should be noted that there are differences in the energy density of the same type of EES made by different manufacturers.

5.7. Life time and cycle life

Also compared in Table 1 are life time and/or cycle life for various EESs. It can be seen that the cycle lives of EES systems whose principles are largely based on the electrical technologies are very long normally greater than 20,000. Examples include SMES, capacitor and supercapacitor.

Mechanical and thermal energy storage systems, including PHS, CAES, flywheel, AL-TES, CES and HT-TES, also have long cycle lives. These technologies are based on conventional mechanical engineering, and the life time is mainly determined by the life time of the mechanical components.

The cycle abilities of batteries, flow batteries, and fuel cells are not as high as other systems owing to chemical deterioration with the operating time. Metal-Air battery only has a life of a few hundred cycles and obviously needs to be further developed.

5.8. Influence on environment

The influences of EES on the environment are also compared in Table 1. One can see that solar fuel and CES have positive influences on the environment. Solar fuels use totally renewable energy, solar, to produce electricity, and store it in the form of green fuel like hydrogen. The usage of solar fuels can decrease the combustion of fossil fuels and hence are benign to the environment. CES can remove contaminants in the air during the liquefaction (charging) process, which would help with mitigating the negative environmental issues associated with the burning of fossil fuels. Undesirable airborne particulates can also be removed during production of liquid air.

PHS, CAES, batteries, flow batteries, fuel cells and SMES have negative influences on the environment due to different reasons. The construction of PHS systems inevitably involves destruction of trees and green lands for building reservoirs. The construction of reservoirs could also change the local ecological system, which may have environmental consequences. CAES is based on conventional gas turbine technology and involves combustion of fossil fuel hence emissions can be an environmental concern. Batteries have been suffering from the toxic remains/wastes for a long time [46]. Flow batteries and fuel cells have similar issues as other batteries [45,69,70]. The major environmental issue confronting the implementation of SMES is associated with strong magnetic field [31] which can be harmful to human health. Other EESs have relatively small influences on the environment as they do not involve fossil combustion, landscape damage and toxic remains.

6. Concluding remarks and perspective

Based on the review, the following conclusions could be drawn:

- (1) EES is urgently needed by the conventional electricity generation industry, DER and intermittent renewable energy supply systems. By using EES, challenges faced by the power industry can be greatly reduced. EESs have numerous applications covering a wide spectrum, ranging from large-scale generation and transmission-related systems, to distribution network and even customer/end-user sites. The EES technologies provide three primary functions of energy management, bridging power and power quality and reliability.
- (2) Although there are various commercially available EES systems, no single storage system meets all the requirements for an ideal EES - being mature, having a long lifetime, low costs, high density and high efficiency, and being environmentally benign. Each EES system has a suitable application range. PHS, CAES, large-scale batteries, flow batteries, fuel cells, solar fuels, TES and CES are suitable for energy

management application; flywheels, batteries, capacitors and supercapacitors are more suitable for power quality and short duration UPS, whereas batteries, flow batteries, fuel cells and Metal-Air cells are promising for the bridging power.

- (3) PHS and Lead-Acid battery are technically mature; CAES, NiCd, NaS, ZEBRA Li-ion, flow battery, SMES, flywheel, capacitor, Supercapacitor, AL-TES and HT-TES are technically developed and commercially available; Fuel Cell, Meta-Air battery, Solar Fuel and CES are under development. The capital costs of CAES, Metal-Air battery, PHS, TES and CES are lower than other EESs. CAES has the lowest capital cost among the developed technologies. Metal-Air battery has the potential to be the cheapest among currently known EES systems.
- (4) The cycle efficiencies of SMES, flywheel, capacitor/supercapacitor, PHS, CAES, batteries, flow batteries are high with the cycle efficiency above 60%. Fuel Cell, DMFC, Metal-Air, solar fuel, TES and CES have a low efficiency mainly due to large losses during the conversion from commercial AC to the storage energy form.
- (5) The cycle lives of the EES systems based on the electrical technologies, such as SMES, capacitor and supercapacitor, are high. Mechanical and thermal-based EES, including PHS, CAES, flywheel, AL-TES, CES and HT-TES, also have a long cycle life. The cycle abilities of batteries, flow batteries, and fuel cells are not as high as other systems owing to chemical deterioration with the operating time.
- (6) PHS, CAES, batteries, flow batteries, fuel cells and SMES are considered to have some negative effects on the environment due to one or more of the following: fossil combustion, strong magnetic field, landscape damage, and toxic remains. Solar fuels and CES are more environmentally friendly. However, a full life-cycle analysis should be done before a firm conclusion can be drawn.

Based on the current state-of-the-art development of EES systems, one could expect the following:

- (1) EES system is currently enjoying somewhat of a renaissance with a rapidly accelerating rate of technological development. The anticipated storage level of EES will increase by 10–15% (currently ~3%) of the delivered inventory for the USA and European countries, and even higher for Japan in the near future. This will build up a huge value chain in the electricity industry.
- (2) PHS will remain a dominant EES system at least in the very near future. CAES is expected to have a rapid commercial development especially in countries with favourable geology like the US.

- (3) Large-scale batteries such as lead-acid batteries and NiCd batteries are expected to be gradually implemented for energy management with decreasing price and increasing cycle life. Medium-scaled batteries, such as NaS batteries and sodium nickel chloride batteries, flow batteries and AL-TES, may find applications in local industrial and commercial services such as peak shaving and UPS.
- (4) Further development is expected for commercially available products such as SMES, flywheel and capacitor/supercapacitor stationary EESs. Their performance is expected to be enhanced considerably. Their applications are still focused on power quality applications at least in the very near future. Fuel cells are expected to be mainly used in vehicle applications.
- (5) New technologies such as solar fuel, CES and Metal-Air battery will attract more research and development attention due to their advantages of being benign to the environment and/or having a very high energy density.

References

- [1] McLaren FR, Cairns EJ. Energy storage. *Ann Rev Energy* 1989;14:241–71.
- [2] Baker JN, Collinson A. Electrical energy storage at the turn of the millennium. *Power Eng J* 1999;6:107–12.
- [3] Dti Report. Status of electrical energy storage systems. DG/DTI/00050/00/00, URN NUMBER 04/1878, UK Department of Trade and Industry; 2004, p. 1–24.
- [4] Australian Greenhouse Office. Advanced electricity storage technologies programme. ISBN: 1 921120 37 1, Australian Greenhouse Office; 2005, p. 1–35.
- [5] Walawalkar R, Apt J, Mancini R. Economics of electric energy storage for energy arbitrage and regulation. *Energy Policy* 2007;5:2558–68.
- [6] Dti Report. Review of electrical energy storage technologies and systems and of their potential for the UK. DG/DTI/00055/00/00, URN NUMBER 04/1876, UK Department of Trade and Industry; 2004, p. 1–34.
- [7] Dobie WC. Electrical energy storage. *Power Eng J* 1998;12:177–81.
- [8] Koot M, Kessels J, Jager B, et al. Energy management strategies for vehicular electric power systems. *IEEE T Veh Technol* 2005;54:771–82.
- [9] Weinstock IB. Recent advances in the US Department of Energy's energy storage technology research and development programs for hybrid electric and electric vehicles. *J Power Sources* 2002;110:471–4.
- [10] Ahearne J. Storage of electric energy, Report on research and development of energy technologies. International Union of Pure and Applied Physics; 2004, p. 76–86. Available online <http://www.iupap.org/wg/energy/report-a.pdf> [2007-03-20].
- [11] http://www.en.wikepeida.org/wiki/Hydroelectric_energy_storage [2007-03-20].
- [12] Linden S. The commercial world of energy storage: a review of operating facilities (under construction or planned). In: Proceeding of 1st annual conference of the energy storage council, Houston, Texas, March 3, 2003.
- [13] Linden S. Bulk energy storage potential in the USA, current developments and future prospects. *Energy* 2006;31:3446–57.
- [14] Makansi J, Abboud J. Energy storage: the missing link in the electricity value chain—An ESC White Paper. Energy storage Council 2002; p. 1-23.

- [15] Akhil A, Swaminathan S, Sen RK. Cost analysis of energy storage systems for electric utility applications. Sandia Report, SAND97-0443 UC-1350, Sandia National Laboratories; 1997; p. 1–62.
- [16] Kondoh J, Ishii I, Yamaguchi H, et al. Electrical energy storage systems for energy networks. *Energy Convers Manage* 2000;41:1863–74.
- [17] Bueno C, Carta JA. Wind powered pumped hydro storage systems, a means of increasing the penetration of renewable energy in the Canary Islands. *Renew Sus Energy Rev* 2006;10:312–40.
- [18] Najjar Y, Zaaout MS. Performance analysis of compressed air energy storage (CAES) plant for dry regions. *Energy Convers Manage* 1998;39:1503–11.
- [19] Sears JR. TEX: The next generation of energy storage technology. Telecommunications Energy Conference, INTELEC 2004. In: 26th annual international volume, Issue, Sept. 19–23 2004; p. 218–22.
- [20] Najjar Y, Jubeh N. Comparison of performance of compressed-air energy-storage plant with compressed-air storage with humidification. In: *Proceeding of IMechE, Part A: Journal of Power and Energy* 2006;220:581–8.
- [21] Bullough C, Gatzen C, Jakiel C, et al. Advanced adiabatic compressed air energy storage for the integration of wind energy. In: *Proceedings of the European wind energy conference*. London, UK, 2004.
- [22] Wang S, Chen G, Fang M, et al. A new compressed air energy storage refrigeration system. *Energy Convers Manage* 2006;47:3408–16.
- [23] Cook GM, Spindler WC, Grefe G. Overview of battery power regulation and storage. *IEEE T Energy Convers* 1991;6:204–11.
- [24] Chalk SG, Miller JF. Key challenges and recent progress in batteries, fuel cells and hydrogen storage for clean energy systems. *J Power Sources* 2006;159:73–80.
- [25] Kashem MA, Ledwich G. Energy requirement for distributed energy resources with battery energy storage for voltage support in three-phase distribution lines. *Electr Pow Syst Res* 2007;77:10–23.
- [26] Kluiters EC, Schmal D, Ter Veen WR, et al. Testing of a sodium/nickel chloride (ZEBRA) battery for electric propulsion of ships and vehicles. *J Power Sources* 1999;80:261–4.
- [27] Karpinski AP, Makovetski B, Russell SJ, et al. Silver-zinc: status of technology and applications. *J Power Sources* 1999;80:53–60.
- [28] Weinmann O. Hydrogen-the flexible storage for electrical energy. *Power Eng J-Special Feature: Electrical energy storage* 1999:164–70.
- [29] Steinfeld A, Meier A. Solar thermochemical process technology. In: *Encycl Energy*. Elsevier Inc; 2004, 5: 623-37.
- [30] Kolkert WJ, Jamet F. Electric energy gun technology: status of the French–German–Netherlands programme. *IEEE T Magn* 1999;35:25–30.
- [31] Koshizuka N, Ishikawa F, Nasu H. Progress of superconducting bearing technologies for flywheel energy storage systems. *Physica C* 2003;386:444–50.
- [32] Xue X, Cheng K, Sutanto D. A study of the status and future of superconducting magnetic energy storage in power systems. *Supercond Sci Tech* 2006;19:39.
- [33] Suzuki Y, Koyanagi A, Kobayashi M. Novel applications of the flywheel energy storage system. *Energy* 2005;30:2128–43.
- [34] <http://www.beaconpower.com/products/EnergyStorageSystems/fly-wheels.htm> [2007-3-20].
- [35] Rosen MA. Second-law analysis of aquifer thermal energy storage systems. *Energy* 1999;24:167–82.
- [36] Ameri M, Hejazi SH, Montaser K. Performance and economics of the thermal energy storage systems to enhance the peaking capacity of the gas turbines. *Appl Therm Eng* 2005;25:241–51.
- [37] Akbari H, Sezgen O. Performance evaluation of thermal energy storage systems. *Energy Buildings* 1995;22:15–24.
- [38] Ordonez CA, Plummer MC. Cold thermal storage and cryogenic heat engines for energy storage applications. *Energy Sources* 1997;19(4):389–96.
- [39] Kessling W, Laevemann E, Peltzer M. Energy storage in open cycle liquid desiccant cooling systems. *Int J Refrig* 1998;21(2):150–6.
- [40] Kishimoto K, Hasegawa K, Asano T. Development of generator of liquid air storage energy system. Mitsubishi Heavy Industries, Ltd. Technical Review, 1998;35(3):117–20.
- [41] Chen HS, Ding YL. A cryogenic energy system using liquid/slush air as the energy carrier and waste heat and waste cold to maximise efficiency, specifically it does not use combustion in the expansion process. UK Patent G042226PT, 2006-02-27.
- [42] Wen DS, Chen HS, Ding YL, et al. Liquid nitrogen injection into water: pressure build-up and heat transfer. *Cryogenics* 2006;46:740–8.
- [43] Chen HS, Ding YL, Toby P, et al. A method of storing energy and a cryogenic energy storage system. International Patent WO/2007/096656, 2007-08-30.
- [44] Chen LG, Zheng JL, Sun FR. Power, power density and efficiency optimization for a closed cycle helium turbine nuclear power plant. *Energy Convers Manage* 2003;44:2393–401.
- [45] Denholm P, Kulcinski GL. Life cycle energy requirements and greenhouse gas emissions from large scale energy storage systems. *Energy Convers Manage* 2004;45:2153–72.
- [46] Denholm P, Holloway T. Improved accounting of emissions from utility energy storage system operation. *Environ Sci Technol* 2005;39:9016–22.
- [47] Alanne K, Saari A. Distributed energy generation and sustainable development. *Renew Sus Energy Rev* 2006;10:539–58.
- [48] McDowall JA. Opportunities for electricity storage in distributed generation and renewables. In: *Proceeding of transmission and distribution conference and exposition, 2001 IEEE/PES, Atlanta, GA, USA, Oct.28–Nov.02, 2001*; p. 1165–8.
- [49] Maclay JD, Brouwer J, Samuelsen GS. Dynamic modeling of hybrid energy storage systems coupled to photovoltaic generation in residential applications. *J Power Sources* 2007;163:916–25.
- [50] Dti Report. Overview report of combined energy storage and renewable generation. K/EL/00246/00/00, URN NUMBER 04/1047, UK Department of Trade and Industry; 2004, p. 1–21.
- [51] Energy and environment, MIT laboratory for energy and the environment July, 2005; p. 1–24. Available online: http://www.lfee.mit.edu/public/e&e_July05_FINAL.pdf [2007-03-20].
- [52] Korpaas M, Holen AT, Hildrum R. Operation and sizing of energy storage for wind power plants in a market system. *Int J Electr Power Energy Syst* 2003;25:599–606.
- [53] Manwell JF, Elkinton CN, Rogers AL. Review of design conditions applicable to offshore wind energy systems in the United States. *Renew Sus Energy Rev* 2007;11(2):210–34.
- [54] Cawallow AJ. Energy storage technologies for utility scale intermittent renewable energy systems. *J Sol Energy – T ASME* 2005;123:387–9.
- [55] Dti Report. Network performance benefits of energy storage for a large wind farm. K/EL/00246/00/00, URN NUMBER 04/1050, UK Department of Trade and Industry, 2004; p. 1–22.
- [56] Dti Report. The future value of storage in the UK with generator intermittency. DG/DTI/00040/00/00, URN NUMBER: 04/1877, UK Department of Trade and Industry, 2004; p. 1–63.
- [57] McDowall J. Integrating energy storage with wind power in weak electricity grids. *J Power Sources* 2006;162:959–64.
- [58] Moore T, Douglas J. Energy storage, big opportunities on a smaller scale. *EPRI J* 2006; Spring Issue, p. 16–23.
- [59] Mears D. EPRI-DOE storage handbook-storage for wind resources. In: *Annual peer review meeting of DOE energy storage systems research*. Washington DC, USA, Nov. 10–11, 2004, p. 1–18.
- [60] Ribeiro PF, Johnson BK, Crow ML, et al. Energy storage systems for advanced power applications. In: *Proceedings of the IEEE* 2001;89:1744–56.
- [61] Ratering-Schnitzler B, Harke R, Schroeder M, et al. Voltage quality and reliability from electrical energy-storage systems. *J Power Sources* 1997;67:173–7.
- [62] Jewitt J. Impact of CAES on Wind in Tx, OK and NM, In: *Annual peer review meeting of DOE energy storage systems research*. San Francisco, USA, Oct. 20, 2005; p. 1–16.

- [63] McDowall JA. High power batteries for utilities – the world's most powerful battery and other developments, In: Powerengineering society general meeting, 2004. IEEE, Denver, USA, 6–10 June, 2004; p. 2034–7.
- [64] http://www.electricitystorage.org/tech/technologies_technologies.htm [2007-03-20].
- [65] <http://www.ngk.co.jp/english/products/power/nas/index.html> [2007-03-20].
- [66] Galloway RC, Dustmann C. ZEBRA battery-material cost availability and recycling. In: Proceeding of international electric vehicle symposium (EVS-20), Long Beach, Canada, Nov. 15–19, 2003; p. 1–9.
- [67] <http://www.betard.co.uk/> [2007-03-20].
- [68] <http://www.saftbatteries.com/> [2007-03-20].
- [69] <http://www.fuelcelltoday.com/> [2007-03-20].
- [70] Electric Mobility Canada. Preliminary analysis of eVionyx Ni–Zn battery and Zn–Air fuel cell. Available on <http://www.mec.ceveq.qc.ca/> [2007-03-20].
- [71] <http://www.zbbenergy.com/technology.htm> [2007-03-20].
- [72] Steinfeld A, Kuhn P, Reller A, et al. Solar-processed metals as clean energy carriers and water-splitters. *Int J Hydrogen Energy* 1998;23:767–74.
- [73] Steinfeld A. Solar hydrogen production via a 2-step water-splitting thermochemical cycle based on Zn/ZnO redox reactions. *Int J Hydrogen Energy* 2002;27:611–9.
- [74] Steinfeld A. Solar thermochemical production of hydrogen – a review. *Sol Energy* 2005;78:603–15.
- [75] Wieckert C, Guillot E, Epstein M, et al. A 300 kW solar chemical pilot plant for the carbothermic production of zinc. *J Sol Energy-T ASME Eng* 2007;129:190–6.
- [76] Lovegrove K, Luzzi A, McCann M, et al. Exergy analysis of ammonia-based thermochemical solar power systems. *Sol Energy* 1999;66:103–15.
- [77] Luzzi A, Lovegrove K, Filippi E, et al. Base-load solar thermal power using thermochemical energy storage. *J de physique. IV* 1999;9:105–10.
- [78] Cheung KYC, Cheung STH, Silva N, et al. Large-scale energy storage systems, Imperial College London, ISE2 2002/2003, Available online: http://www.homes.doc.ic.ac.uk/~matti/ise2grp/energystorage_report/ [2007-03-20].
- [79] <http://www.beaconpower.com/products/EnergyStorageSystems/DocsPresentations.htm> [2007-03-20].
- [80] Lazarewicz M, Arseneaux J. Flywheel-based frequency regulation demonstration projects status. In: Proceedings of EESAT conference, San Francisco, USA, Oct. 17–19, 2005, p. 1–22.
- [81] Knowlen C, Herzberg A, Mattick AT. Automotive propulsion using liquid nitrogen. AIAA paper 1994; No. 1994-3349.
- [82] Knowlen C, Williams J, Mattick AT. Quasi-isothermal expansion engines for liquid nitrogen automotive propulsion. SAE paper 1997; No 972649.
- [83] Williams J. Cryogenic automobile propulsion: heat exchanger design and performance issues. AIAA paper 1997; No. 1997-0017.
- [84] Ordonez CA. Liquid nitrogen fueled, closed brayton cycle cryogenic heat engine. *Energy Convers Manage* 2000;41:331–41.
- [85] Knowlen C, Matick AT, Bruckner AP. High efficiency energy conversion systems for liquid nitrogen automobiles. SAE paper 1998; No 981898.
- [86] ECOSTAR: European concentrated solar thermal road-mapping, Deliverable No. 7, Roadmap Document, Nov. 2004, Available online: http://www.vgb.org/data.o/vgborg_/Forschung/roadmap252.pdf [2007-03-20].