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Physical energy storage employed worldwide

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Abstract

The increasing level in renewable energy capacity presents new challenges. In essence, renewables are weather-dependent and inputs such as solar radiation or wind are not constantly available. The integration of energy storage technologies are important to improve the potential for flexible energy demand and ensure that excess renewable energy can be stored for use at a later time. This paper will explore various types of physical energy storage technologies that are currently employed worldwide. Such examples include direct electrical storage in batteries, thermal storages in hot water tanks or building fabrics via electricity conversion as well as compressed air energy storage. Through this study it has been shown that no single storage system can meet all the criteria to become the *ideal* energy storage system, each system has its own suitable application range.

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Keywords: Economics, Energy storage; Mechanical storage, Rechargeable battery, Renewable energy, Scenarios, Thermal storage

1. Introduction

Energy storage is increasingly an important part of future energy systems making a substantial contribution to energy supply and to future energy security. Energy storage comes in a wide range such as chemical (gas, liquid, solid), potential energy (pumped storage), thermal, kinetic, electrochemical being implemented in various locations at different scales. However, while many Governments have enacted programmes to support the growth of renewable energy, fewer have recognised the importance of storage. Globally, the United States is the leading energy storage with a total of 1500 MW non-pumped hydro energy storage capacity, followed by Japan with 420 MW total. Europe as a whole consists of only 550 MW [1]. Pumped hydro storage (PHS) remains the only dominant technology accumulating for 99% of the worldwide installed storage capacity[2].

We looked at the worldwide leading countries in this area, such as USA, Japan and Germany. The electricity sector in the USA is made up of a number of regional networks, each of whom has individual drivers for energy storage. One of the aims of the recent American Recovery and Reinvestment Act (ARRA) [3] was to improve the flexibility of US electricity grids making them more reliable and robust

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as well as more economically competitive. The ARRA [2] has provided approximately €185m to support demonstration projects worth a total of $772m in the areas of battery storage for balancing wind generation and frequency regulation, compressed air storage and other storage technologies. The US Department of Energy has provided further support for research, mostly targeted on storage components and technologies, such as batteries, and thermal storage under the umbrella of Advanced Research Projects – Energy scheme.

In Japan continuous investment into battery development has led to battery storage technologies achieving a commercially stable level. Battery development has been driven by performance and cost targets set by the Ministry of Economy, Trade and Industry (METI) supported by five focused research and development programmes. The METI have targeted a 5 fold increase in energy density with 2.5 times current power density and a 95% cost reduction [4]. The research programs designed to achieve these targets are focused both on developing existing battery technologies, next-generation technologies as well as the integration of battery technologies with generation and the grid, and their use in residential contexts and electric vehicles. The growth in Japan's battery industry has been indirectly helped by the grid connection demonstration projects set up by the New Energy and Industrial Technology Development Organization (NEDO). Some demonstrative projects are not related to energy storage development but have directly led to battery storage being operated. A combined effort between electric utility, TEPCO and NaS battery manufacturer, NGK pioneered the development of NaS battery storage.

Innovation, policy and regulation are now focusing on developing the potential of energy storage in various countries. Therefore, this paper explores energy storage alternatives.

3. Energy storage technologies

We split the storage technologies in the following groups: *mechanical energy storage* (MES) (pumped hydro storage (PHS), compressed air energy storage (CAES), flywheel energy storage (FES)); *electrical energy storage* (EES) (supercapacitor, superconducting magnetic energy storage (SMES)); *thermal energy storage* (TES) (low and high temperature TES); *electrochemical energy storage* (EES) (lead acid battery (PbA), sodium-based high temperature battery, lithium-ion battery (Li-ion), redox flow cell, hydrogen-based energy storage). Next table provides a summary of energy storage technologies, their efficiency, expected lifetime, cost. Details about each category are provided in the sections bellow.

Table 1 Energy storage technologies

Category	Technology Type		Roundtrip Efficiency (%)	Expected Lifetime (Years)	Replacement Period	Replacement Needed	Future Replacement Cost ($/kWh)	Power Cost($/kW)	Energy Cost($/kWh)	BOP Cost ($/kWh)	O&M Fixed Cost ($/kW-y)	Storage Cost ($)	Power Conversion Cost ($)	BOP Cost ($)	Total Cost ($)	Capital Recovery Factor	Replacement Cost ($/kWh)	Annualized Capital Cost ($)	Annualized Replacement Cost ($)	O&M Cost ($)	Total Annualized Cost ($)
Mechanical	Pumped Hydro	Min	65%	30	-	-	0	500	5	Included	3.8	115385	1500000	0	1615385	0.07265	-	117355.9339	0	11400	128755.9
		Max	85%	60	-	-	0	4300	430	Included	3.8	7588235	12900000	0	20488235	0.06188	-	1267724.341	0	11400	1279124
	CAES	Min	70%	20	-	-	0	400	2	40	1.42	42857	1200000	600000	1842857	0.08718	-	160668.6836	0	4260	164929
		Max	80%	40	-	-	0	3140	430	50	3.77	8062500	9420000	750000	18232500	0.06646	-	1211759.954	0	11310	1223070
	Flywheel	Min	80%	15	-	-	0	250	380	80	7.5	7125000	750000	1200000	9075000	0.10296	-	934387.0829	0	22500	956887
		Max	85%	20	-	-	16000	2200	8800	1000	7.5	155294118	6600000	15000000	176894118	0.08718	-	15422435.28	0	22500	15444935
Electrical	Supercapacitor	Min	65%	8	-	-	0	100	300	10000	5.55	6923077	300000	1.5E+08	157223077	0.16104	-	25318566.4	0	16650	25335216
		Max	98%	20	-	-	0	2355	20000	10000	5.55	306122449	7065000	1.5E+08	463187449	0.08718	-	40382792.54	0	16650	40399443
	SMES	Min	80%	5	-	-	0	200	1000	1500	8	18750000	600000	22500000	41850000	0.23740	-	9935039.358	0	24000	9959039
		Max	85%	15	-	-	0	500	10000	1500	26	176470588	1500000	22500000	200470588	0.10296	-	20641005.86	0	78000	20719006
Chemical	Lead-Acid Battery	Min	70%	5	5	1	150	175	150	50	1.55	3214286	525000	750000	4489286	0.23740	26.61	1065740.269	570202.7157	4650	1640593
		Max	90%	16	6	2	200	4600	3800	50	1.55	63333333	13800000	750000	77883333	0.09895	23.79	7706722.783	396445.1348	4650	8107818
	Li-ion Battery	Min	78%	5	10	NO	500	175	500	120	12	9615385	525000	1800000	11940385	0.23740	-	2834604.327	0	36000	2870604
		Max	99%	16	10	1	500	7850	6200	600	30	93939394	23550000	9000000	126489394	0.09895	27.63	12516396.67	418593.6375	90000	13024990
	NaS Battery	Min	70%	5	10	NO	230	150	250	120	23	5357143	450000	1800000	7607143	0.23740	-	1805908.332	0	69000	1874908
		Max	90%	20	15	1	230	4000	555	500	61	9250000	12000000	7500000	28750000	0.08718	8.37	2506556.013	139453.0996	183000	2829009
	ZEBRA	Min	85%	5	10	NO	230	150	100	120	23	1764706	450000	1800000	4014706	0.23740	-	953076.7253	0	69000	1022077
		Max	90%	15	15	1	230	1960	250	500	61	4166667	5880000	7500000	17546667	0.10296	9.88	1806653.298	164690.5952	183000	2154344
	ZnBr Battery	Min	60%	5	8	NO	100	175	150	120	15	3750000	525000	1800000	6075000	0.23740	-	1442183.133	0	45000	1487183
		Max	90%	10	8	1	100	6300	1350	600	47	22500000	18900000	9000000	50400000	0.13587	8.52	6847745.094	142075.3964	141000	7130820
	VRB Battery	Min	60%	5	10	NO	600	175	150	30	24	3750000	525000	450000	4725000	0.23740	-	1121697.992	0	72000	1193698
		Max	90%	20	10	2	600	3700	2350	600	65	39166667	11100000	9000000	59266667	0.08718	104.6	5167138.077	1743691.14	195000	7105829
	Hydrogen Storage	Min	20%	5	0	-	100	1100	2	37	10	150000	3300000	111000	3561000	0.23740	-	845368.5819	0	30000	875369
		Max	50%	20	0	-	100	10000	20	42	10	600000	30000000	126000	30726000	0.08718	-	2678832.698	0	30000	2708833
Heat	Thermal Storage	Min	40%	5	0	-	-	200	3	450	0.1	112500	600000	1350000	2062500	0.23740	-	489630.0759	0	300	489930
		Max	50%	40	0	-	-	3140	310	525	0.4	9300000	9420000	1575000	20295000	0.06646	-	1348836.872	0	1200	1350037

3.1 Mechanical energy storage (MES)

MES options basically store energy via potential or kinetic energy. Potential energy storage includes *pumped hydro storage* (PHS) and *compressed air energy storage* (CAES).

- PHS is based on pumping water from a lower reservoir to another at a higher elevation at low-demand period. When demand hits the peak, the collected water is discharged to the bottom reservoir through a turbine to re-produce electricity. The storage capacity is determined by the height in water discharge and volume [5]. Typically, PHS can provide reliable power within a short time period such as within 1 minute when necessary [6]. Taking into account evaporation and conversion losses, the efficiency of PHS is in the range of 70-85%. There is approximately 127GW of pumped storage in operation worldwide as the technology is continuously being installed around the world [2]. The high capital cost involved in construction has been a limiting constraint to pumped hydro storages.

- CAES is based on the energy stored in the form of elastic potential of the compressed air. During low demand period, energy is stored via air compression in airtight space such as underground storage caverns at pressures ranging between 4 to 8 MPa [7]. During high demand period, energy is extracted by drawing the compressed air from the storage vessels. This compressed air is heated and expanded through a high-pressure turbine. CAES systems are capable of operating efficiently under partial load conditions as CAES units are usually designed to cycle on a daily basis. The main advantage is that CAES unit can interchange quickly between generation and compression modes [7]. Hence, utility systems that have significant load variation in a daily cycle would benefit greatly from CAES. Another plus to CAES systems is the relatively long storage period, which can exceed a year due to minimal system losses [7].
- FES is essentially an electromechanical system that stores energy in the form of kinetic energy within the rotating cylinders supported by magnetic bearings. The rotating mass converts mechanical energy into electrical energy via an electrical machine and vice versa. FESSs are suitable in applications in which numerous charge and discharge cycles (hundreds of thousands) are required at medium to high power (between kW to MW) during short period (seconds to minutes), with energy efficiency above 85%. Since long number of cycles achievable is independent of the depth of discharge (DOD) and temperature, the FESSs have relatively long useful lifetime (>20 years) [8].

3.2 Electrical energy storage (EES)

EES is categorized into electrostatic energy storage such as *conventional capacitors or supercapacitors* and *magnetic/current storage* including superconducting magnetic energy storage (SMES).

- Classic capacitors operate by storing energy in an electric field between two parallel metal plates with separated by an air-gap or dielectric. Capacitors can be charged substantially quicker and cycled thousands times more than batteries [7]. Due to limitations in capacity and energy density they have been superseded by the more recent supercapacitors. Supercapacitors have porous carbon electrodes with high surface area and much lower separation distance between electrodes due to the membrane separators and have better energy density than any other storage devices [9]. These devices are able to respond to changes in power demand in hundreds of milliseconds and thus making them suitable in short-term energy storage application. However, they can only store for short duration and troubled by energy dissipation due to self-discharge is [7]. Despite their clear advantages, electrochemical capacitors are still in early development stages and there is little cost data available.
- The superconducting coils can be classified as High Temperature Coils (HTS) or Low Temperature Coils (LTS), based on the system's operating temperature. Typically, HTS operates at temperatures around 70K and LTS works around the 5K regions [8]. Hence, cooling systems are integral as most SMES systems have two cryocoolers, one that cools down the superconductor coil via immersing it in liquid helium or nitrogen bath, and another coolant to cool the vessel holding the helium/nitrogen bath [10]. Compared to other energy storage systems, SMES exhibits relatively high storage efficiency (above 97%) and rapid response, in which it has the ability to inject or absorb energy in a very short time [8]. SMES typically has long cycle life thus making them suitable for application that requires constant, full-cycle operation mode. SMES with energy capacity between 1-10MW have a storage time of seconds while larger SMES in the range of 10-100 MW can store up to minutes [11]. The major obstacle confronting widespread SMES implementation is the cost. The capital power cost can vary from 1,000 $/kW up to 10,000$/kW [8].

3.3 Thermal Energy Storage (TES)

TES mainly uses materials that can be kept at either low or high temperatures in insulated containment to store energy in the form of heat.

- *Low-temperature TES* can be split into two types: *Aquifers low-temperature* TES (AL-TES) and *cryogenic energy storage* (CES). In AL-TES, water is cooled by coolant or refrigerator during off-peak hours and stored in thermal storage tank. The water or ice stored can later be used to meet peak period cooling demand. The energy stored depends on the temperature gap between the chilled water or ice in the storage tank and the warm water returned by the heat exchanger. AL-TES is commonly found in commercial buildings, leading to smaller chillers being used and substantially reducing the air-conditioning system operating costs [7]. Ice thermal storage is widely implemented across the United States, with the Ice Bear Energy a popular option in commercial and industrial load peak shaving [12]. While AL-TES such as the ice storage system can reduce a building's electricity use during peak daytime hours by great margins, it does not have the capability to generate electricity and hence their application remains fairly restricted to commercial building. CES is a relatively new technology that makes use of either off-peak power or renewable energy sources to generate cryogenic fluid (e.g. liquid nitrogen or liquid air) that is then used in cryogenic heat engine to produce electricity. This is when the energy is stored. During peak times, the cryogenic liquid is heated by surrounding heat in the atmosphere and passed through a heat engine. This is when energy is released and generated as electricity. The main advantage CES has over AL-TES is that they can generate electricity as well as provide direct cooling and refrigeration [7]. CES have relatively high energy density in the range of 100-200 Wh/kg and low capital cost per unit energy of about 200$/kW, but relatively low efficiency (40-50%) according to the current energy consumption for air liquefaction. CES remains at the early demonstration stage and one notable installation is the 300kW liquid air storage system installed in Slough, Scotland [13].
- There are mainly two types of *high temperature TES systems*: the *sensible heat storage* systems and *latent heat storage* systems. Sensible heat refers to the energy absorbed or released when a certain material's temperature rises or drops. The common material types are concrete storage (solid) and molten salt storage (liquid) [14]. For solid type storage, concrete and castable ceramics are the most researched material mainly due to their decent thermal conductivity and low prices since rocks and sand are readily available and easy to process. Concrete materials have recently been mooted as a potential energy storage medium in parabolic trough power plants [15]. For liquid type thermal storage, molten salts commonly used as they prove to be an efficient, low cost medium that stores thermal energy [14]. Their operating temperature are compatible with steam turbines running on high-pressure and high-temperature, hence making electricity generation a more direct task.

3.4 Electrochemical Energy Storage (EES)

- *Lead acid batteries* (PbA) are the most matured and least costly rechargeable battery on a cost per kWh basis [16]. The basic composition of a PbA battery is a metallic lead oxide anode, a lead oxide cathode and aqueous sulfuric acid electrolyte. PbA batteries have relatively low specific energy, typically around 35 Wh/kg as well relatively poor cycle life [7]. The cycle life is dependent on the depth of discharge (DOD) and operating temperature, which could lead a stark drop in the battery's performance, making them less suitable in some situations. Despite wide recognition that PbA is already at a matured level as a storage technology, research are ongoing to address issues such as poor energy density and short cycle life. One way to increase the cycle life is by adding carbon to either electrode, which has been proven to provide significantly cycling advantage over conventional PbA [17]. Another potential solution is to the lead acid flow battery, in which soluble lead is dissolved in an aqueous methane-sulfuric acid electrolyte, eliminating the need for an electrolyte separator [18].
- There are two major *high temperature sodium-based batteries*, namely the *sodium sulphur batteries* (NaS) and *sodium nickel chloride* ($NaNiCl_2$) otherwise known as ZEBRA batteries. NaS battery is made up of an anode made of liquid (molten) sodium (Na) and a cathode made by liquid

(molten) sulphur (S). Typically, NaS batteries are characterized by their need and capability to operation in high temperature condition between 300 to 350°C [8]. As opposed to NaS batteries, ZEBRA batteries use solid metal chloride as cathode. Other compositions such as the anode and solid electrolyte material are the same with NaS batteries. Compared to NaS batteries, ZEBRA batteries bring several advantages including a higher cell voltage at about 2.58V [7] and increased operational temperature range due to the lower electrolyte melting point. Safety wise, ZEBRA cells have less corrosive cathodes and the handling of metallic sodium that is potentially explosive can be avoided [19]. The disadvantage is that ZEBRA cells have relatively low energy and power density. To reduce cost, improvements in materials and battery design are necessary. Research into a stacked planar cell design to replace the tubular deign could contribute to cost reduction as the specific energy and power can be improved greatly [20]. Optimization of the current electrolytes, development of alternative sodium conductors or improvement in stack materials are possible research areas as well enable the battery to possibly operate at room temperature [21].

- The electrochemical reaction of a *Li-ion battery* is based on charge transfer that occurs through ion intercalation rather than chemical reactions on the electrodes like in some other battery types. Performance wise, Li-ion batteries have always been popular for their high specific energy, which is between 75 -125 Wh/kg [8]. Li-ion have displayed quick charging and discharging capability (reaching 90% capacity in 0.2s) in a test carried in Japan [22], thus making them suitable for applications that demand quick responses and where weight or space is an issue. Li-ion batteries can be easily overcharged causing temperature rise as they consistently generates more heat that it can dissipate, which can cause risk of leakage and in the worst scenario explosion. Particular areas of interest for research and development are cost reduction as well as battery longevity and safety improvements. Technical enhancements include improved cathode and anode, new electrolyte materials and manufacturing process [16]. For example, cathode materials based on transition metal have shown better operating voltage and overall capacity but still require work on reducing the production cost and extending the effective lifetime [23]. However, each improvement comes with an opportunity cost. Lithium titanate anode have shown promises in improving the safety, longevity and efficiency but on the flip side has a significantly lower cell voltage as well as a reduced capacity of as much as 50% compared to conventional graphite anode Li-ion batteries [18].
- In contrary to most other batteries, *redox batteries* contain two distinct aqueous electrolyte contained in separate tanks. The liquid electrolyte is pumped through a “stack” or an electrode array [18]. Energy is primarily stored in the active materials dissolved into the electrolytes that are stored externally. The main advantages in these batteries are that the power and energy components are easily scalable and can be determined independently since electrolytes are stored externally. The storage capacity is determined by the quantity of electrolyte used while the active area of the cell stack decides the power rating [7]. The two major types of flow battery that are in early commercialization/demonstration stage are vanadium redox (VRB) and zinc-bromine batteries (ZnBr). The electrolytes in VRB cells can be used indefinitely, contributing to very long lifetime capable of achieving over 10000 cycles or above 10 years [2]. The main drawback with VRB is their relatively low specific energy and energy density compared to other battery technologies reducing their suitability in some non-stationary applications. The main advantage over VRB is the higher specific energy. While large amount of energy can be stored within flow batteries for long period with virtually no self-discharge, the major issue is their relatively low energy density which has become a major research area. On-going research was conducted to increase the volumetric energy density by 70% as well as enhancing the temperature range into -5 to 50°C. Another key are for improvement is the design and manufacturing of new separator/membrane materials, with better ionic conductivity and slower degradation the main aims.
- *Hydrogen-based Energy Storage* **-** This power-to-gas technology converts electricity

into hydrogen via electrolyzers. Electrolyzer technologies can be divided into alkaline (AFC), proton exchange membrane (PEM) and solid oxide electrolysis cells (SOEC) based on the electrolyte used [24]. Excess hydrogen can be stored in metal hydride or as gas in pressure tanks (CHG) depending on the application [24]. There are cases in which hydrogen have been stored at the electrolyzers to avoid using hydrogen compressor [25]. Pressure tank stores for about 30 hours while mental hydrides can keep hydrogen up to 3-hours storage period [26]. Alternatively, hydrogen can be stored in less common methods such as with liquid organic hydrogen carriers (LOHC) like ethylcarbazole $C_{14}H_{13}N$ [24]. To reproduce electricity, Regenerative Fuel Cells (RFC) is required and they are divided into Polymer Electrolyte Membrane Fuel Cell (PEMFC), Alkaline Fuel Cell (AFC), Molten Carbonate Fuel Cell (MCFC), Phosphoric Acid Fuel Cell (PAFC), Direct Methanol Fuel Cell (DMFC) and Solid Oxide Fuel Cell (SOFC). AFC, PAFC and PEMFC are the more common options. PEMFC is the most dominant technology, mainly due to its low operation temperature, longer lifetime as well as cheaper manufacturing cost [27]. They are easily maintainable and the only by-product is hydrogen [28].

4. Scenarios and economic analysis of energy storage technologies

There are many papers covering the benefits and applications of energy storage technologies. Potential energy storage application at the generation, transmission and distribution levels while providing cost estimates for each technology in each of the applications is discussed in [29], [30], [31], [32]. The EPRI reports took a broader approach in their cost-benefit assessment by comparing technologies for a range of applications. Comparisons between each storage technology that included characteristics such as technology maturity, applicable markets and technical performances are provided in [33], [34], [35]. While many papers have the estimated capital cost for energy storage technologies, the levelized ownership cost over a technology's lifetime is a much more indicative index for a more well-rounded analysis. In this paper, the cost analysis is extended to total annualized storage cost and aims to use a holistic approach in evaluating the potential of energy storage technologies.

Key areas we considered in the assessment include:

- o Compiling cost estimates for each technology which has been reviewed from multiple sources.
- o Integrating performance parameters such as round-trip efficiency and life expectancy into cost estimation for specific applications.
- o Perform multiple criteria analysis to rank storage technologies
- o Perform sensitivity analysis to illustrate key characteristics that determine technology's cost efficiency

The methodology is based on the methods developed by [29] and [36]. The total storage cost includes TSS_s is the annualized cost of the storage system and is calculated with the equations below

$$TSS_C = Cost_{CC}(\$) + Cost_{O\&M}(\$) + Cost_{ARC}(\$)$$

where $Cost_{cc}$ is the total capital cost that includes the storage cost ($Cost_{storage}$), power conversion system cost ($Cost_{PCS}$) and the balance of plant cost ($Cost_{BOP}$).

The annualized O&M cost is simply calculated by multiplying $Cost_{O\&M}$ with the power capacity (P).

$$Cost_{O\&M}(\$) = C_{O\&M} \times P$$

A model was developed in Excel/VBA to put together the three mentioned modules and rank the energy storage technologies with all the criteria considered. Several assumptions were made within the model calculations. A 6% discount rate was used for the baseline estimate based on the discount rates for low-carbon and renewable generation technologies as considered in [37]. For this work, it was assumed that every storage technology can be sized to fit any application. This is not possible in reality since storage capacity and duration are limited by the storage device's physical nature. Another assumption made in the cost estimation is that batteries are replaced as soon as they hit the replacement period. The possibility of some batteries being recycled has not been considered in this model.

As mentioned earlier, the relationship between energy storage and its application is interdependent. The importance of each criterion is diverse in every storage application. For this reason, multiple scenarios are required to evaluate the storage technologies adequacy in every application area considered. To access the potential of energy storage, the areas in which energy storage can provide functionality to meet energy system challenges have been identified in [38]. Next table describes three scenarios that were explored in this work with respect to the findings in ERP.

Table 2 Scenarios explored in the model

Energy Storage Demand	Description
Renewable Back Up	With more than 30GW installed wind capacity expected by 2030, a lull in wind could see a shortfall of electricity generated in the order of TWh. Energy storage is required to help system cope with low wind generation. Thermal storage (hot water) is seen as a potential short-term solution by ERP.
Load Shifting	There is a need for energy storage to meet the early evening winter electricity peak (4pm-8pm) demands about 7GWh and obviate the need for high-carbon peaking plant. CAES and lithium battery storages are touted as potential solutions.
Power Quality	This is required to balance the electricity grid to ensure reliability and quality of supply. The generation variability can increase or decrease by 50% in merely three hours due to intermittent wind output. For such quick response needs, NaS and Li-ion batteries are seen as viable options.

For each scenario, assumptions were made about the power and energy requirements as well as the relative important of each criterion. Next table shows the values used each scenario.

Table 3Assumptions used in the model

Scenario	Renewable Back Up	Load Shifting	Power Quality
Power Requirement	1 MW	3 MW	10 MW
Duration Needs	Days	Hours	Minutes
Energy Requirement	100 MWh	15 MWh	0.1 MWh
Criteria Ranking (Descending Order)	1. Storage Capacity 2. Storage Duration 3. Cost Performance 4. Specific Energy 5. Energy Density 6. Technology Maturity 7. CO_2 Emission 8. Cycle Life 9. Social Acceptability 10. Specific Power	1. Cost Performance 2. Technology Maturity 3. CO_2 Emission 4. Social Acceptability 5. Cycle Life 6. Storage Duration 7. Storage Capacity 8. Specific Energy 9. Specific Density 10. Specific Power	1. Cost Performance 2. Specific Power 3. Cycle Life 4. CO_2 Emission 5. Social Acceptability 6. Technology Maturity 7. Storage Duration 8. Storage Capacity 9. Energy Density 10. Specific Energy

To evaluate the potential of the energy storage technologies, we took a holistic approach that included not only the cost performances. The energy storage solutions were analysed against a pre-determined set of criteria and the relative importance each criterion such as technology maturity, energy and power characteristics, system cycle life and various others. In this analysis three separate situations were considered: renewable integration, load shifting and power quality management.

Figure 2 shows the total annualized storage cost ($) for each energy storage solution in each scenario. For renewable integration and load shifting applications, supercapacitor storage systems are the most costly to build and maintain. For load matching, CAES' long lifetime expectancy and decent round trip efficiency help drive down the cost making it the least costly option Superconducting magnetic storage is the cheapest solution to power quality management, mainly due to its relative low power cost while hydrogen storage is the most expensive due to extremely high power cost.

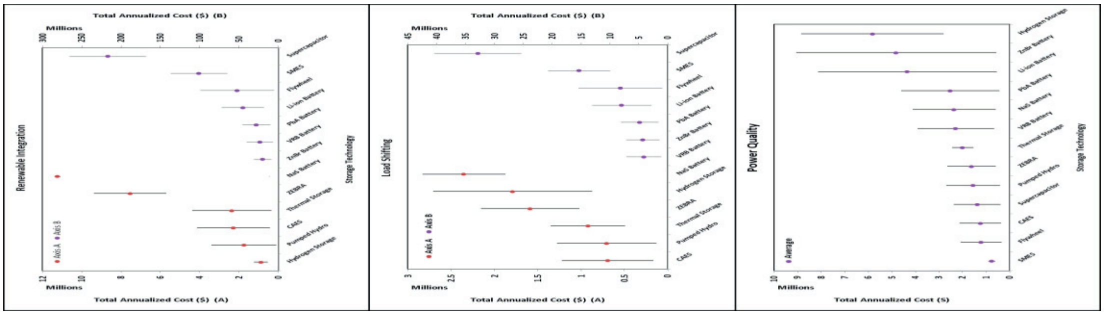

Figure 1 Estimated total annualized cost for each storage technology in three separate scenarios

The relative importance of each criterion is dependent on the scenario. Figure 2 shows the relative suitability under three separate applications areas: renewable integration, load shifting and power quality.

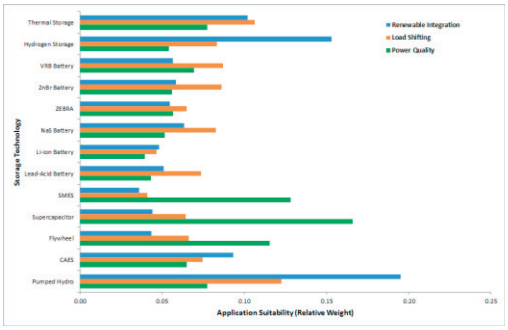

Figure 2 Energy storage systems' relative suitability under three separate applications areas: renewable integration, load shifting and power quality

Pumped hydro provides the best storage solution in renewable integration and load shifting applications since they possess the largest capacity and longest expected lifetime. However, pumped hydro storage is severely restricted by geographical constraints and environmental concerns. The second best option for renewable integration is hydrogen storages but the technology remains in early demonstration stage and lack proven track record as distribution level energy storage.

Thermal storage is a strong option to be considered in both renewable integration and load shifting. However, in reality, it is not cost efficient to have huge thermal storage capacity. For load shifting, low-temperature thermal storage in particular may turn out to be the most realistic option yet. For instance, the Ice Bear Energy Storage has been fairly successfully in the United States and this success could be replicated in other countries.

The supercapacitor storage systems had the best score in power quality management due to their excellent specific power and response time ensuring uninterrupted power supply. SMES and flywheel systems are the next best options in power quality management but SMES is still in development stage while flywheel implementation is restricted by high material costs.

Battery technologies including VRB, ZnBr, PbA and Li-ion are well-rounded and would make decent options in load shifting in particular. For example, protection circuits are required in Li-ion battery systems which could make them less attractive options in some cases. Despite the results suggested by the analysis, the choice of battery technology used is most often decided by factors such as energy/power cost, specific energy/power and achievable lifecycles. Results from this analysis are only indicative as to areas where certain energy storage is more suited to. Limitations such as data inaccuracy and ranking irregularities in the AHP can have a knock-on effect on the analysis results. In a real world situation, storage technologies should be able to discharge energy at multiple power ratings and discharge durations. Thus, a system consisting of a combination of various storage technologies may be required to tackle energy problems.

7. Conclusions

The primary function of storage systems can be vaguely categorized into three major groups: energy management, maintaining power quality and renewable integration. Technologies such as PHS and lead acid batteries are already commercially ready.

The annualized storage cost for any technology is largely dominated by the initial capital costs. Even with replacement costs included, battery storage technologies are not the most expensive storage system to install and operate. In addition, the simulations have shown that battery systems are mid-range options in most applications, making them very versatile options. Pumped hydro and hydrogen storage are the ones recommended for renewable integration. These technologies have large capacities and are able to store excess renewable energy for relatively long period, making them ideal to curb renewable intermittency. For load shifting purposes, pumped hydro storage is again the favoured choice. However, the UK has limited sites available to construct new storage sites. Next best options such as thermal storage and the batteries (VRB, ZnBr and NaS) and the more realistic options for load shifting. For power quality scenario, the most appropriate choices are supercapacitor, SMES and flywheel storage. These technologies are characterized by quick response time, high power density and low losses.

The ideal solution is an energy storage system that is technically mature with long lifetime, low cost, high energy and power density as well as high efficiency. However, no single storage system can meet all the criteria to become *the ideal* energy storage system. Each system has its own suitable application range. PHS, CAES and hydrogen storage are potential options for renewable integration since they can store energy for longer period and have larger capacity. Large-scale batteries and thermal storage could play a role in energy management. For power quality improvements, technologies that can provide high power at short duration such as supercapacitor.

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