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Overview of current development in electrical energy storage technologies and the application potential in power system operation ☆

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HIGHLIGHTS

- An overview of the state-of-the-art in Electrical Energy Storage (EES) is provided.
- A comprehensive analysis of various EES technologies is carried out.
- An application potential analysis of the reviewed EES technologies is presented.
- The presented synthesis to EES technologies can be used to support future R&D and deployment.

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ABSTRACT

Electrical power generation is changing dramatically across the world because of the need to reduce greenhouse gas emissions and to introduce mixed energy sources. The power network faces great challenges in transmission and distribution to meet demand with unpredictable daily and seasonal variations. Electrical Energy Storage (EES) is recognized as underpinning technologies to have great potential in meeting these challenges, whereby energy is stored in a certain state, according to the technology used, and is converted to electrical energy when needed. However, the wide variety of options and complex characteristic matrices make it difficult to appraise a specific EES technology for a particular application. This paper intends to mitigate this problem by providing a comprehensive and clear picture of the state-of-the-art technologies available, and where they would be suited for integration into a power generation and distribution system. The paper starts with an overview of the operation principles, technical and economic performance features and the current research and development of important EES technologies, sorted into six main categories based on the types of energy stored. Following this, a comprehensive comparison and an application potential analysis of the reviewed technologies are presented.

1. Introduction

Global electricity generation has grown rapidly over the last decade. As of 2012, the annual gross production of electricity reached approximately 22,200 TW h, of which fossil fuels (including coal/peat, natural gas and oil) contribute around 70% of global electricity generation [1–3]. To maintain the power network stability, the load balance has mainly been managed through fossil fuel power plants. To achieve the target of reducing CO_2 emissions, future electricity generation will progress with diminishing reliance on fossil fuels, growing use of renewable energy sources and with a greater respect for the environment [3]. However, most renewable energy sources are intermittent in their nature, which presents a great challenge in energy generation and load balance maintenance to ensure power network stability and reliability. Great efforts have been made in searching for viable solutions, including Electrical Energy Storage (EES), load shifting through demand management, interconnection with external grids, etc. Amongst all the possible solutions, EES has been recognized as one of the most promising approaches [4,5].

EES technology refers to the process of converting energy from one form (mainly electrical energy) to a storable form and reserving it in various mediums; then the stored energy can be converted back into electrical energy when needed [4,5]. EES can have multiple attractive value propositions (functions) to power network operation and load balancing, such as: (i) helping in meeting peak electrical load demands, (ii) providing time varying energy

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management, (iii) alleviating the intermittence of renewable source power generation, (iv) improving power quality/reliability, (v) meeting remote and vehicle load needs, (vi) supporting the realization of smart grids, (vii) helping with the management of distributed/standby power generation, (viii) reducing electrical energy import during peak demand periods.

In many scenarios, demand for EES and selection of appropriate EES technologies have been considered to be important and challenging in countries with a relatively small network size and inertia. For example, the UK electric power network currently has a capacity of Pumped Hydroelectric Storage (PHS) at 27.6 GW h [6]. Although PHS facilities have been built worldwide as a mature and commercially available technology, it is considered that the potential for further major PHS schemes is restricted in the UK [6]. Therefore, it is of great importance that suitable EES technologies in addition to PHS are explored. Derived from the study of recent publications, Fig. 1 illustrates various EES technologies with potentials to address the challenges faced by the UK energy systems [4,6,7–9]. Many countries potentially need to address similar challenges which can be solved or improved by suitable EES technologies.

Due to the great potential and the multiple functions of EES, in the literature many authors have reviewed and summarized the EES research and development, demonstrations and industrial applications from different perspectives, particularly in recent years. The paper presented by Ibrahim et al. highlighted the need to store energy for improving power networks and maintaining load levels [10]. A group of characteristics of different EES technologies is given, which can help improve performance and cost estimates for storage systems. However relatively few references are cited in [10]. Chen et al. provided a well-organized and comprehensive critical review on progress in EES systems, which covered various types of EES technologies and their applications/deployment status [4]. The discussion on the selection of appropriate EES candidates for specific applications was relatively brief. Hall et al. also presented a review article concentrating on several EES technologies, i.e., batteries, supercapacitors, superconducting magnetic energy storage and flywheels [11]. Liu et al. provided an insightful review of the advanced materials for several EES technologies [12]. The strategies for developing high-performance hydrogen storage materials and electrochemical lithium-ion battery materials were discussed in detail [12]. The paper also highlighted the prospects in the future development of advanced materials for EES. With the rapid penetration of intermittent renewables, the review articles [13–16] have made effort to assess and summarize the EES options for increased renewable electricity applications. Díaz-González et al. [13] and Zhao et al. [15] focus on the review of EES technologies for wind power applications. A detailed discussion of existing EES applications in wind power is a highlight provided by the article [13], whilst the planning issues, the operation and control strategies of the ESS applications for wind power integration support are summarized by the paper [15]. Furthermore, from a novel viewpoint, Connolly et al. assessed available computer tools for analyzing the integration of renewable energy into various energy systems [17]. Researchers have also reviewed specific aspects of EES systems, such as in [18–22]. For instance, Dunn et al. contributed a high quality review on battery energy storage for the grid applications, mainly focusing on commercially available sodium–sulfur batteries, relatively low cost redox-flow batteries and developing lithium-ion batteries, all with the aim to be used in grid storage [22]. The reviews of the developments and challenges in materials for electrochemical relevant energy storage are presented in [23–25]. For example, Whittingham addressed the current challenges in the subject of electrochemical energy storage materials, which can be summarized as: reducing the cost and extending the lifetime of devices whilst improving their performance and making them more environmentally friendly [23]. In addition, some journals have published special issues dedicated to EES research and development, such as the special issue in 2013 from the Wiley journal Advanced Functional Materials: "Grand Challenges in Energy Storage".

A brief statistical study has been carried out to ascertain the trends in EES related research using the search engine 'Web of Science' and choosing 'Topic' as the search field. Fig. 2 shows the results detailing the number of research papers published in six EES related fields over the past ten years (2004–2013). The titles of the subfigures in Fig. 2 are the input keywords used in the search engine. The results indicate that research in EES in the past ten years has tended to increase, with rapid increases in 2012 and 2013. In particular, research into compressed air energy storage

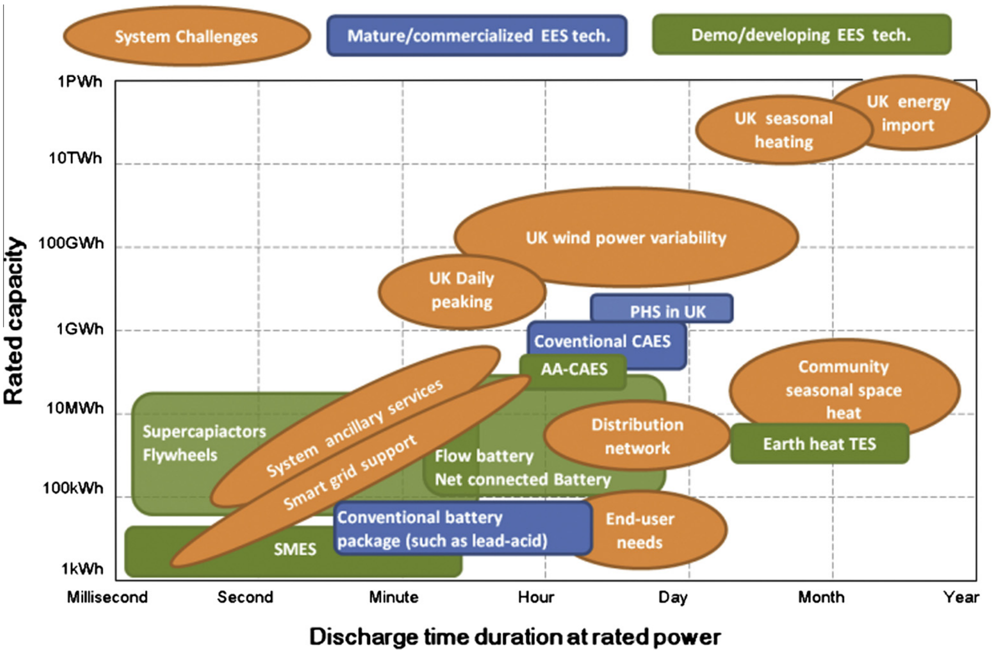

Fig. 1. Electrical energy storage technologies with challenges to the UK energy systems [4,6,7–9].

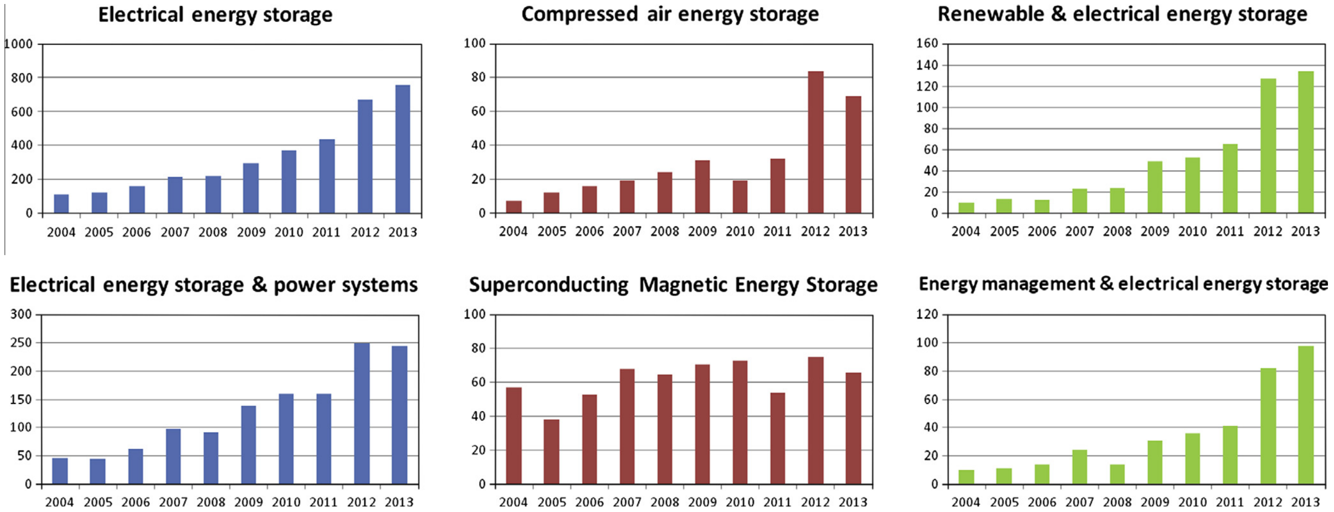

Fig. 2. A brief statistical study to the trend in EES related research.

grew significantly in 2012 whilst, in contrast, research into superconducting magnetic energy storage has remained relatively stable. It can also be seen that there has been a large increase in the research into renewable and energy management with EES topics. The statistic figure in EES research literatures shows that the entire EES research and technology development have changed and advanced rapidly in the years since some previous reviews, such as [4,10,11], were published. Thus it is timely to have a new critical overview of the current development in EES.

Although the potential benefits of EES installation to power system operation have been widely recognized, some significant challenges in the deployment of EES systems exist, mainly in: (1) how to choose the suitable EES technology to match the power system application requirements; (2) how to accurately evaluate the actual values of deployed EES facilities including technical and economic benefits; (3) how to bring the cost down to a realistically acceptable level for deployment, especially for newly developing EES technologies.

The objective of this paper is to provide a updated picture of the state-of-the-art EES technologies, in comparison with the previous review articles [4,10,11]. The paper begins with an overview of the operation principles, technical and economic performance features and the current research and development of important EES technologies. Following this, a comprehensive comparison of EES technologies is conducted. The paper presents a detailed summarization and predication of the existing and promising EES technology options for different power system applications with their corresponding technical specifications. The overview will help address the challenges faced in deployment of EES and provide useful information and guidance in selecting suitable technologies for specific applications based on the nature of EES characteristics.

2. Classification of electrical energy storage technologies

There are several suggested methods for categorization of various EES technologies, such as, in terms of their functions, response times, and suitable storage durations [4,26,27]. One of the most widely used methods is based on the form of energy stored in the system [15,16] as shown in Fig. 3, which can be categorized into mechanical (pumped hydroelectric storage, compressed air energy storage and flywheels), electrochemical (conventional rechargeable batteries and flow batteries), electrical (capacitors, supercapacitors and superconducting magnetic energy storage), thermochemical (solar fuels), chemical (hydrogen storage with fuel cells) and thermal energy storage (sensible heat storage and latent heat storage). A detailed description and discussion of each type of EES technology will be given in the next section following the above order of category.

3. Description of electrical energy storage technology

3.1. Pumped Hydroelectric Storage (PHS)

PHS is an EES technology with a long history, high technical maturity and large energy capacity. With an installed capacity of 127–129 GW in 2012, PHS represents more than 99% of worldwide bulk storage capacity and contributes to about 3% of global generation [26,28,29]. As shown in Fig. 4, a typical PHS plant uses two water reservoirs, separated vertically. During off-peak electricity demand hours, the water is pumped into the higher level reservoir; during peak hours, the water can be released back into the lower level reservoir. In the process, the water powers turbine units which drive the electrical machines to generate electricity. The amount of energy stored depends on the height difference between the two reservoirs and the total volume of water stored. The rated power of PHS plants depends on the water pressure and flow rate through the turbines and rated power of the pump/turbine and generator/motor units, and [30].

Various PHS plants exist with power ratings ranging from 1 MW to 3003 MW, with approximately 70–85% cycle efficiency and more than 40 years lifetime [4,29,31,32]. Some PHS facilities along with their features are listed in Table 1. The nature of the operation of PHS systems means that their applications mainly involve energy management in the fields of time shifting, frequency control, non-spinning reserve and supply reserve. However, with the restriction of site selection, PHS plants suffer long construction time and high capital investment.

Recently, with the advance of technology, some PHS plants using flooded mine shafts, underground caves and oceans as reservoirs have been planned or are in operation , such as the Okinawa Yanbaru in Japan, a 300 MW seawater-based PHS plant in Hawaii, the Summit project in Ohio and the Mount Hope project in New Jersey [28,34,35]. In addition, wind or solar power generation coupled with PHS is now being developed. This could help the adoption of renewable energy in isolated or distributed networks [36,37]. For instance, the Ikaria Island power station will integrate a 3 × 900 kW wind farms with a PHS facility [28]. The development trend of PHS facilities consists of building the hydroelectric set

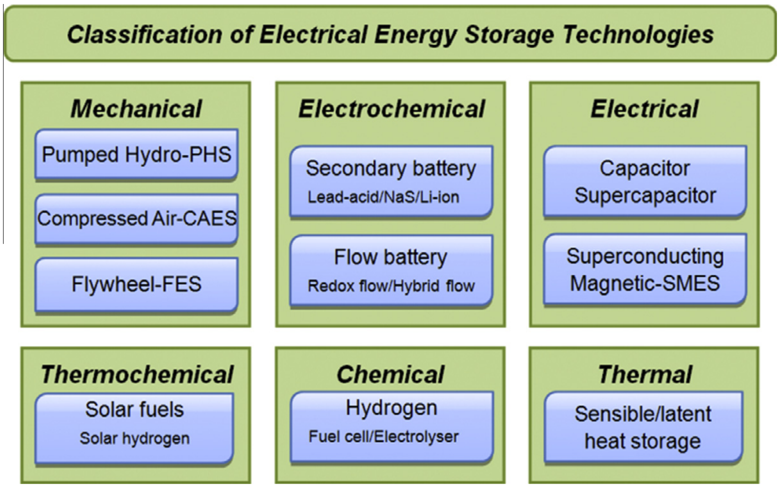

Fig. 3. Classification of EES technologies by the form of stored energy.

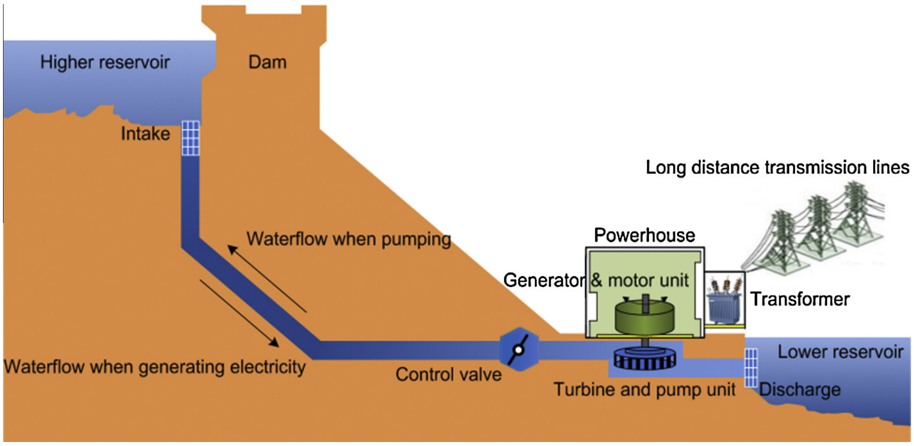

Fig. 4. A pumped hydroelectric storage plant layout.

Table 1
Selected pumped hydroelectric storage plants [4,26,31–33].

Plant name	Country	Power rating	Features
Rocky river PHS plant	US	32 MW	The world's first large-scale commercial PHS plant
Bath County PHS plant	US	3003 MW	The world's largest power rated PHS plant
Okinawa Yanbaru PHS	Japan	~30 MW	Only commercial seawater PHS plant
Hawaiian Elec. Co. PHS facility	US	–	Claimed 87% relatively high cycle efficiency
HPS of Ikaria Island	Greece	2.655 MW	One of the first wind-PHS plants (under construction)

with higher speed and larger capacity compared to the current technical level, installing centralized monitoring and using intelligent control systems [26,28,38].

3.2. Compressed Air Energy Storage (CAES)

In addition to PHS, CAES is another type of commercialized EES technology which can provide power output of over 100 MW with a single unit. A schematic diagram of a CAES plant is shown in Fig. 5. During the periods of low power demand, the surplus electricity drives a reversible motor/generator unit in turn to run a chain of compressors for injecting air into a storage vessel, which is either an underground cavern or over ground tanks. The energy is stored in the form of high pressure air. When the power generation cannot meet the load demand, the stored compressed air is released and heated by a heat source which can be from the combustion of fossil fuel or the heat recovered from the compression process. The compressed air energy is finally captured by the turbines. The waste heat from the exhaust can be recycled by a recuperator unit (Fig. 5).

The world's first utility-scale CAES plant, the Huntorf power plant, was installed in Germany in 1978 [39–41]. It uses two salt domes as the storage caverns and it runs on a daily cycle with 8 h of compressed air charging and 2 h of operation at a rated power of 290 MW [39]. This plant provides black-start power to nuclear units, back-up to local power systems and extra electrical power to fill the gap between the electricity generation and demand. Another commercial CAES plant started operation in McIntosh, the US, in 1991 [39–41]. The 110 MW McIntosh plant can operate for up to 26 h at full power. The compressed air is stored in a salt cavern. A recuperator is operated to reuse the exhaust heat energy. This reduces the fuel consumption by 22–25% and improves the cycle efficiency from ~42% to ~54%, in comparison with the Huntorf plant [4,42]. These two CAES plants have

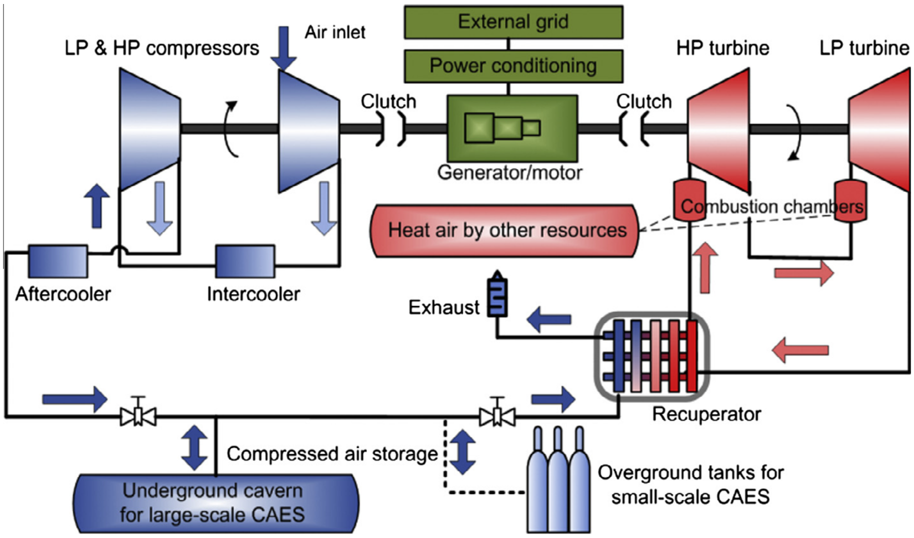

Fig. 5. Schematic diagram of a CAES plant/facility.

consistently shown good performances with 91.2–99.5% starting and running reliabilities [38,39].

CAES system can be built to have small to large scale of capacities; CAES technology can provide the moderate speed of responses and good partial-load performance. The practical uses of large-scale CAES plants involve grid applications for load shifting, peak shaving, and frequency and voltage control. CAES can work with intermittent renewable energy applications, especially in wind power, to smooth the power output, which have attracted much attentions from academic researchers and industrial sectors as described in [40,43–45]. The major barrier to implementing large-scale CAES plants is identifying appropriate geographical locations which will decide the main investment cost of the plant. Relative low round trip efficiency is another barrier for CAES compared to PHS and battery technologies.

In addition, the developing Liquid Air Energy Storage (LAES) has many components which are the same or similar as those used for CAES, such as compressors, turbines, electric machines and heat exchangers. Considering the type of energy stored, LAES can be classified into thermal energy storage, which will be introduced in Section 3.10.

Currently, the newly developing Advanced Adiabatic CAES (AA-CAES) is attracting attention. AA-CAES technology is normally integrated with a thermal energy storage subsystem, which has no fuel combustion involved in the expansion mode [39,42,43,46]. The world's first AA-CAES demonstration plant – ADELE – is in the development stage, at Saxony-Anhalt in Germany. The plant will have a storage capacity of 360 MWh and an electric output of 90 MW, aiming for ~70% cycle efficiency [43]. Because its compression mode will be powered by wind energy, the ADELE plant emits no CO_2 in a full cycle. The US based LightSail Energy Ltd. is also developing the AA-CAES facilities by using reversible reciprocating piston machines [46]. In 2007 Luminant and Shell-Wind Energy proposed wind farm projects involving CAES in Texas, intending to evaluate the potential of incorporating CAES facilities in conjunction with the wind farm; after a long wait, in 2013 the project got underway and hosting 317 MW of CAES has been set as the current target [39,44]. In addition, a comparison between different adiabatic CAES plant configurations was recently published in [47].

Recently, apart from using salt caverns, researchers have attempted to study other geological structures for use in underground CAES technology. A 2 MW field test program has used a concrete-lined tunnel in an abandoned mine in Japan [39,48]. A test facility made by Electric Power Research Institute and others utilized a hard rock cavern with water compensation [49]. Italy's Enel operated a 25 MW porous rock based CAES facility in Sesta – the test was stopped due to a disturbed geothermal issue [39]. The Iowa Stored Energy Park project aimed to use porous sandstone aquifers to build an underground reservoir for constructing a 270 MW CAES plant; unfortunately, this project stopped in 2011 as the field test result indicated that the geological structure in Iowa cannot obtain a fast enough flow for large-scale CAES [50].

Over ground small-scale CAES has recently undergone rapid development. It can be used as an alternative to the battery for industrial applications, such as Uninterruptible Power Supplies (UPS) and back-up power systems. Compressed air battery systems developed by the UK based Flowbattery (previously named Pnu Power) were recently successfully commercialized [51]. It uses pre-prepared compressed air from air cylinders to drive a combination of a scroll expander and a generator to produce electricity [51,52]. In addition, the guideline study for the efficient design and sizing of small-scale CAES pressure vessels considering minimizing its cost was reported in [53]. Also, the feasibility on the direct mechanical coupling of a wind turbine and a scroll expander with small-scale CAES has been studied by the University of Warwick, and its on-site tests are on-going [52,54].

3.3. Flywheel Energy Storage (FES)

A modern FES system is composed of five primary components: a flywheel, a group of bearings, a reversible electrical motor/generator, a power electronic unit and a vacuum chamber [18]. Fig. 6 shows the simplified structure of a modern FES facility. FES systems use electricity to accelerate or decelerate the flywheel, that is, the stored energy is transferred to or from the flywheel through an integrated motor/generator. For reducing wind shear and energy loss from air resistance, the FES system can be placed in a high vacuum environment. The amount of energy stored is dependent on the rotating speed of flywheel and its inertia.

FES can be classified into two groups: (1) low speed FES: it uses steel as the flywheel material and rotates below 6×10^3 rpm; (2) high speed FES: it uses advanced composite materials for the flywheel, such as carbon-fiber, which can run up to $\sim 10^5$ rpm [55]. Low speed FES systems are typically used for short-term and medium/high power applications. High speed FES systems use

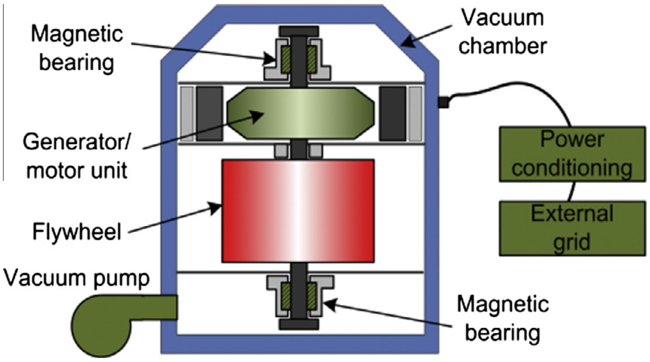

Fig. 6. System description of a flywheel energy storage facility.

non-contact magnetic bearings to mitigate the wear of bearings, thereby improving the efficiency. The application areas of high speed FES are continuously expanding, mainly in high power quality and ride-through power service in traction and the aerospace industry [56]. The specific energy of low speed flywheels is ~5 W h/kg, and the high speed composite rotor can achieve a specific energy of up to ~100 W h/kg [57]. The cost of high speed composite systems can be much higher than that of conventional metal flywheel systems. FES has some favorable characteristics, including high cycle efficiency (up to ~95% at rated power), relatively high power density, no depth-of-discharge effects and easy maintenance [18,55,57].

Table 2 lists some selected FES facilities. In June 2011, a 20 MW modular plant built by Beacon Power was put into commercial operation in New York, which was the largest advanced EES facility operating in North America [58,59]. It employs 200 high speed flywheel systems to provide fast response frequency regulation services to the grid, providing ~10% of the whole state frequency regulation demand [58,59]. Normally, FES devices can supply sufficient power in a short time period with modest capacity. Thus it is not used as standalone backup power unless operated with other EES or power generation systems, such as batteries or fuel-fired generators. The main weakness of FES is that flywheel devices suffer from the idling losses during the time when the flywheel is on standby. This can lead to relatively high self-discharge, up to ~20% of stored capacity per hour [57].

Currently, the research and development area of FES includes the material of the flywheel for increasing their rotation speed capabilities and power densities, high speed electrical machines, high carrying capacity of the bearings and the flywheel array technology. An advance in FES technology is the High Temperature Superconductor (HTS) bearings which is a promising option for improving bearing performance. The US Argonne National Laboratory developed a 2 kW h FES system using high-temperature superconductors and permanent magnets as passive bearings for a feasibility study [61]. A model-based power flow control strategy has been studied for improving flywheel performance in high power pulse systems [62]. The rail traction industry has tested FES devices for trackside voltage support [63]. Optimizing flywheels for relatively long-term operation (up to several hours) are being studied for use in vehicles and power plants [26].

3.4. Battery Energy Storage (BES)

The rechargeable battery is one of the most widely used EES technologies in industry and daily life. Fig. 7 shows the simplified operational principle of a typical BES system. A BES system consists of a number of electrochemical cells connected in series or parallel, which produce electricity with a desired voltage from an electrochemical reaction. Each cell contains two electrodes (one anode and one cathode) with an electrolyte which can be at solid, liquid or ropy/viscous states [64,65]. A cell can bi-directionally convert energy between electrical and chemical energy. During discharging, the electrochemical reactions occur at the anodes and the cathodes simultaneously. To the external circuit, electrons are provided from the anodes and are collected at the cathodes. During charging, the reverse reactions happen and the battery is recharged by applying an external voltage to the two electrodes (Fig. 7).

Batteries can be widely used in different applications, such as power quality, energy management, ride-through power and transportation systems. The construction of BES systems takes a relatively short time period (roughly within 12 months) [4,66]. The location for installation can be quite flexible, either housed inside a building or close to the facilities where needed. Currently, relatively low cycling times and high maintenance costs have been considered as the main barriers to implementing large-scale facilities. The disposal or recycling of dumped batteries must be considered if toxic chemical materials are used [9]. Furthermore, many types of battery cannot be completely discharged due to their lifetime depending on the cycle Depth-of-Discharge (DoD) [13]. A description of several important BES technologies will be presented in the following five subsections. The chemical reactions taking place in these battery types are listed in Table 3.

3.4.1. Lead–acid batteries

The most widely used rechargeable battery is the lead–acid battery [4,10]. The cathode is made of PbO_2, the anode is made of *Pb*, and the electrolyte is sulfuric acid. Lead–acid batteries have fast response times, small daily self-discharge rates (<0.3%), relatively high cycle efficiencies (~63-90%) and low capital costs (50–600 $/kW h) [4,14,57,69]. Some examples of EES facilities using lead–acid batteries are listed in Table 4. Lead–acid batteries can be used in stationary devices as back-up power supplies for data and telecommunication systems, and energy management applications. Also, they have been developed as power sources for hybrid or full electric vehicles. However, there are still limited installations around the world as utility-scale EES, mainly due to their relatively low cycling times (up to ~2000), energy density (50–90 W h/L) and specific energy (25–50 Wh/kg) [4,70,71]. In addition, they may perform poorly at low temperatures so a thermal management system is normally required, which increases the cost [72].

Currently, the research and development of lead–acid batteries focuses on: (1) innovating materials for performance improvement,

Table 2
Selected flywheel energy storage facilities [18,55,57–60].

Firms/Institutes	Characteristics	Application area
Active Power Company	Clean Source series 100–2000 kW	Backup power supply, UPS systems
Beacon Power Company	100/150 kW a unit, 20 MW/5 MW h plant	Freq. regulation, power quality, voltage support
Boeing Phantom Works	100 kW/5 kW h, HT magnetic bearings	Power quality and peak shaving
Japan Atomic Energy Center	235 MVA, steel flywheel	High power supply to Nuclear fusion furnace
Piller power systems Ltd.	3600–1500 rpm, 2.4 MW for 8 s	Ride-through power and sources of backup power
NASA Glenn research center	2×10^4–6×10^4 rpm, 3.6 MW h	Supply on aerospace aviation & other transports

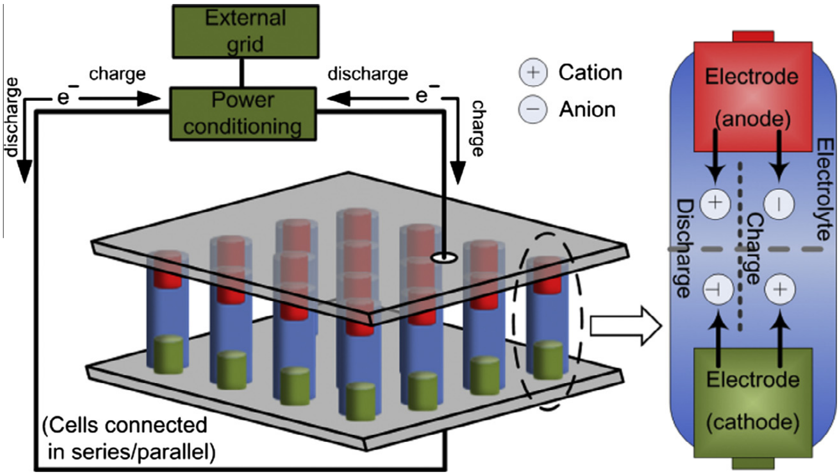

Fig. 7. Schematic diagram of a battery energy storage system operation.

Table 3
Chemical reactions and single unit voltages of main batteries available to EES [4,13,67,68].

Battery type	Chemical reactions at anodes and cathodes	Unit voltage
Lead–acid	$Pb + SO_4^{2-} \Longleftrightarrow PbSO_4 + 2e^-$ $PbO_2 + SO_4^{2-} + 4H^+ + 2e^- \Longleftrightarrow PbSO_4 + 2H_2O$	2.0 V
Lithium-ion	$C + nLi^+ + ne^- \Longleftrightarrow Li_nC$ $LiXXO_2 \Longleftrightarrow Li_{1-n}XXO_2 + nLi^+ + ne^-$	3.7 V
Sodium–sulfur	$2Na \Longleftrightarrow 2Na^+ + 2e^-$ $\chi S + 2e^- \Longleftrightarrow \chi S^{2-}$	~2.08 V
Nickel–cadmium	$Cd + 2OH^- \Longleftrightarrow Cd(OH)_2 + 2e^-$ $2NiOOH + 2H_2O + 2e^- \Longleftrightarrow 2Ni(OH)_2 + 2OH^-$	1.0–1.3 V
Nickel–metal hydride	$H_2O + e^- \Longleftrightarrow 1/2H_2 + OH^-$ $Ni(OH)_2 + OH^- \Longleftrightarrow NiOOH + H_2O + e^-$	1.0–1.3 V
Sodium nickel chloride	$2Na \Longleftrightarrow 2Na^+ + 2e^-$ $NiCl_2 + 2e^- \Longleftrightarrow Ni + 2Cl^-$	~2.58 V

Table 4
Selected lead–acid battery energy storage facilities [4,13,67,75,76].

Name/locations	Characteristics	Application area
BEWAG, Berlin	8.5 MW/8.5 MW h	Spinning reserve, frequency control
Chino, California	10 MW/40 MW h	Spinning reserve, load leveling
PREPA, Puerto Rico	20MW/14 MW h	Spinning reserve, frequency control
Metlakatla, Alaska	1 MW/1.4 MW h	Enhancing stabilization of island grid
Kahuku Wind Farm, Hawaii	15 MW/3.75 MW h	Power management, load firming, grid integration
Notrees EES project, U.S.	36 MW/24 MW h	Solving intermittency issues of wind energy

such as extending cycling times and enhancing the deep discharge capability; (2) implementing the battery technology for applications in the wind, photovoltaic power integration and automotive sectors. Several advanced lead–acid batteries that have fast responses comparable to flywheels and supercapacitors are being developed or are in the demonstration phase, such as Ecoult UltraBattery smart systems and Xtreme Power advanced lead–acid "Dry Cell" [73,74].

3.4.2. Lithium-ion (Li-ion) batteries

In a Li-ion battery, the cathode is made of a lithium metal oxide, such as $LiCoO_2$ and $LiMO_2$, and the anode is made of graphitic carbon. The electrolyte is normally a non-aqueous organic liquid containing dissolved lithium salts, such as $LiClO_4$ [13]. The Li-ion battery is considered as a good candidate for applications where the response time, small dimension and/or weight of equipment are important (milliseconds response time, ~1500–10,000 W/L, ~75–200 W h/kg, ~150–2000 W/kg) [4,9,26,57]. Li-ion batteries also have high cycle efficiencies, up to ~97% [4,26]. The main drawbacks are that the cycle DoD can affect the Li-ion battery's lifetime and the battery pack usually requires an on-board computer to manage its operation, which increases its overall cost.

The current research focuses for the Li-ion battery include: (1) increasing battery power capability with the use of nanoscale materials; (2) enhancing battery specific energy by developing advanced electrode materials and electrolyte solutions. Several companies have experience in using Li-ion batteries in the utility-scale energy market. The U.S. based AES Energy Storage has been commercially operating a Li-ion BES system (8 MW/2 MW h in 2010, enlarged 16 MW in 2011) in New York for supplying frequency regulation [8,77]. The AES also installed a 32 MW/8 MW h Li-ion BES system (Laurel Mountain) for supporting a 98 MW wind generation plant in 2011 [77,78]. Currently, the largest European Li-ion battery EES trial is underway in the UK. The project will deploy a 6 MW/10 MWh Li-ion battery at a primary substation to assess the cost effectiveness of EES as part of the UK's Carbon Plan [79]. The companies claimed that the storage could save more than $9 million compared to traditional system upgrades; the project can be used to balance the intermittency of wind and other renewables [79]. Also, in December 2013 Toshiba announced a project to install a 40 MW/20 MWh Li-ion battery project in Tohoku, which will help integrate renewables into the grid [80]. In addition, Li-ion batteries are now applied in Hybrid and full Electric Vehicles (HEVs and EVs), which use large-format cells and packs with capacities of 15–20 kW h for HEVs and up to 50 kW h for EVs [28].

3.4.3. Sodium–sulfur (NaS) batteries

A NaS battery uses molten sodium and molten sulfur as the two electrodes, and employs beta alumina as the solid electrolyte. The reactions normally require a temperature of 574–624 K to ensure the electrodes are in liquid states, which leads to a high reactivity [8]. The desirable features of NaS batteries include relatively high energy densities (150–300 W h/L), almost zero daily self-discharge, higher rated capacity than other types of batteries (up to 244.8 MW h) and high pulse power capability [13,26,81]. The battery uses inexpensive, non-toxic materials leading to high recyclability (~99%) [4,13]. However, the limitations are high annual operating cost (80 \$/kW/year) and an extra system required to ensure its operating temperature [72].

The NaS battery is considered as one of the most promising candidates for high power EES applications. Table 5 lists some NaS battery facilities with their applications. The research and development focuses are mainly on enhancing the cell performance indices and decreasing/eliminating the high temperature operating constrains. For instance, Sumitomo Electric Industries and Kyoto University developed a low temperature sodium related battery – the novel sodium-containing material can be melted at 330 K [84]. The inventor claimed that the new battery can achieve an energy density as high as 290 W h/L [84]. In addition, a part of the outcome to the "Wind to Battery" project led by Xcel Energy was recently presented in [83], mainly on the field results and analyses quantifying the ability and the value of NaS battery EES toward wind generation integration support [15,83].

3.4.4. Nickel–cadmium (NiCd) batteries

A NiCd battery uses nickel hydroxide and metallic cadmium as the two electrodes and an aqueous alkali solution as the electrolyte. It normally has relatively high robust reliabilities and low maintenance requirements. The weaknesses of NiCd batteries are: cadmium and nickel are toxic heavy metals, resulting in environmental hazards [9,85]; the battery suffers from the memory effect – the maximum capacity can be dramatically decreased if the battery is repeatedly recharged after being only partially discharged [86].

To date there have been very few commercial successes using NiCd batteries for utility-scale EES applications. One example is at Golden Valley, Alaska, in the US [77]. This NiCd facility was officially put into operation in 2003 by Golden Valley Electric Association. It offers services in spinning reserve, power supply and compensation to an "electrical island system" due to the geographic restrictions, i.e. remote areas [77,87]. The system has the ability to deliver the rated power at ~27 MW for 15 min or 40 MW for 7 min, and the efficiency is in the range of 72–78% with the operating temperature at 233–323 K [77,87,88]. The local cold temperature was the primary driving force behind the choice of the NiCd battery. It was reported that the NiCd technology for utility-scale EES applications was not pursued further after the Golden Valley installation [8,77]. It seems unlikely that NiCd batteries will be heavily used for future large-scale EES projects.

3.4.5. Other candidates of battery energy storage

The Nickel–metal Hydride (NiMH) battery is similar to the NiCd battery except that a hydrogen-absorbing alloy is used as the electrode instead of cadmium. It has moderate specific energy (~70–100 W h/kg) and relatively high energy density (~170–420 W h/L), significantly better than those of the NiCd battery [89–92]. Other advantages of NiMH batteries over NiCd batteries include a reduced "memory effect" and they are more environmental friendly. NiMH batteries have the longer cycle life in comparison with Li-ion batteries [89]. The NiMH battery has a wealth of applications from portable products to HEVs & EVs and potential industrial standby applications, such as UPS devices [89,90,93]. However, the significant barrier for EES applications is the high rate of self-discharge, losing ~5–20% of its capacity within the first 24 h after fully charging [89–91]. It is also sensitive to deep cycling – the performance decreases after a few hundreds full cycles [89–92].

The technology of sodium nickel chloride battery (also known as ZEBRA battery) is similar to that of the NaS battery. The ZEBRA battery has moderate specific energy (~94–120 W h/kg), energy density (~150 W h/L), specific power (150–170 W/kg), and a high operating temperature (~523–623 K) [4,94–98]. The advantages consist of good pulse power capability, cell maintenance free, very little self-discharge and relatively high cycle life. This battery technology has been applied in EV demonstrations and Rolls Royce has used it to replace lead–acid in surface ships applications [97]. GE launched Durathon sodium–metal halide battery for UPS and utility market, which can be considered as a continuing improvement on the ZEBRA technology [98]. A GE Durathon battery manufacturing facility in New York was officially opened in 2012 [98]. Recently, a new venture, FIAMM Energy Storage Solutions, also started to produce such batteries (named SoNick batteries) for stationary storage applications [99]. With regard to its drawback, the battery takes 12–15 h to heat up after it has been solidified (frozen) [94]. In addition, only a few companies have been involved in the development of this technology and have produced this type of battery, which may limit its potential [4,94,98].

3.5. Flow Battery Energy Storage (FBES)

A flow battery stores energy in two soluble redox couples contained in external liquid electrolyte tanks. These electrolytes can be pumped from the tanks to the cell stack which consists of two electrolyte flow compartments separated by ion selective membranes. The operation is based on reduction-oxidation reactions of the electrolyte solutions. During the charging phase, one electrolyte is oxidized at the anode and another electrolyte is reduced at the cathode, and the electrical energy is converted to the electrolyte chemical energy. The above process is reversed during the discharging phase.

Flow batteries can be classified into the categories of redox flow batteries and hybrid flow batteries, depending on whether all electroactive components can be dissolved in the electrolyte. Fig. 8 shows a schematic diagram of a vanadium redox flow battery system. A crucial advantage of FBES is that the power of a FBES system is independent of its storage capacity. The power of the FBES system is determined by the size of the electrodes and the number of cells in the stack; whereas the storage capacity is determined by the concentration and the amount of electrolyte [26,100,101]. Also, the very small self-discharge is an inherent strength of the FBES system due to the electrolytes being stored in separate sealed tanks [4,13]. Drawbacks of flow batteries include low performance resulting from non-uniform pressure drops and the reactant mass transfer limitation, relatively high manufacturing costs and more complicated system requirements compared to traditional batteries [102,103].

Table 5
Selected sodium-sulfur battery energy storage facilities [77,81–83].

Name/locations	Rated power/capacity	Application area
Kawasaki EES test facility, Japan	0.05 MW	The 1st large-scale, proof principle, operated in 1992
Long Island Bus's BES System, New York, US	1 MW/7 MW h	Refueling the fixed route vehicles
Rokkasho Wind Farm ES project, Japan	34 MW/244.8 MW h	Wind power fluctuation mitigation
Saint Andre, La reunion, France	1 MW	Wind power on an island
Graciosa Island, Younicos, Germany	3 MW/18 MW h	Wind & solar power EES for islands, commissioning 2013
Abu Dhabi Island, UAE	40 MW	Load levelling

FBES facilities have been demonstrated at a few hundred kW and even multi-MW levels, and there are not many commercially available FBES systems at present [4,19,104]. The current research activities undertaken cover: low-cost, efficient and reliable electrodes; highly permselective and durable membranes; power and energy management of large-scale FBES systems, etc. Some types of flow battery technologies have been used or can potentially be used for utility EES applications, including vanadium redox, zinc bromine and polysulfide bromine, which are described in the following three subsections.

3.5.1. Vanadium Redox Flow Battery (VRB)

The VRB is one of the most mature flow battery systems [4,87]. The VRB stores energy by using vanadium redox couples (V^{2+}/V^{3+} and V^{4+}/V^{5+}) in two electrolyte tanks (Fig. 8). VRBs exploit the vanadium in these four oxidation states which makes the flow battery have only one active element in both anolyte and catholyte [100]. During the charge/discharge cycles, H^+ ions are exchanged through the ion selective membrane. The chemical reaction is: $V^{4+} \leftrightarrow V^{5+} + e^-$ and $V^{3+} + e^- \leftrightarrow V^{2+}$; the cell voltage is ∼1.4 V [100,102].

VRBs have quick responses (faster than 0.001 s) and can operate for 10,000–16,000+ cycles [18,105]. They have relatively high efficiencies, up to ∼85% [100,105]. Manufacturers can design VRBs to provide continuous power (discharge duration time 24+ hours) [4,106]. Although VRBs now tends to expand their range of applications by enhancing the physical scale, there are some technical challenges that need to be solved, for instance, low electrolyte stability and solubility leading to low quality of energy density [107,108]. Also, the relatively high operating cost needs to be further reduced [103].

VRBs can be used in a large number of applications, mainly including enhancing power quality used for stationary applications and UPS devices, improving load levelling and power security, supporting the intermittent nature of renewable energy-based power generation. Some VRB facilities worldwide are introduced in Table 6. Currently, two projects on VRBs have been funded with a combined cost of £1.2 million in the UK. One project has been developed by Scottish Power, the University of Southampton and others, which planned to test a 100 kW redox flow battery for utility EES [6]. Another VRB energy storage system project has been developed by C-Tech Innovation Ltd, E.ON UK plc. and other institutes, which is especially for storing surplus energy from renewable energy sources [108]. Both of these two projects intend to be developed to a larger scale after the successes of initial small-scale trials [6,109].

3.5.2. Zinc Bromine (ZnBr) flow battery

ZnBr flow batteries belong to the hybrid flow batteries category. In a ZnBr battery, two aqueous electrolyte solutions contain the reactive components, which are based on zinc and bromine elements, stored in two external tanks. During the charging/discharging phases, these two electrolyte solutions flow through the cell stack consisting of carbon-plastic composite electrodes with compartments. Thus the reversible electrochemical reactions occur in these electrolytic cells. The corresponding chemical reactions are: $2Br^- \leftrightarrow Br_2 + 2e^-$ and $Zn^{2+} + 2e^- \leftrightarrow Zn$ [4,102].

The ZnBr flow battery has relatively high energy density (∼30–65 W h/L) and cell voltage (1.8 V) [4,26]. It also has deep discharge capability and good reversibility [19,102]. Module sizes vary from 3 kW to 500 kW, with estimated lifetimes of 10-20 years and discharge durations of up to ∼10 h [4,112,113]. The disadvantages of the ZnBr battery are: material corrosion, dendrite formation and relatively low cycle efficiencies (around 65–75%) compared to traditional batteries, which can limit its applications [4,114,115]. Furthermore, ZnBr batteries normally operate in a narrow temperature range [102,116].

Utility EES applications using ZnBr batteries are in the early stage of demonstration/commercialization. ZBB Energy Corporation and Premium Power Corporation have developed this technology for commercial purposes (50 kW h, recently tested up to ∼2 MW) [14]. The firm RedFlow in Australia successfully commercialized a fully functional ZnBr module product, named ZBM, which delivers up to 3 kW of continuous power (5 kW peak) and up to 8 kW h of energy; the company claimed that it can achieve up to 80% DC-DC max net energy efficiency [113]. In 2011, U.S. electric utilities conducted early trials of 0.5 MW/2.8 MW h transportable ZnBr systems for grid support and reliability [117]. In the same year, Sacramento Municipal Utility District (SMUD) planned to demonstrate a 1 MW ZnBr flow battery system for multi EES applications [100,118]. A relevant project, named “flow batteries

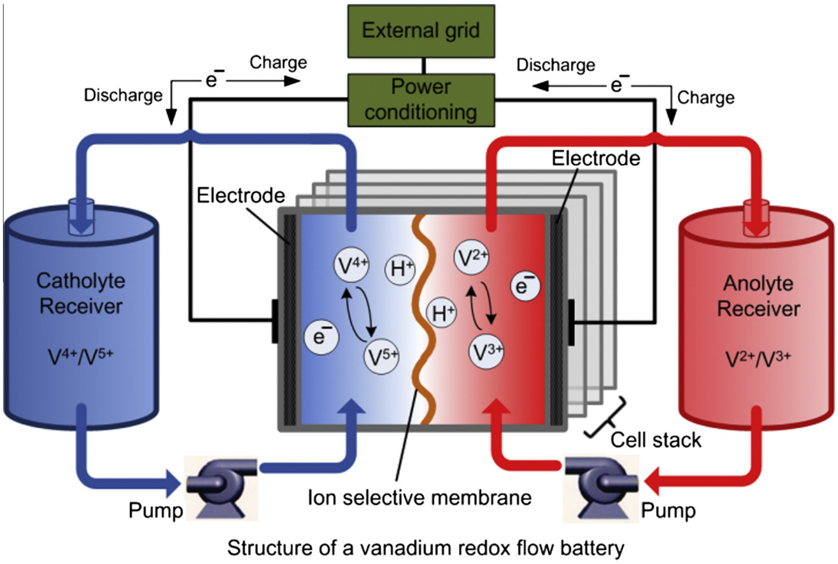

Fig. 8. Schematic diagram of a vanadium redox flow battery system.

Table 6
Selected vanadium redox flow battery energy storage facilities [67,105,107,110,111].

Name/locations	Power/capacity	Application area
Edison VRB EES facility, Italy	5 kW, 25 kW h	Telecommunications back-up application
Wind power EES facility King Island, Australia	200 kW, 800 kW h	Integrated wind power, foil fuel energy with EES
Wind Farm EES project, Ireland	2 MW, 12 MW h	Wind power fluctuation mitigation, grid integration
VRB EES facility installed by SEI, Japan	1.5 MW, 3 MW h	Power quality application
VRB facility by PacifiCorp, Utah, U.S.	250 kW, 2 MW h	Peak power, voltage support, load shifting
VRB EES system build by SEI, Japan	500 kW, 5 MW h	Peak shaving, voltage support

for grid scale energy storage", has been implemented by Lawrence Berkeley National Laboratory in Berkeley, U.S. [100].

3.5.3. Polysulfide Bromine (PSB) flow battery

A PSB system uses sodium bromide and sodium polysulphide as salt solution electrolytes. The chemical reactions are: $3Br^- \leftrightarrow Br_3^- + 2e^-$ and $2S_2^{2-} \leftrightarrow S_4^- + 2e^-$ [4,19]. The significant advantages of PSB systems are: the materials of two electrolytes are abundant and highly soluble in aqueous electrolytes, and they are also cost-effective [19]. The voltage generated across the membrane is ~1.5 V; the PSB system has a fast response time, reacting within 20 ms [4,105]. PSBs have a wide range of potential application areas, especially for power system frequency control and voltage control due to their fast response characteristic. Because bromine and sodium sulfate crystals are produced during the chemical reactions, this may result in environmental issues.

Several PSB systems have been demonstrated at multi-kW scales. For instance, a 100 kW stack using PSB technology had been built by the UK Company Innogy, with a net efficiency of ~75% [104]. Concerning large-scale PSB facility deployment, Regenesys Technologies had tried to build a 15 MW/120 MW h energy storage plant at a power station in the UK; another demonstration plant to be located at Tennessee Valley in the U.S. was designed with a 12 MW/120 MW h capacity for EES to support a wind power plant operation [4]. However, due to engineering difficulties and financial constraints, the construction of these two large storage plants was ceased and the demonstration plants were uncompleted [77,104,119]. Thus the PSB technology for large-scale EES applications still needs practical experience.

3.6. Capacitor and supercapacitor

A capacitor is composed of at least two electrical conductors (normally made of metal foils) separated by a thin layer of insulator (normally made of ceramic, glass or a plastic film). When a capacitor is charged, energy is stored in the dielectric material in an electrostatic field [4,120,121]. Its maximum operating voltage is dependent on the breakdown characteristics of the dielectric material. Capacitors are appropriate for storing small quantities of electrical energy and conducting a varying voltage; they have a higher power density and shorter charging time compared to conventional batteries [70]. However, they have limited capacity, relatively low energy density and high energy dissipation due to the high self-discharge losses [4,120–122]. According to these characteristics, capacitors can be used for some power quality applications, such as high voltage power correction, smoothing the output of power supplies, bridging and energy recovery in mass transit systems.

Supercapacitors, also named electric double-layer capacitors or ultracapacitors, contain two conductor electrodes, an electrolyte and a porous membrane separator (refer to Fig. 9) [13]. Due to their structures, supercapacitors can have both the characteristics of traditional capacitors and electrochemical batteries. The energy is stored in the form of static charge on the surfaces between the electrolyte and the two conductor electrodes. The supercapacitors with high-performance are based on nano materials to increase electrode surface area for enhancing the capacitance.

The power and energy densities of supercapacitors are between those of rechargeable batteries and traditional capacitors

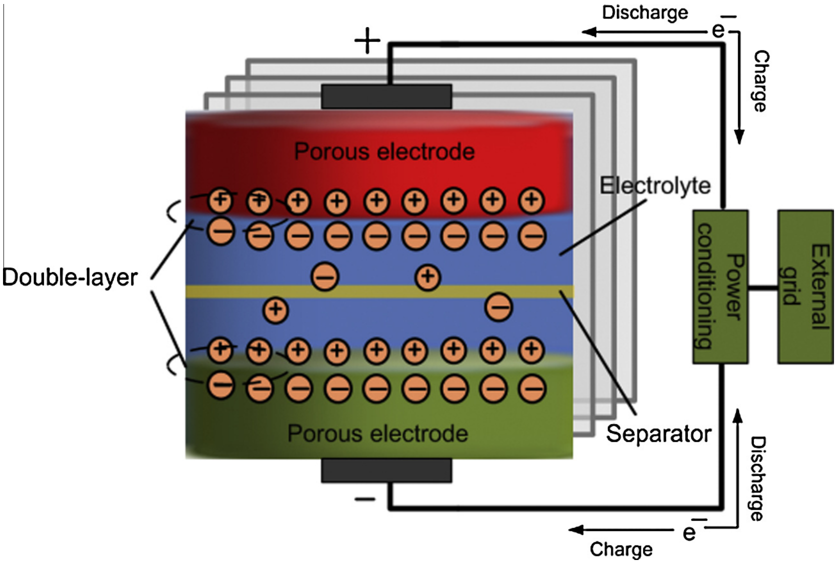

Fig. 9. Schematic diagram of a supercapacitor system.

Table 7
Selected manufacturers of supercapacitors for utility applications [20,67,126,127].

Device/Company name	Country	Technical information
Super capacitor, CAP-XX	Australia	Single cell 2.3–2.9 V, up to ~2.4 F, 233-358 K
Gold capacitor, Panasonic	Japan	Single cell 2.3–5.5 V, 0.1–2000 F
Ultracapacitor/ Boostcap, Maxwell	U.S.	Single cell 2.2–2.7 V, 1–3000 F, UPS, pulse, transportation
Supercapacitor, NEC	Japan	3.5–12 V, 0.01–6.5 F, power quality application
Supercapacitor, Siemens	Germany	21 MJ/5.7 W h, 2600 F, metro distribution net application
Supercapacitor, TVA company	U.S.	200 kW, supporting the start of high power dc machines

[20,123,124]. The most important features of supercapacitors are their long cycling times, more than 1×10^5 cycles, and high cycle efficiency, ~84–97% [4,66]. However, the daily self-discharge rate of supercapacitors is high, ~5–40%, and the capital cost is also high, in excess of 6000 $/kW h [4,10,13,125]. Thus supercapacitors are well suited for short-term storage applications but not for large-scale and long-term EES. Typical applications in power quality consist of pulse power, hold-up/bridging power to equipment, solenoid and valve actuation in factories, UPS devices, etc. There are a number of manufacturers producing supercapacitors worldwide (refer to Table 7).

Research and development in supercapacitors has been very active in recent years. Some recent good quality reviews have focused on the recent development of materials for chemical capacitive energy storage, such as an overview of carbon materials for super-capacitors is given in [24] and an overview of graphene-based electrodes can be found in [25]. To be more specific, a new composite material formed by dispersing ultra-small silicon nanoparticles in polyaniline was developed as the electrode material for supercapacitors [128]. The integration of a short-term supercapacitor EES device in a doubly fed induction generator has been studied in order to smooth the fast wind-induced power variations [129]. One UK EPSRC funded project aiming to develop high-performance supercapacitors with enhanced energy density had been implemented. The prototype had been tested for designing an effective and sustainable power system. Some achievements of this project were published in 2013 [130].

3.7. Superconducting Magnetic Energy Storage (SMES)

A typical SMES system is composed of three main components which include: a superconducting coil unit, a power conditioning subsystem, and a refrigeration and vacuum subsystem [13,109,131]. The SMES system stores electrical energy in the magnetic field generated by the Direct Current (DC) in the superconducting coil which has been cryogenically cooled to a temperature below its superconducting critical temperature. In general, when current passes through a coil, the electrical energy will be dissipated as heat due to the resistance of the wire; however, if the coil is made from a superconducting material, such as mercury or vanadium, under its superconducting state (normally at a very low temperature), zero resistance occurs and the electrical energy can be stored with almost no losses. One commonly used superconducting material is Niobium–Titanium which has a superconducting critical temperature of 9.2 K [4,132]. In the discharging phase, the SMES system can release the stored electrical energy back to the Alternating Current (AC) system, by a connected power converter module. The magnitude of stored energy is determined by the self-inductance of coil and the current flowing through it [133]. A simplified structure of a SMES system is illustrated in Fig. 10.

Superconducting coils can be classified into two groups: Low Temperature Superconducting (LTS) coils, working at ~5 K, and High Temperature Superconducting (HTS) coils, working at ~70 K [13,131]. The LTS-SMES technology is more mature and commercially available while the HTS-SMES is currently in the development stage. SMES devices in the range of 0.1–10 MW have been used commercially; while SMES systems with 100 MW h could be available in the next decade.

The features of SMES include relatively high power density (up to ~4000 W/L), fast response time (millisecond level), very quick full discharge time (less than 1 min), high cycle efficiency (~95–98%) and long lifetime (up to ~30 years) [4,66,114,134]. In contrast to rechargeable batteries, SMES devices are capable of discharging near to the totality of the stored energy with little degradation after thousands of full cycles. The drawbacks are that they have high capital cost (up to 10,000 $/kW h, 7200 $/kW), high daily self-discharge (10–15%) and a negative environmental impact due to the strong magnetic field [4,14,114]. Moreover, the coil is sensitive to small temperature variations which can cause the loss of energy. From the above, SMES is suitable for short-term storage in power and energy system applications and it is expected to have an important role in the increased use of intermittent renewable energy [131]. Table 8 shows selected SMES facilities with their application fields.

Recently, considerable research and development effort has been made: (1) to reduce the costs of superconducting coils and related refrigeration systems; (2) to develop HTS coil materials which are less cryogenically sensitive [14,109,131]. Since 2011, SuperPower Inc., in partnership with ABB Inc., Brookhaven national laboratory and the Texas center for superconductivity at the University of Houston has been developing an advanced SMES demonstrator 20 kW ultra-high field SMES system with a capacity up to 2 MJ [135]. This demonstration project aims to pave the way of grid-scale SMES technology for the U.S. electric grid operation

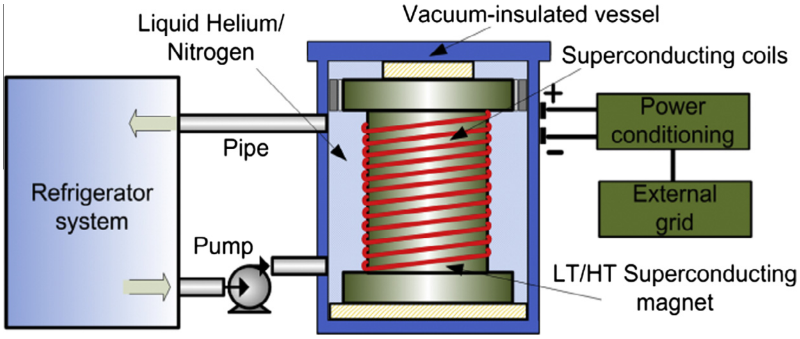

Fig. 10. Schematic diagram of a SMES system.

Table 8
Some projects of superconducting magnetic energy storage [67,131,133,138].

Locations/organizations	Technical data	Features/applications
Proof principle, tested in a grid in Germany	5 KJ, 2 s to max 100 A at 25 K	World first significant HTS-SMES, by ASC
Nosoo power station in Japan	10 MW	Improve system stability and power quality
Upper Wisconsin by American Transmission	3 MW/0.83 kW h, each 8 MV A	Power quality application reactive power support
Bruker EST in Germany	2 MJ	High temperature superconductors
Korea Electric Power Corporation, Hyundai	3 MJ, 750 kV A	Improving power supply quality for sensitive loads
Chubu Electric Power Co. in Japan	7.3 MJ/5 MW and 1 MJ	Provide comparison to transient voltage
University of Houston, SuperPower & others	20 kW, up to 2 MJ class	UHF-SMES, voltage distribution

and for the integration of renewable sources. The University of Bath in the UK continuously focus on SMES technology development and a relevant on-going project funded by the UK EPSRC aims to investigate HTS-SMES as part of hybrid EES systems for renewable energy micro-grids [136,137].

3.8. Solar fuels

Solar fuel is a relatively new technology to EES. Approaches to produce solar fuels include: (1) natural photosynthesis; (2) artificial photosynthesis; (3) thermochemical approaches [4,139,140]. A number of fuels can be produced by solar energy, such as solar hydrogen, carbon-based fuels, and solar chemical heat pipe [4,140–143]. These fuels can be stored and subsequently provide the basis for later electricity generation.

For the first two approaches to produce solar fuels, solar energy is captured via photosynthesis and then stored in chemical bonds, i.e., the sunlight is used to convert water and/or carbon dioxide into oxygen and other materials [144]. Fig. 11 shows a comparison of natural and artificial photosynthesis. The artificial system for water-splitting catalysts generally relies on scarce elements, e.g., Ruthenium (*Ru*), Palladium (*Pd*) and Rhenium (*Re*) [140,145]. For example, sunlight can be captured by Ruthenium (*Ru*) as a catalyst, and electrons moves from the donor (marked as "D") to the acceptor (Fig. 11) [140,145].

The thermochemical approach uses thermal processes for solar fuels production, which involve the generation of very high temperatures in a closed environment to split water into its constituent parts [4]. Thus this method is more dependent on strong sunlight compared to the other two [144,146]. After the solar radiant energy is concentrated by heliostats, an endothermic chemical transformation is carried out in a reaction vessel. The reaction produces hydrogen and/or carbon monoxide and/or other materials [142,143,147].

Solar fuel technology is currently at the development stage. The power rating of solar fuels is potentially up to 20 MW and the specific energy estimate is from 800 W h/kg to 100,000 W h/kg [4,148]. The storage duration can range from a few hours to several months [4]. One drawback of artificial photosynthesis is that the water-splitting catalysts normally depend on scarce, expensive elements [145]. Another disadvantage is that solar fuel facilities need a large area to place devices to concentrate sunlight, especially when using the thermochemical approach to produce solar fuels.

Research in solar fuels has recently undergone substantial advances, making it possible for it to become cost-effective for utility EES applications in the near future. There are on-going research projects in the U.S., the Netherlands, South Korea, Singapore, Japan and China. In the US, there are several organizations focusing on this area, such as Energy Innovation Hub at DoE, the MIT spin-out Sun Catalytix and the Princeton University spin-out Liquid Light. The "Towards BioSolar Cells" research programme has focused on increasing the photosynthetic efficiency and creating solar collectors [140,149]. Concerning the issue of the reliance on scarce and expensive elements, one important breakthrough in the development of using earth-abundant, relatively cheap catalysts (e.g. cobalt and phosphate) and silicon-based semiconductors for the water-splitting process has been recently reported by the Nocera's team from MIT [150,151]. Asia's pioneering solar fuel research laboratory at Nanyang Technological University of Singapore has also made effort on the investigation of affordable approaches to extract large amounts of hydrogen from water using sunlight for engineering applications [151,152].

3.9. Hydrogen storage and fuel cell

Hydrogen energy storage systems use two separate processes for storing energy and producing electricity (refer to Fig. 12). The use of a water electrolysis unit is a common way to produce hydrogen which can be stored in high pressure containers and/or transmitted by pipelines for later use (Fig. 12) [8,13]. When using the stored hydrogen for electricity generation, the fuel cell (also known as regenerative fuel cell) is adopted, which is the key technology in hydrogen EES.

Fuel cells can convert chemical energy in hydrogen (or hydrogen-rich fuel) and oxygen (from air) to electricity [8,13,153]. The overall reaction is: $2H_2 + O_2 \rightarrow 2H_2O$ + energy [154]. Electrical and heat energy are released during the process (Fig. 12). Depending

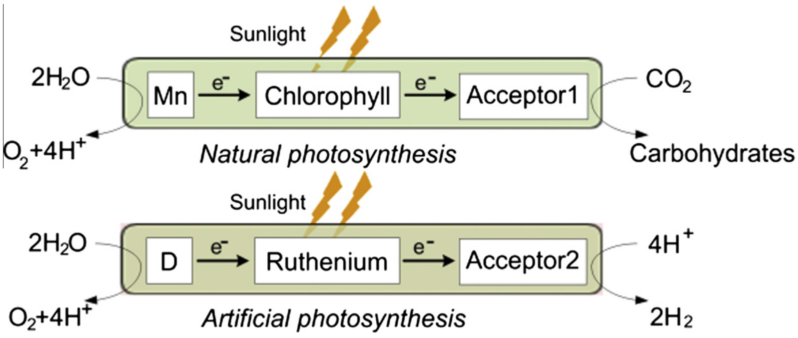

Fig. 11. Comparison of natural and artificial photosynthesis [140].

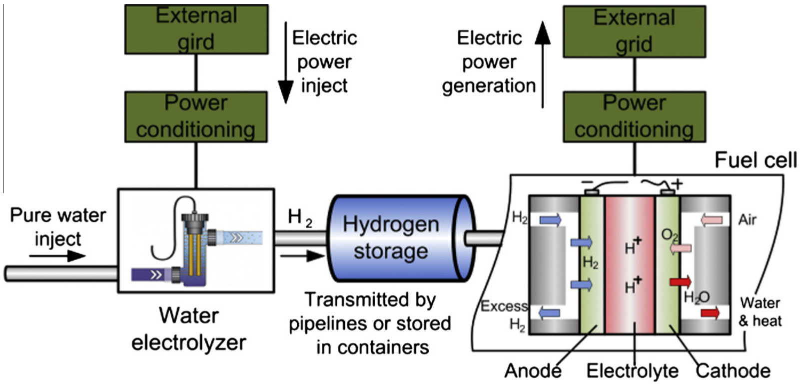

Fig. 12. Topology of hydrogen storage and fuel cell.

on the choice of fuel and electrolyte, there are six major groups of fuel cells, which are: Alkaline Fuel Cell (AFC), Phosphoric Acid Fuel Cell (PAFC), Solid Oxide Fuel Cell (SOFC), Molten Carbonate Fuel Cell (MCFC), Proton Exchange Membrane Fuel Cell (PEMFC) and Direct Methanol Fuel Cell (DMFC) [154]. Their chemical reactions and application fields are listed in Table 9.

In general, the electricity generation by using fuel cells is quieter, produces less pollution and is more efficient than the fossil fuel combustion approach [156]. Other features include easy scaling (potential from 1 kW to hundreds of MW) and compact design [153,157]. Fuel cell systems combined with hydrogen production and storage can provide stationary or distributed power (primary electrical power, heating/cooling or backup power) and transportation power (potentially replacing fossil fuels for vehicles) [153,154]. Such hydrogen EES systems can offer capacity and power independence in energy production, storage and usage, due to the separate processes. It should be noted that the disposal of exhaust fuel cells must consider degradation and recycling while toxic metals are used as electrodes or catalysts. Many of the relevant aspects and approaches have been under investigation [158,159]. For instance, palladium in catalysts of fuel cells can be reprocessed into other products in theory [159].

Currently, hydrogen EES with fuel cell technology is in the development and demonstration stage. Stationary power applications are relatively mature. In 2012 nearly 80% of total investment in the global fuel cell industry was made by the U.S. companies [153]. Cost reduction and durability verification/improvement are essential to deploy this technology in large-scale EES applications [109]. Some research or demonstration projects are in place and on-going across the world. The world's first utility-scale test of a stand-alone renewable energy system integrated with hydrogen storage and fuel cells was installed in Norway, which delivered power with required quality and high reliability [157]. One of the world's largest biogas fuel cell power plants was launched in 2012 in California (2.8 MW), which converts biogas into electricity and usable high-quality heat [160]. In 2013, the US Naval Air Warfare Center Weapons Division in California successfully tested a novel 5 kW trailer-mounted regenerative fuel cell system to use solar power to produce hydrogen with fuel cells [161]. Since 2013, McPhy and Enertrag AG in Germany have worked jointly to develop economic wind-hydrogen solutions for EES and for transportation fuel cell applications [162]. Currently, the on-going hydrogen storage and fuel cell relevant projects include IdealHy (the Netherlands), RE4CELL (Spain), Sapphire (Norway), SmartCat (France), etc.

Table 9
Chemical reactions of main fuel cells [154,155].

Fuel cell Type	Chemical reactions at anodes and cathodes	Applications
AFC	$2H_2 + 4OH^- \rightarrow 4H_2O + 4e^-$ $O_2 + 2H_2O + 4e^- \rightarrow 4OH^-$	Military, space applications
PAFC	$2H_2 \rightarrow 4H^+ + 4e^-$ $O_2 + 4H^+ + 4e^- \rightarrow H_2O$	Distributed generation
SOFC	$O^{2-}(S) + H_2(g) \rightarrow H_2O(g) + 2e^-$ $1/2O_2(g) + 2e^- \rightarrow O^{2-}(s)$	Utility EES, distributed generation
MCFC	$H_2O + CO_3^{2-} \rightarrow H_2O + CO_2 + 2e^-$ $2H_2 + 4OH^- \rightarrow 4H_2O + 4e^-$	Electric utility EES, distributed generation
PEMFC	$H_2(g) \rightarrow 2H^+ + 2e^-$ $1/2O_2(g) + 2H^+ + 2e^- \rightarrow H_2O$	Backup power, small distributed generation
DMFC	$CH_3OH + H_2O \rightarrow CO_2 + 6H^+ + 6e^-$ $3/2O_2 + 6e^- + 6H^+ \rightarrow 3H_2O$	Transportation, portable devices

3.10. Thermal Energy Storage (TES)

TES encompasses a variety of technologies that store available heat energy using different approaches in insulated repositories [6,26]. A TES system normally consists of a storage medium in a reservoir/tank, a packaged chiller or built-up refrigeration system, piping, pump(s), and controls. Based on the range of operating temperature, TES can be classified into two groups: low-temperature TES (consisting of aquiferous low-temperature TES and cryogenic energy storage) and high- temperature TES (including latent (fusion) heat TES, sensible heat TES and concrete thermal storage) [4,163–166]. Aquiferous low-temperature TES normally uses water cooled/iced and reheating processes, which is more suitable for peak shaving and industrial cooling loads [4]. Cryogenic energy storage employs a cryogen (such as liquid nitrogen or liquid air) to achieve the electrical and thermal energy conversion. For instance, Liquid Air Energy Storage (LAES) is attracting attention due to the high expansion ratio from the liquid state to the gaseous state and the high power densities of liquid air compared to that of gaseous state of air. Latent heat TES employs Phase Change Materials (PCMs) as the storage media and uses the energy absorption or emission in liquid-solid transition of these PCMs at constant temperature. Concrete thermal storage utilizes concrete or castable ceramics to store heat energy, normally supported by synthetic oil as a heat transfer fluid. The above TES technologies have different features with various applications. For instance, latent heat storage can provide a relatively high storage density with a small dimension reservoir, thus the use of this technology in buildings receives attention [21]. In addition, cryogenic energy storage is expected to be used for future grid power management.

The TES system can store large quantities of energy without any major hazards and its daily self-discharge loss is small (~0.05–1%); the reservoir offers good energy density and specific energy (80–500 W h/L, 80–250 W h/kg) and the system is economically viable with relatively low capital cost (3–60 $/kW h) [4,10,166–168]. However, the cycle efficiency of TES systems is normally low (~30–60%) [4]. TES has been used in a wide spectrum of

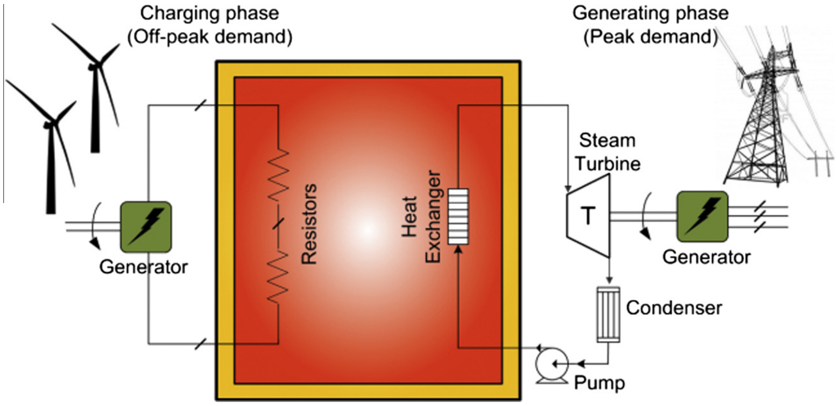

Fig. 13. A sensible heat storage system for wind power generation.

applications, such as load shifting and electricity generation for heat engine cycles.

With particular focus on using TES for power system and grid applications, there are many active research projects worldwide and, in addition, numerous demonstration projects are built, under construction or planned. The UK based company Highview Power Storage designed and assembled a pilot LAES facility (300 kW/2.5 MW h storage capacity) which has been in operation at Scottish and Southern Energy's 80 MW biomass plant since 2010 [168,169]. In February 2014, this firm has been awarded £8 million funding from the UK government for a 5 MW/15 MW h demonstration LAES project; the designed LAES system will be alongside one landfill gas generation plant in the UK [169]. A TES system in an office building was built by a joint U.S. and China demonstration project in Beijing, which can reduce peak electric energy consumption of 6100 kW h per month [170]. A new central energy plant including an ice-based TES system is being built in South Florida. The completely built plant will have a total capacity of 11,500 tons of chilled water with 68,000 ton-hour of TES [170]. A 15 MW commercial power plant, named "Solar Tres Power Tower", is being built in Spain by Torresol Energy, and it uses molten salt as the working fluid to store heat energy [165]. A wind power generation system combined with a sensible heat storage facility had been proposed (Fig. 13) [165]. The electrical energy from wind power is used to heat a bulk storage material; the heat energy is recovered to produce water vapor which in turn drives a turbo-alternator to generate electricity. A detailed study of load shifting of nuclear power plants by using cryogenic energy storage technology was recently reported in [171]. A UKERC funded project, "the future role of TES in the UK energy system", has investigated the potential for, and limitations of, the role of TES in the transition to a sustainable low carbon energy supply system; the project has also studied the suitability of TES in managing energy generation and distribution systems with large-scale penetration [6].

3.11. Hybrid electrical energy storage

Hybrid EES refers to the integration of at least two different EES technologies into one system or application. Advantages of each EES technology can be utilized to achieve specific requirements, meet harsh working environments, optimize the whole system performance or improve the cycle efficiency. For example, the first large pilot power plant (ADELE) utilizes CAES and TES technologies for enhancing the efficiency and avoiding fossil fuel consumption [42,43]. The combination of supercapacitor and battery technologies can offer relatively large storage capacity and very fast charge/discharge rates. One project in the theme of a hybrid supercapacitor-battery system, funded by E.ON, was completed in UK and a corresponding demonstration system was developed [6]. Another project funded by UK EPSRC, named "Ultra battery feasibility - investigation into the combined battery- supercapacitor for hybrid electric vehicle applications", was completed in 2012, and some achievements were recently published in [172]. Researchers in Japan High Energy Accelerator Research Organization, Tohoku University and others have designed a back-up system for renewable energy power generation, which combines a liquid hydrogen refrigeration-based SMES system with a hydrogen-fuel cell system [109,173].

4. Comparison and evaluation of electrical energy storage technologies

It is well recognized that no single EES technology can meet the requirements for all power system applications. Comprehensive analysis of different EES technologies is conducted and Tables 10–12 provide the matrices to clearly show the positions of different EES performance and characteristics. The selection of representative matrices in Tables 10–12 is derived with consideration of the focuses in both academic research and industry application areas, which is drawn from the comprehensive literature review in this paper. The selection of EES indices also relies on the assessment in the characteristics of different EES options against the requirements of power system applications, which will be discussed in Section 5.

Size of storage devices is an important factor for many applications. Fig. 14 shows the comparison of power density and energy density of different EES technologies. For a given amount of energy, the higher the power and energy densities are, the smaller the volume of the required energy storage system will be. In Fig. 14, the highly compact technologies suitable for volume-limited applications can be found at the top right corner and the large volume consuming storage systems are located at the bottom left corner. It can be seen that most batteries, flywheel and fuel cells have relatively moderate energy densities and power densities. PHS and CAES have lower densities, thus they are mainly used in stationary EES and require large reservoirs for grid scale applications. Supercapacitors and capacitors have very high power densities but low energy densities. The densities of flow batteries are commonly lower than those of conventional batteries. The Li-ion battery has both a high energy density and a high power density, which leads to widespread uses in portable devices and promising potential in transportation and other small-scale EES applications.

Specific energy and specific power are important indices which represent the total energy and power per unit weight. Fig. 15 presents the comparison of the specific energy and specific power of

Table 10
Technical characteristics of electrical energy storage technologies.

Technology	Energy density (W h/L)	Power density (W/L)	Specific energy (W h/kg)	Specific power (W/kg)	Power rating (MW)	Rated energy capacity (MW h)
PHS	0.5–1.5 [4], 1–2 [26]	0.5–1.5 [4], ∼1 [26],	0.5–1.5 [4]	–	100–5000 [4], 30 [34], < 4000 [114]	500–8000 [4], 180 Okinawa PHS[34,77]
Large–scale CAES	3–6 [4], 2–6 [26]	0.5–2 [4], ∼1 [26]	30–60 [4]	–	Up to 300 [4], 110 & 290 [39], 1000 [70]	∼ < 1000[10], 580 & 2860 [38,42]
Overground small CAES	Higher than large-scale CAES	Higher than large-scale CAES	140 at 300 bar [174]	–	0.003–3 [51] Potential ∼10 [175]	∼0.01[10], ∼0.002–0.0083 [51]
Flywheel	20–80 [4,26,123]	1000–2000 [4], ∼5000 [26]	10–30 [4], 5–100 [57], 5–80 [176]	400–1500 [4]	<0.25 [4], 3.6 [60], 0.1–20 [13,177]	0.0052 [60], 0.75 [70], up to 5 [177]
Lead–acid	50–80 [4], 50–90 [70]	10–400 [4]	30–50 [4], 25–50[178]	75–300 [4], 250 [70], 180 [57]	0–20 [4], 0–40 [14], 0.05–10 [179]	0.001–40 [179] More than 0.0005[180]
Li-ion	200–500 [4], 200–400 [26], 150 [70]	1500–10,000 [26]	75–200 [4], 90 [70], 120–200 [181]	150–315 [4], 300 [70], 500–2000 [57]	0–0.1 [4], 1–100 [73], 0.005–50 [182]	0.024 [79], ∼0.004–10 [182]
NaS	150–250 [4], 150–300 [26]	∼140–180 [26]	150–240 [4], 100 [183], 174 [184]	150–230 [4], 90–230 [9], 115 [13],	<8 [4], <34 [14]	0.4–244.8 [81], 0.4 [185]
NiCd	60–150 [4], 15–80 [26], 80 [70]	80–600 [26]	50–75 [4], 50 [70], 45–80 [71]	150–300 [4], 160 [13], 150 [70],	0–40 [4], 27 [88], 40 [186]	6.75 [57,88]
VRB	16–33 [4], 25–35 [19]	∼ < 2 [26]	10–30 [4]	166 [187]	∼0.03–3 [4], 2 [188] possible 50 [5]	<60 [13], 2 [88], 3.6 [189]
ZnBr	30–60 [4], ∼55–65 [26]	∼ < 25 [26]	30–50 [4], 80 [190], 75 [191]	100 [190], 45 [191]	0.05–2 [4], 1–10 [73]	0.1–3 [13], 4 [14], 0.05 & 0.5 [192]
PSB	∼20–30 [123]	∼ < 2 [26]	∼15–30 [123]	–	1–15 [4], 1 [193], 0.004 [194]	Potential up to 120 [193], 0.06 [194]
Capacitor	2–10 [4], ∼0.05 [124]	100,000+ [4],	0.05–5 [4], <∼0.05 [121,124]	∼100,000 [4], >∼3000–10^7[124]	0–0.05 [4]	–
Super-capacitor	10–30 [4], ∼10–30 [123]	100,000+ [4],	2.5–15 [4], ∼0.05–15 [124]	500–5000 [4], ∼10,000 [124]	0–0.3 [4], ∼0.3+[26] ∼0.001–0.1 [70]	0.0005 [70]
SMES	0.2–2.5 [4], ∼6 [26]	1000–4000 [4], ∼2500 [26]	0.5–5 [4], 10–75 [195]	500–2000 [4]	0.1–10 [4,14], ∼1–10 [70]	0.0008 [70], 0.015 [138], 0.001 [196]
Solar fuel	500–10,000 [4]	–	800–100,000 [4]	–	0–10 [4], 6 and developing 20 [197]	–
Hydrogen Fuel cell	500–3000 [4]	500+ [4]	800–10,000 [4], ∼150–1500 [124]	500+ [4], ∼5–800 [124]	<50 [4], <10 [26], 58.8 [199]	0.312 [198], developing 39 [200]
TES	80–120, 120–200, 200–500 [4]	–	80–120, 80–200 [4], 150–250 [4]	10–30 [4]	0.1–300 [4], 15 [165], 10 [201]	–
Liquid air Storage	4–6 times than CAES at 200 bar [202]	–	214 [174]	–	10–200 [8], 0.3 [168]	2.5 [168]

EES technologies. For acquiring a certain amount of energy, the higher the specific power and the specific energy are, the lighter the weight of the EES system will be. The EES technologies suitable for light weight applications can be found at the top right corner of the figure. It can be seen that SMES capacitors and supercapacitors have high specific power but low specific energy; because of their fast response time (Table 11), they are more suitable for power quality applications for electric power (current) delivery. Fuel cells and TES have high specific energy with low specific power. Flywheel, flow batteries and most conventional batteries are located at the middle levels in terms of specific power and specific energy, which may serve for different EES application domains. Li-ion batteries are outstanding due to both high specific energy and specific power, which offers a reasonable explanation to the current broad range of development and applications for Li-ion batteries.

Fig. 16 shows a comparison of power ratings and rated energy capacities of EES technologies. The nominal discharge time duration at the rated power is also shown within the range from seconds to months. The data of practical EES facilities/plants in Section 2 are marked in Fig. 16 to highlight the positions of their characteristics. This figure indicates the general application areas of current EES systems and also provides a guiding range for potential future applications. From Table 12 and Fig. 16, EES technologies can be categorized by the nominal discharge time at rated power: (1) discharge time less than 1 hour: flywheel, supercapacitor and SMES; (2) discharge time up to around 10 hours: over ground small-scale CAES, Lead–acid, Li-ion, NiCd, ZnBr and PSB; (3) discharge time longer than 10 h: PHS, underground large-scale CAES, liquid air energy storage, VRB, solar fuel, fuel cell and TES.

Cycle efficiency, also named the round-trip efficiency, is the ratio of the whole system electricity output to the electricity input. Derived from the data shown in Table 11, Fig. 17 shows the comparison of cycle efficiencies of EES technologies. Most commercialized (including early commercialized) techniques have medium-to-high cycle efficiencies (above 60% from all cited references), such as PHS, flywheels, conventional batteries, flow batteries, capacitors, supercapacitors and SMES. CAES, TES, solar fuels and fuel cells have low cycle efficiency (below 60%) reported in some published literatures. In general, the efficiency has been continuously improved with time through dedicated research and development efforts. For instance, the cycle efficiency for CAES has increased from 42% (in 1978), ∼54% (in 1991) to the expected 70% (AA-CAES, announced by RWE power in 2011, ADELE project) [38,39,42,43]. Table 11 lists the discharge efficiencies of EES technologies. Discharge efficiency represents the energy transmission ability from the energy-storing phase to the energy-releasing phase, which contributes to the overall cycle efficiency achieved. For example, the compressed air UPS products from Flowbattery have relatively high discharge efficiency (75–90%), which improved the related cycle efficiency and became a key factor for the company to launch the product successfully [51].

Self-discharge is related to energy dissipation, in the forms of heat transfer losses in thermal storage, air leakage losses in compressed air storage, electrochemical losses in batteries, etc. The level of self-discharge of an EES system is one of the major factors in deciding the associated suitable storage duration. From Tables 11 and 12, PHS, CAES, NaS batteries, flow batteries, fuel cells and solar fuels have very small daily self-discharge ratios so it is

Table 11
Additional technical characteristics of electrical energy storage technologies.

Technology	Daily self-discharge (%)	Lifetime (years)	Cycling times (cycles)	Discharge efficiency (%)	Cycle efficiency (%)	Response time
PHS	Very small [4,192]	40–60 [4], 40+[69], 30+[175]	10,000–30,000 [14]	∼87 [114]	70–85 [4], 70–80 [175] 87 [33], 75–85 [203]	Minutes [114], not rapid discharge [203]
Large-scale CAES	Small [4], Almost zero [192]	20–40 [4], 30 [70], 20+[69,203]	8000–12,000 [14]	∼70–79 [114]	42,54 [4,42] AA-CAES 70 [43,203]	Minutes [114]
Over-ground small CAES	Very small [51]	23+[51]	Test 30,000stop/starts [51]	∼75–90 [51]	–	Seconds–minutes [114]
Flywheel	100 [4], ⩾20% per hour [57]	∼15 [4], 15+[69], 20 [114]	20,000+ [4], 21,000+[69]	90–93 [114]	∼90–95 [4], 90 & 95 [70]	<1 cycle [114], seconds [203]
Lead–acid	0.1–0.3 [4], <0.1 [57], 0.2 [69]	5–15 [4,57], 13 [69]	500–1000 [4], 200–1800 [13]	85 [114]	70–80[4], 63–90 [14], 75–80 [204]	<1/4 cycle [114] milli-seconds
Li-ion	0.1–0.3 [4], 1 & 5 [13]	5– 15 [4], 14–16 [205]	1000–10,000 [4], up to 20,000 [9]	85 [114]	∼90–97 [4], 75–90 [73]	Milliseconds, <1/4 cycle [14]
NaS	Almost zero [13,185]	10–15 [4], 15 [69], 12–20 [192]	2500 [4], 3000[206] 2500–4500 [14]	85 [114]	∼75–90 [4], 75 [206], 75–85 [204]	–
NiCd	0.2–0.6 [4],0.3 [57], 0.03–0.6 [14]	10–20 [4], 3–20 [13], 15–20 [57]	2000–2500 [4], 3500 [179]	85 [114]	∼60–70 [4], 60–83 [14]	Milliseconds, <1/4 cycle [14]
VRB	Small [4], very low [13]	5–10 [4], 20 [193]	12,000+ [4], 13,342 [69]	∼75–82 [207]	75–85 [4,62], 65–75 [73]	<1/4 cycle [14]
ZnBr	Small [4,100]	5–10 [4], 10 [69], 8–10 [205]	2000+ [4], 1500 [69]	∼60–70 [208]	∼65–75 [4], 66–80 [14], 66 [114]	<1/4cycle [114]
PSB	Small [4] Almost zero [193]	10–15 [4], 15 [209]	–	–	∼60–75 [4], 60–75 [209]	20 ms [116]
Capacitor	40 [4], ∼50 in about 15 minutes [122]	∼5 [4], ∼1–10 [122]	50,000+ [4], 5000 (100% DoD) [210]	∼75–90 [127]	∼60–70 [4], 70+[210]	Milliseconds, <1/4 cycle [14]
Super-capacitor	20–40 [4], 5 [10], 10–20 [211]	10–30 [4], 10–12 [66]	100,000+ [4], 50,000+[69]	95 [114] Up to ∼98 [127]	∼90–97 [4], 84–95 [66]	Milliseconds, ¼ cycle [114]
SMES	10–15 [4]	20+[4], 30 [114]	100,000+4], 20,000+ [14]	95 [114]	∼95–97 [4], 95–98 [66], 95 [70]	Milliseconds, <1/4 cycle [114]
Solar fuel	Almost zero [4]	–	–	–	∼20–30 [4], planned eff.>54 [197]	–
Hydrogen Fuel cell	Almost zero [4,192]	5–15 [4], 20 [119] 20+[212]	1000+ [4], 20,000+[212]	59 [114]	∼20–50 [4], 32 [106], 45–66 [213]	Seconds, <1/4 cycle [114]
TES	0.05–1 [4]	10–20 [4], 5–15[4], 30 [203]	–	–	∼30–60 [4]	Not for rapid response [203]
Liquid air Storage	Small [169,214]	25+[214]	–	–	55–80+[214]	Minutes [215]

technically possible for the energy to be stored in long-term durations (up to months); most conventional batteries (except NaS batteries) have daily self-discharge ratios, from 0.03% to 5%, which can be used for medium-term storage durations (up to days); SMES, flywheel, capacitors and supercapacitors have very high daily self-charge ratios, from 10% to 100%, that is, they could completely release their stored energy after a few hours or even shorter. Hence, they can only be utilized for short-term storage durations (up to hours). TES encompasses a variety of technologies and thus it may be suitable for medium-term and/or long-term storage durations.

Lifetime and cycling times are two factors which affect the overall investment cost. Low lifetime and low cycling times will increase the cost of maintenance and replacement. Table 11 shows the comparison of lifetime and cycling times of different EES technologies discussed in the paper. It can be seen that these two indices more or less associate with the EES technology's category – in the form of the type of energy stored in the system. Mechanical energy storage systems, including PHS, CAES and flywheels, normally have high cycling times (around 10,000 or more) which mainly depend on their mechanical components. The cycle times for EES with energy stored in electrical energy, such as SMES, capacitors and supercapacitors, are normally higher than 20,000. From Table 11, it can be seen that the cycle abilities of conventional batteries are not as high as other EES systems mainly due to chemical deterioration with the accumulated operating time.

The maturities of EES technologies are linked to the level of commercialization, the technical risk and the related economic benefits. Table 12 compares the levels of technical maturity of the EES technologies reviewed in the paper. The technology maturity level for utility EES applications can be classified into five categories: (1) Developing (AA-CAES, PSB and solar fuel); (2) Demonstration (liquid air storage, Li-ion, VRB, ZnBr, supercapacitor, SMES, fuel cell and TES); (3) Early Commercialized (over-ground small CAES and flywheel); (4) Commercialized (conventional CAES, NaS, NiCd and capacitor); (5) Mature (PHS & Lead–acid). It can be seen that several technologies are undergoing breakthroughs from one category evolving to another (Table 12). The technologies in the developing stage are technically possible and have great potential for future EES projects.

Table 12 lists the EES cost in terms of energy capacity and the cost for Operating and Maintenance (O&M). Fig. 18 presents the comparison of energy capital cost and annual O&M cost. A complete economic analysis of EES technologies needs to consider not only the capital cost but also the O&M cost and the impact of the equipment lifetime. For instance, although the energy capital cost of lead–acid battery is relatively low, it may not be the best option for large-scale EES applications due to its relatively high O&M cost and short lifetime. The cost of EES is tending to decreases with the continuous effort in research and development, and some key technology breakthroughs can lead to dramatic changes in cost. From Fig. 18, among the mature and commercialized techniques, PHS and CAES have lowest energy capital costs compared to all other technologies; NaS, VRB and Lead–acid battery have relatively high O&M cost. As shown in Table 12, TES is in the low range in terms of energy capital cost; SMES and flywheel are suitable for high power and small-scale applications as they are cheap in terms of the power capital cost but expensive in terms of the

Table 12
Other technical and economical characteristics of electrical energy storage technologies.

Technology	Suitable storage duration	Discharge time at power rating	Power capital cost ($/kW)	Energy capital cost ($/kW h)	Operating and maintenance cost	Maturity
PHS	Hours–months [4], long-term [27]	1–24 h+[4], 6–10 h [73] 10 h [175]	2500–4300 [73], 2000–4000 [175]	5–100 [4], 10–12 [114]	0.004 $/kW h [70], ∼3 $/kW/year [72]	Mature
Large-scale CAES	Hours–months [4], long-term [27]	1–24 h+ [4], 8–20 h [73]	400–800 [4], 800–1000 [175]	2–50 [4], 2–120 [8], 2 [70]	0.003 $/kW h [70], 19–25 $/kW/year [72]	CAES commercialized, AA-CAES developing
Over-ground small CAES	Hours–months, long-term [27]	30 s–40 min [51], 3 h [216]	517 [114], 1300–1550 [216]	1MVA from £296 k [51], 200–250 [216]	Very low [51]	Early commercialized
Flywheel	Seconds–minutes [4] short-term(<1 h)[27]	Up to 8 s [4], 15 s–15 min [175]	250–350 [4]	1000–5000 [4], 1000–14,000 [8]	∼0.004 $/kW h[70], ∼20 $/kW/year [72]	Early commercialized
Lead–acid	Minutes–days [4], short-to-med. term	Seconds–hours [4], up to 10 h [14]	300–600 [4], 200–300 [114], 400 [206]	200–400 [4], 50–100 [57], 330 [206]	∼50 $/kW/year [72]	Mature
Li-ion	Minutes–days [4], short-to-med. term	Minutes–hours [4], ∼1–8 h [209]	1200–4000[4], 900–1300[57], 1590[73]	600–2500 [4], 2770–3800 [73]	–	Demonstration
NaS	Long term[82]	Seconds–hours [4], ∼1 h [209]	1000–3000 [4], 350–3000 [8]	300–500 [4], 350 [206], 450 [217]	∼80 $/kW/year [72]	Commercialized
NiCd	Minutes–days [4], Short and long term	Seconds–hours [4], ∼1–8 h [209]	500–1500 [4]	800–1500 [4], 400–2400 [57]	∼20 $/kW/year [72]	Commercialized
VRB	Hours–months [4], Long term [27]	Seconds–24 h+ [4], 2–12 h [106]	600–1500 [4]	150–1000 [4], 600 [217]	∼70 $/kW/year [72]	Demo/early commercialized
ZnBr	Hours–months [4] long term [27]	Seconds–10 h+ [4], ∼10 h [209]	700–2500 [4], 400 [87], 200 [114]	150–1000 [4], 500 [71]	–	Demonstration
PSB	Hours–months [4] long term [27]	Seconds–10 h+ [4], ∼10 h [209]	700–2500 [4]	150–1000 [4], 450 [217]	–	Developing
Capacitor	Seconds–hours [4], ∼5 h [210]	Milliseconds–1 h [4]	200–400 [4],	500–1000 [4],	13 $/kW/year [72], <0.05 $/kW h [210]	Commercialized
Super-capacitor	Seconds–hours [4] short-term(<1 h)[27]	Milliseconds–1 h [4], 1 min[209], 10 s[216]	100–300 [4], 250–450 [216]	300–2000 [4]	0.005 $/kW h [70], ∼6 $/kW-year [114]	Developing/demo.
SMES	Minutes–hours [4] short-term (<1 h)[27]	Milliseconds–8 s [4], up to 30 min [209]	200–300 [4], 300 [114], 380–489[216]	1000–10,000 [4], 500–72,000 [114]	0.001 $/kW h [70], 18.5 $/kW/year [72]	Demo/early commercialized
Solar fuel	Hours–months [4]	1–24 h+ [4]	–	–	–	Developing
Hydrogen Fuel cell	Hours–months [4]	Seconds–24 h+ [4]	500 [114], 1500–3000 [154]	15 [114], 2–15€/kW h [204]	0.0019–0.0153 $/kW [154]	Developing/demo.
TES	Minutes–days [4], minutes–months [4]	1–8 h [4], 1–24 h+ [4], 4–13 h [203]	200–300[4], 250 [203], 100–400[203]	20–50 [4], 30–60 [4], 3–30 [4]	–	Demo/early commercialized
Liquid air Storage	Long-term [214]	Several hours [168,214]	900–1900 [214]	260–530 [214]	–	Developing/demo.

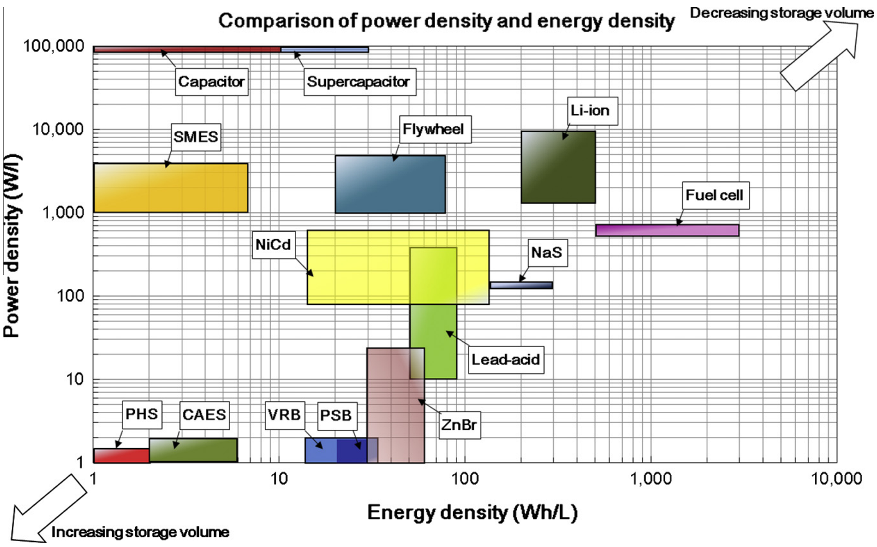

Fig. 14. Comparison of energy density and power density.

energy capital cost. It should be noted that the capital cost of a specific EES system varies in terms of the timescale of EES construction, the location of the plant/facility and the size of the system. The economic analyses of different EES technologies in various application scenarios are attracting attention due to their great application prospects, which can be found in [40,171,218–220].

5. Analysis and recommendations of EES technologies for various applications

The application outlooks and potentials of EES in power system operations have been widely reported in recent years [6,13,14,26,114,123]. Table 13 summarizes the current and

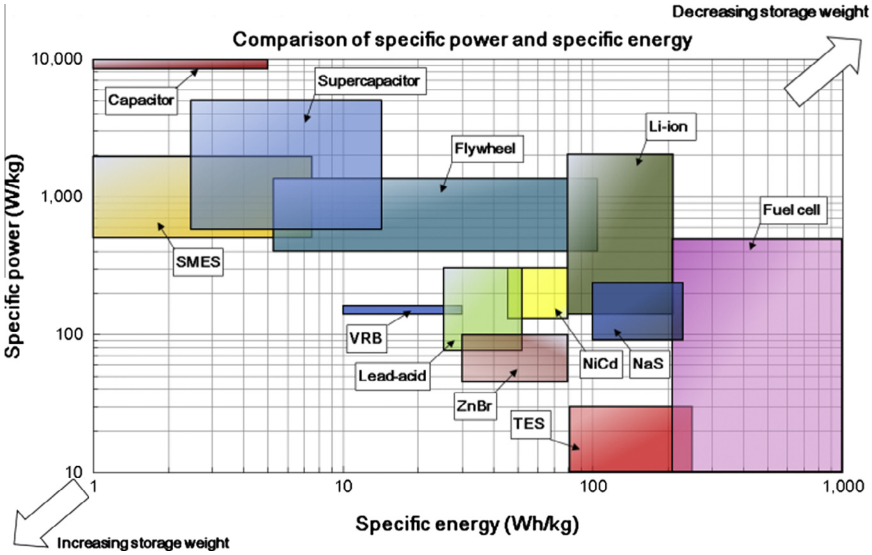

Fig. 15. Comparison of specific energy and specific power.

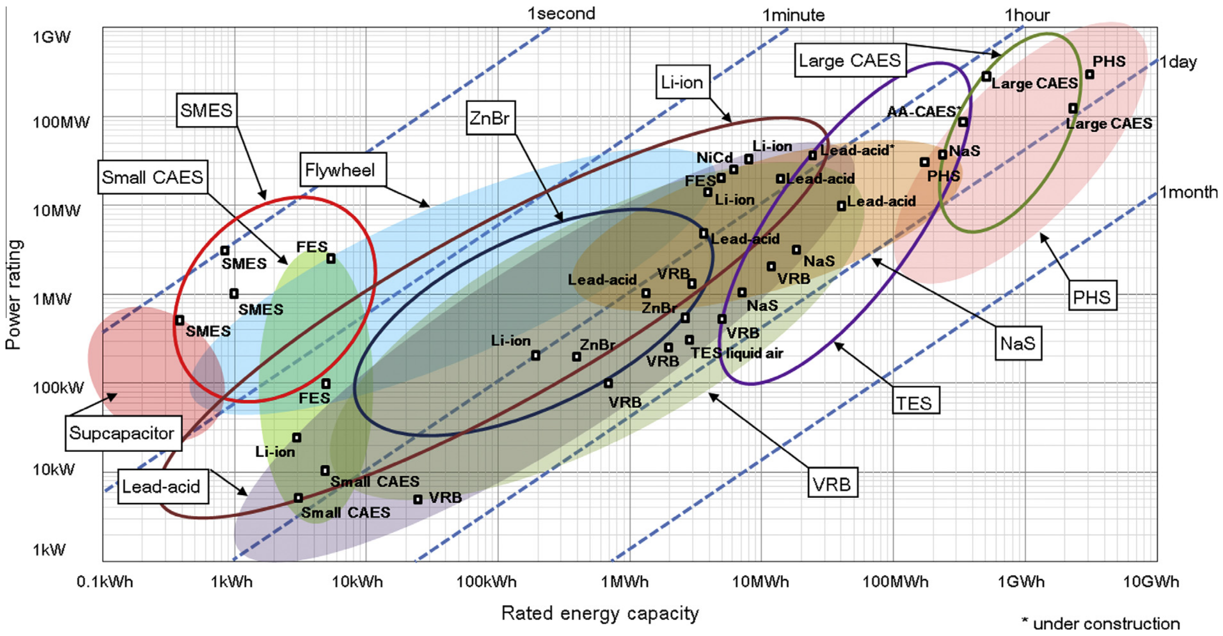

Fig. 16. Comparison of power rating and rated energy capacity with discharge time duration at power rating. The marked data of EES facilities from the cited references in Section 2 of the paper).

promising EES options for various applications with corresponding specifications. The applications of EES technologies cover a wide range including the maintenance of power quality, power system protections and energy management.

The EES technologies used for maintaining power quality will need to have very fast response time (at the millisecond level). Flywheels, conventional batteries, SMES, capacitors and supercapacitors are well suited for this service. Some flow batteries, such as VRB and PSB, are also technically suitable for this service. For studies of EES systems for power quality applications refer to [63,80,129,221,222]. The papers [129,221] present the power quality enhancement of renewable energy source power (wind and photovoltaic power generation systems) by using supercapacitors and SMES respectively. In [231], the applications of VRB systems to maintain power quality have been studied. One example from the study is the Sumitomo Electric Industries (SEI) VRB facility (rated power 170 kW) which works in combination with a wind turbine (275 kW) for stabilization of wind turbine output fluctuations; the system demonstrated good performance [222].

When EES is adopted for bridging power, they are required to have moderate power rating (100 kW–10 MW) and response time (up to around 1 s), in order to provide the continuity of power supply at energy gap periods (up to several hours), such as the time interval for switching the system from one source of power generation to another. Conventional batteries and flow batteries are suitable for this application. Flywheels, supercapacitors and fuel cells are also reported for such types of applications [60,126,223]. Piller Power Systems Ltd. has practical experiences in using flywheels as ride-through power sources [60]. The article [223] presents a decoupled P–Q control strategy of a supercapacitor energy storage

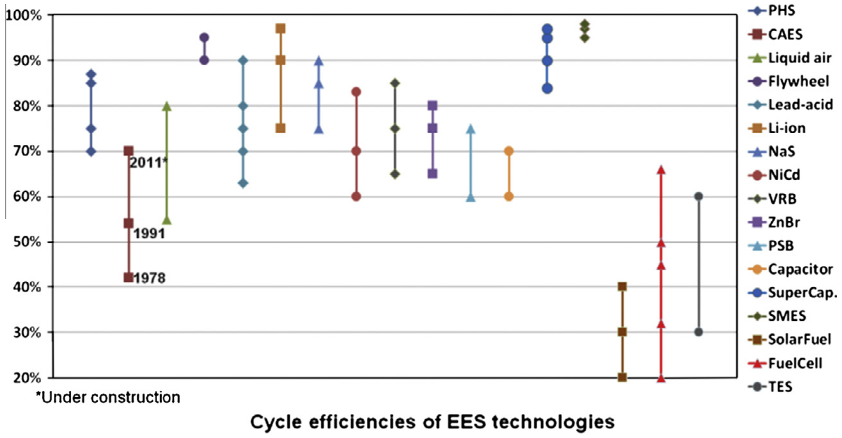

Fig. 17. Comparison of cycle efficiencies of EES technologies.

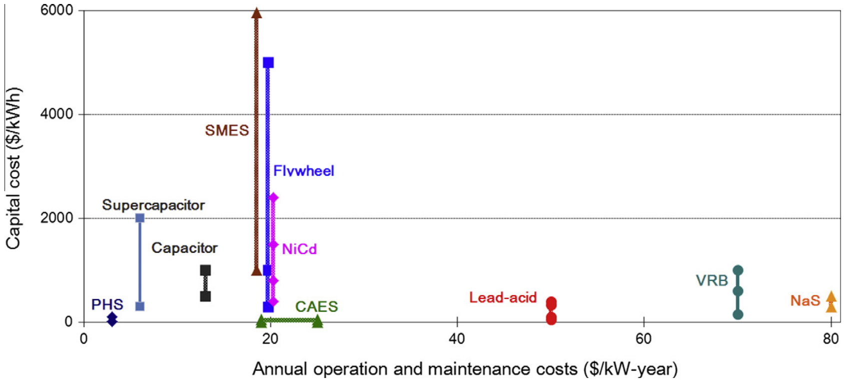

Fig. 18. Comparison of energy capital cost and annual operating & maintenance cost.

system for low voltage ride-through as well as damping enhancement of the doubly fed induction generator system. The fault ride-through capability of the generator has been investigated for a severe symmetrical three-phase to ground fault on the grid bus.

EES plays an important role in energy management for optimizing energy uses and decoupling the timing of generation and consumption of electric energy. Time shifting and peak shaving are typical applications in energy management. Energy management application can be further classified based on the application power rating: large-scale (above 100 MW) and medium/small-scale (∼1–100 MW). PHS, large-scale CAES and TES can be used for large-scale energy management. Flow batteries, large-scale conventional batteries, fuel cells and solar fuels are more suitable for small/medium-scale energy management. Practical examples are described in [34,39,88,170]. For instance, both the Huntorf and the McIntosh large-scale CAES plants provide the functions of energy management.

Table 13 also summarizes an overview of EES options for more specific applications with their specifications. A brief explanation of most of these applications is given below:

- Integration of renewable power generation: The inherent intermittent renewable generation can be backed up, stabilized or smoothed through integration with EES facilities. The recent research, development and demonstrations in this area are described in [76,108,157,173].
- Emergency and telecommunications back-up power: In the case of power failure, EES systems can be operated as an emergency power supply to provide adequate power to important users including telecommunication systems until the main supply is restored, or to ensure the system enabling orderly shutdown. For emergency back-up power, instant-to-medium response time and relatively long duration of discharge time are required. The suitable EES technologies for this application are given in Table 13, and relevant reports and studies can be found in [227–229]. For example, one of the world's first utility (hybrid) CAES back-up systems was recently installed at a Co-op Bank data center to provide an emergency supply of electricity [227]. For telecommunications back-up, the instant response time is essential. Several technologies are suited to this application (see Table 13) and related publications include [114,230,231].
- Ramping and load following: EES facilities can provide support in following load changes to electricity demand. The relevant research and demonstration projects can be found in [77,232,233]. One EES trial project, named Irvine Smart Grid Demonstration, using advanced batteries (25 kW) in California offers services in load following and voltage support [77]. A flexible load following operation mode for operating a NaS battery EES system with its control method has been studied in [233].
- Time shifting: Time shifting can be achieved by storing electrical energy when it is less expensive and then using or selling the stored energy during peak demand periods. EES technologies are required to provide power ratings in the range of around 1-100 MW. PHS, CAES and conventional batteries have experience in this service; flow batteries, solar fuels and TES have demonstration plants or are potentially available for this application. Some associated discussions can be found in [234–236].

Table 13
Overview of current and potential electrical energy storage options for various applications with their specifications.

Application area	Application characteristics & specifications (refer to [6,10–16,26,114,123,209,224])	Experienced and promising EES technology options	Related references
Power quality	∼ < 1 MW, response time (∼milliseconds, <1/4 cycle), discharge duration (milliseconds to seconds)	Experienced: flywheels, batteries, SMES, capacitors, supercapacitors. Promising: flow batteries	[26,80,129,221,222]
Ride-through capability (bridging power)	∼100 kW–10 MW, response time (up to ∼1 s), discharge duration (seconds to minutes and even hours)	Experienced: batteries and flow batteries; Promising: fuel cells, flywheels and supercapacitors	[4,60,87,126,223]
Energy management	Large (>100 MW), medium/small (∼1–100 MW), response time (minutes), discharge duration (hours–days)	Experienced: Large (PHS, CAES, TES); small (batteries, flow batteries, TES) Promising: flywheels, fuel cells	[34,39,56,88,170]
More specific applications			
Integration renewable smoothing intermittent	Up to ∼20 MW, response time (normally up to 1 s, <1 cycle), discharge duration (minutes to hours)	Experienced: flywheels, batteries and supercapacitors; Promising: flow batteries, SMES and fuel cells	[56,157,173,217,226]
Integration renewable for back-up	∼100 kW–40 MW, response time (seconds to minutes), discharge duration (up to days)	Experienced: batteries and flow batteries; Promising: PHS, CAES, solar fuels, and fuel cells	[13,26,40,76,108]
Emergency back-up power	Up to ∼1 MW, response time (milliseconds to minutes), discharge duration (up to ∼24 h)	Experienced: batteries, flywheels, flow batteries; Promising: small-scale CAES and fuel cells	[13,227,228,229]
Telecommunications back-up	Up to a few of kW, response time (milliseconds), discharge duration (minutes to hours)	Experienced: batteries; Promising: fuel cells, supercapacitors and flywheels	[114,228,230,231]
Ramping and load following	MW level (up to hundreds of MW), response time (up to ∼1 second), duration (minutes to a few hours)	Experienced: batteries, flow batteries and SMES; Promising: fuel cells	[13,88,232,233]
Time shifting	∼1–100 MW and even more, response time (minutes), discharge duration (∼3–12 h)	Experienced: PHS, CAES and batteries; Promising: flow batteries, solar fuels, fuel cells and TES	[26,234,235,236]
Peak shaving	∼100 kW–100 MW and even more, response time (minutes), discharge duration (hour level, ∼ < 10 h)	Experienced: PHS, CAES and batteries; Promising: flow batteries, solar fuels, fuel cells and TES	[114,237,238]
Load levelling	MW level (up to several hundreds of MW), response time (minutes), discharge duration (∼12 h and even more)	Experienced: PHS, CAES and batteries; Promising: flow batteries, fuel cells and TES	[38,159,218,239]
Seasonal energy storage	Energy management, 30–500 MW, quite long term storagedischarge duration (up to weeks), response time (minutes)	Promising: PHS, TES and fuel cells; Possible: large-scale CAES and solar fuels	[26,240,241,242]
Low voltage ride-through	Normally lower than 10 MW, response time (∼milliseconds), discharge duration (up to minutes)	Experienced: Flywheels, batteries; Promising: flow batteries, SMES and supercapacitors	[13,129,244]
Transmission and distribution stab.	Up to 100 MW, response time (∼milliseconds, <1/4 cycle), discharge duration (milliseconds to seconds)	Experienced: batteries and SMES; Promising: flow batteries, flywheels and supercapacitors	[26,114,224,245,246]
Black-start	Up to ∼40 MW, response time (∼minutes), discharge duration (seconds to hours)	Experienced: small-scale CAES, batteries, flow batteries; Promising: fuel cells and TES	[15,39,87]
Voltage regulation and control	Up to a few of MW, response time (milliseconds), discharge duration (up to minutes)	Experienced: batteries and flow batteries; Promising: SMES, flywheels and supercapacitors	[247,248,249]
Grid/network fluctuation suppression	Up to MW level, response time (milliseconds), duration (up to ∼minutes)	Experienced: batteries, flywheels, flow batteries, SMES, capacitors and supercapacitors,	[114,137,225,250]
Spinning reserve	Up to MW level, response time (up to a few seconds), discharge duration (30 minutes to a few hours)	Experienced: batteries; Promising: small-scale CAES, flywheels, flow batteries, SMES and fuel cells	[251,252,254,255]
Transportation applications	Up to ∼50 kW, response time (milliseconds–seconds), discharge duration (seconds to hours)	Experienced: batteries, fuel cells and supercapacitors; Promising: flywheels, liquid air storage and solar fuels	[256,257,258,259]
End-user electricity service reliability	∼ up to 1 MW, response time (milliseconds, <1/4 cycle), storage time at rated capacity (0.08–5 hours)	Experienced: batteries; Promising: flow batteries, flywheels, SMES and supercapacitors	[6,13,114,170]
Motor starting	Up to ∼1 MW, response time (milliseconds–seconds), discharge duration (seconds to minutes)	Experienced: batteries and supercapacitors; Promising: flywheels, SMES, flow batteries and fuel cells	[51,114,198]
Uninterruptible power supply	Up to ∼5 MW, response time (normally up to seconds), discharge duration (∼10 min to 2 h)	Experienced: Flywheels, supercapacitors, batteries; Promising: SMES, small CAES, fuel cells, flow batteries	[57,262,263,264]
Transmission upgrade deferral	∼10–100 + MW, response time (∼minutes), storage time at rated capacity (1–6 h)	Experienced: PHS and batteries; Promising: CAES, flow batteries, TES and fuel cells	[4,101,220]
Standing reserve	Around 1–100 MW, response time (<10 min), storage time at rated capacity (∼1–5 h)	Experienced: batteries; Promising: CAES, flow batteries, PHS and fuel cells	[6,265,266]

- Peak shaving and load levelling: Peak shaving means using energy stored at off-peak periods to compensate electrical power generation during periods of maximum power demand. This function of EES can provide economic benefits by mitigating the need to use expensive peak electricity generation.
- Load levelling is a method of balancing the large fluctuations associated with electricity demand. Conventional batteries and flow batteries in peak shaving applications, as well as in load following and time shifting, need a reduction in overall cost and an increase in the cycling times to enhance their competitiveness. Economic and technical studies and related demonstrations of these two applications are shown in [159,218,237–239,243]. For instance, an optimization model of the weekly economic operation of isolated systems was developed and then applied to two Spanish isolated power systems in the Canary Islands [237].
- Seasonal energy storage: Storing energy in the time frame of months, for community seasonal space heating and the energy networks with large seasonal variation in power generation and consumption. EES technologies which have a very large energy capacity and almost zero self-discharge are required. At present, there are no commercialized EES technologies for

this application and storing fossil fuels is still a practical solution. PHS, hydrogen-based fuel cells, CAES, TES and solar fuels have potential to serve this application. Some relevant research and development is introduced in [26,240–242].

- Low voltage ride-through: It is crucial to some electrical devices, especially to renewable generation systems. It is a capability associated with voltage control operating through the periods of external grid voltage dips. High power ability and instant response are essential for this application. In order to smooth the fast wind-induced power variations and to reinforce the low voltage ride-through capability, the integration of a supercapacitor EES device in a doubly fed induction generator design was studied in [129]. A VRB-based EES system was simulated, to improve low voltage ride through capability and to stabilize output power of direct-drive permanent magnet wind power system [244].
- Transmission and distribution stabilization: EES systems can be used to support the synchronous operation of components on a power transmission line or a distribution unit to regulate power quality, to reduce congestion and/or to ensure the system operating under normal working conditions. Instant response and relatively large power capacity with grid demand are essential for such applications. Studies in this area can be found in [26,114,245,246].
- Black-start: EES can provide capability to a system for its start-up from a shutdown condition without taking power from the grid. A typical example is the Huntorf CAES plant that provides black-start power to nuclear units located near to the North Sea [39,42].
- Voltage regulation and control: Electric power systems react dynamically to changes in active and reactive power, thus influencing the magnitude and profile of the voltage in networks [193]. With the functions of EES facilities, the control of voltage dynamic behaviors can be improved. Several EES technologies can be used or potentially used for voltage control solutions (Table 13). A preliminary analysis of a pilot project for the exploitation of EES devices for distribution network voltage regulation was given in [247]. The modeling and measurement of a high-speed composite flywheel system to regulate a specific DC voltage on a metro network has been studied in [248].
- Grid/network fluctuation suppression: Some power electronic, information and communication systems in the grid/network are highly sensitive to power related fluctuation. EES facilities can provide the function to protect these systems, which requires the capabilities of high ramp power rates and high cycling times with fast response time. Some recent research and development is given in [114,137,225,250].
- Spinning reserve: In the case of a fast increase in generation (or a decrease in load) to result in a contingency, EES systems can feature the function of spinning reserve. The EES units must respond immediately and have the ability of maintaining the outputs for up to a few hours. This function is described and studied in [13,251–255].
- Transportation applications: Providing power to transportation, such as HEVs and EVs. High energy density, small dimension, light weight and fast response are necessary for implemented EES units. The research and development of EES applications on transportation can be found in [256–260]. For instance, a hybrid powertrain using fuel cell, battery, and supercapacitor technologies for the tramway was simulated based on commercially available devices, and a predicative control strategy was implemented for performance requirements [256].
- Uninterruptible Power Supply (UPS): EES systems can feature the function of UPS to maintain electrical load power in the event of the power interruption or to provide protection from a power surge. A typical UPS device offers instantaneous (or near to instantaneous) reaction, by supplying energy mostly stored in batteries, flywheels or supercapacitors. Some research papers regarding to UPS by using different EES technologies can be found in [9,57,261–264].
- Standing reserve: In order to balance the supply and demand of electricity on a certain timescale, EES facilities/plants can provide service as temporary extra generating units to the middle-to-large scale grid. Standing reserve can be used to deal with actual demand being greater than forecast demand and/or plant breakdowns. The descriptions related to this application were introduced in [6,114,265,266].

6. Concluding remarks

This paper provides an overview of the current development of various types of EES technologies, from the recent achievements in both the academic research community and industrial sectors. A comprehensive analysis is carried out based on the relevant technical and economic data, which leads to a number of tables and figures showing a detailed comparison of various EES technologies from different perspectives. Further discussion on EES power system application potentials is given based on the current characteristics of EES and the relevant application specifications. The overview has shown a synthesis of the state-of-the-art in important EES technologies, which can be used for supporting further research and development in this area and for assessing EES technologies for deployment.

The review identified that PHS plants have been deployed worldwide, mainly due to its technological maturity. Since PHS has relatively low power/energy densities it is mainly used in stationary large-scale EES. The Li-ion battery has relatively high power/energy densities and specific power/energy, which has resulted in the current broad range of development, particularly in small-scale EES applications. The cycle efficiencies of EES technologies have been continuously improved with time through development efforts leading to technology breakthroughs, and most commercialized techniques normally have medium-to-high cycle efficiencies. The energy capacity and the self-discharge of EES systems are the major factors in deciding the associated suitable storage duration. From the overview, it is clear that there is no suitable commercialized technology for seasonal energy storage at present. Several EES technologies, such as PHS, fuel cells and TES, have the potential to be applied in this area. On the whole, the various applications with different network sizes will have different decision-making factors to consider when choosing suitable EES options for deployment. For the national regulator, the level of technological maturity, reliability and potential environmental impacts (such as the toxic chemical materials used in batteries described in Section 3) may be considered as the main decision-making factors and the cost-effectiveness may not be particularly important; for the end-user customers or local (private) networks, in addition to the above factors, the investment cost and the economic gain will also be dominant factors.

From this overview, it can be seen that the current technologies have wide ranging technological characteristics. With a suitable combination of different technologies, EES can meet most technical requirements for different power system and network operations. However, apart from PHS, most EES technologies are not cost-effective or mature enough for widespread implementation within the current large network operation regulation and energy market frame. On the other hand, the benefits brought to power system operation by utilizing EES technologies need further exploration. The capital and the maintenance cost of an EES system varies with the timescale of construction, the location of the facility, the size of the system, the material chosen for storing energy (such as PCMs in TES) and many other factors. Although a number of demonstration projects or EES trial stations were completed, the corresponding detailed techno-economic analysis, which can enhance the relevant database to practical EES experience, is still not sufficient. The widespread deployment of EES will depend on advances in relevant technologies, but it also relies on progress in further quantification and analysis of the benefits brought by EES.

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