ENERGY STORAGE TECHNOLOGY PRIMER: A SUMMARY

BACKGROUND

Energy can be stored in electrical, mechanical, electro-chemical, chemical and thermal means, while delivering the final energy in electrical form. *(See Figure 1.)*

Type	Sub-group	Examples (not exhaustive)	Typical Applications
Electrical	Capacitors	Capacitors and ultracapacitors	Power quality
	Superconductors	Superconducting Magnetic Energy Storage (SMES)	Power quality, reliability
Mechanical	Potential energy in storage medium	Pumped hydro,	Energy management, reserve
		Compressed air energy storage (CAES)	Energy management, reserve
	Kinetic energy in storage medium	Low-speed flywheels	Uninterruptible power supply
		Advanced flywheels	Power quality
Electro-chemical	Low-temperature batteries	Lead-acid	Power quality, standby power
		Nickel-cadmium	Power quality
		Lithium cells	Power quality
	High-temperature batteries	Sodium-sulphur	Multi-functional
		Sodium-nickel chloride	Standby power, remote area applications
	Flow batteries	Zinc-bromine	Multi-functional
		Vanadium	Remote area applications
		Polysulphide-bromine	Multi-functional
		Cerium-zinc	-
Chemical	Hydrogen cycle	Electrolyser/ fuel cell combination	-
	Other storage media	e.g. chemical hydrides	-
Thermal	Hot water	-	Peak shaving
	Ceramics	-	Peak shaving
	Molten salt/ steam	-	Integration of renewable
	Ice	-	Peak shaving

Figure 1: Storage Type Grouped by Technology[1]

[1] Source: Anthony Price, "Electrical Energy Storage- A review of Technology Options" (Nov 2005), Proceedings of ICE, Civil Engineering 158, pgs 52-58.

STAGES OF COMMERCIAL MATURITY

Currently, energy storage (ES) systems presented in *Figure 2* are in various stages of commercial maturity. For stationary utility application[2], pumped hydroelectricity is the dominant commercially available solution (~123GW) globally, with other advanced energy solutions such as sodium-sulfur, lead-acid and zinc-bromine batteries[3], compressed air energy storage (CAES)[4], thermal energy storage[5], batteries, flywheels[6] and others trailing behind and under development. For transport application (i.e. electromobility, or e-mobility), extensive developmental work has been focused on battery technologies. Lead-acid battery is a mature energy storage technology[7] but has not been commercially viable for e-mobility application. The main energy storage technologies are described at *Appendix A*. *Figure 3* presents estimated worldwide installed energy storage capacity.

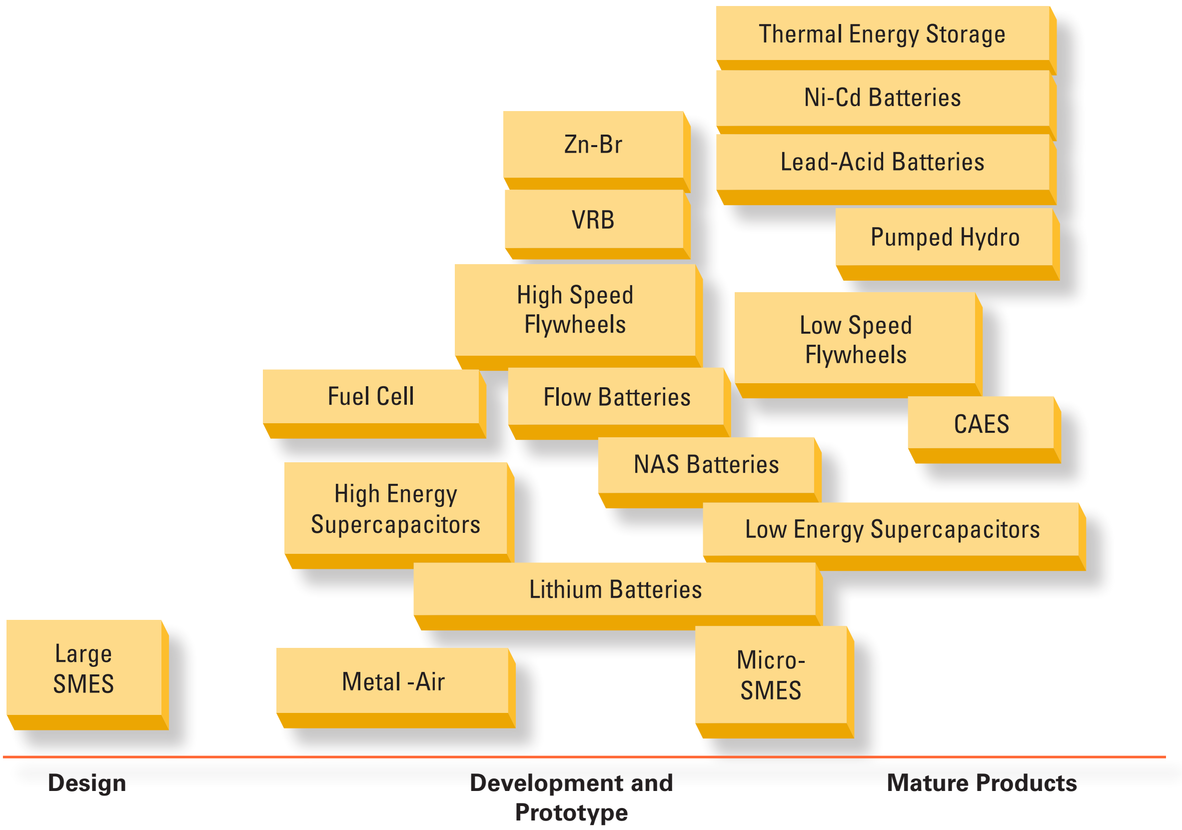

Figure 2: Commercial maturity of different energy storage systems

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2 Can be either centralized or distributed and can be utility-owned, customer-owned or third-party owned.

3 Mainly demonstration or prototype units and often along side renewable and/or distributed energy sources.

4 In CAES, off-peak power is used to pump air into a sealed underground cavern to a high pressure. When needed, this high pressure air can drive turbines to generate power during peak hours.

5 Thermal energy storage (TES) is a concept whereby energy is stored as thermal energy in energy storage reservoirs to balance energy demand between day time and night time. The thermal reservoir may be maintained at a temperature above (hotter) or below (colder) that of the ambient environment. The main uses are production of ice or chilled water to cool environments during the day, and the generation of electrical energy (through the use of steam) by high temperature storage salts when the demand is high in the day.

6 Flywheels work by accelerating rotors with a significant moment of inertia, and maintaining the energy in the system as rotational energy. This energy can be converted to electrical energy when needed.

7 Not as a main source of energy, replacing gasoline, but mainly as an auxiliary power source.

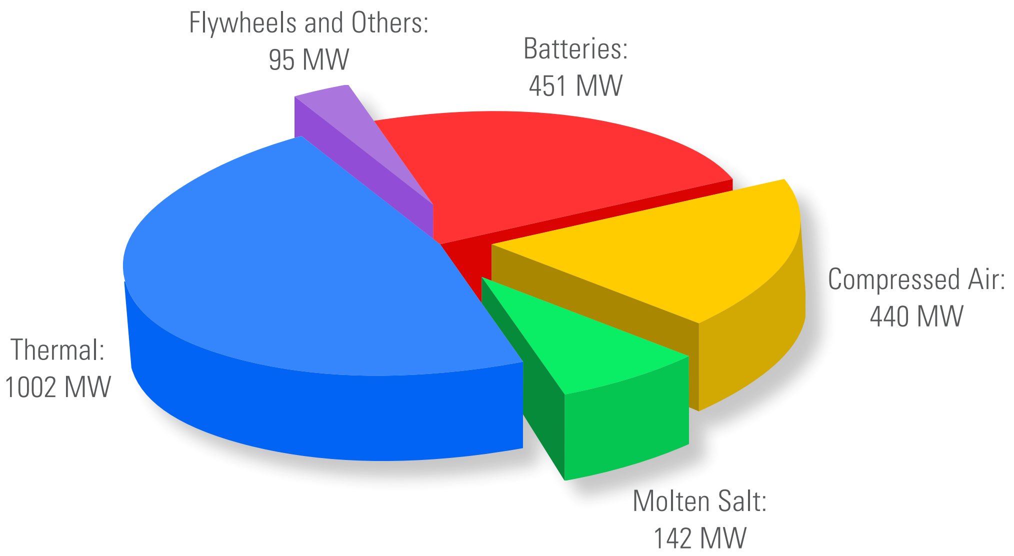

Figure 3: Estimated worldwide installed energy storage capacity (2128 MW) in 2010[8]

APPLICATION OF ENERGY STORAGE IN SINGAPORE

The use of energy storage in Singapore is most applicable in the following areas:

a. *Electric vehicles* which require medium scale energy storage (100kW to 500 kW);

b. *Smart grid supporting infrastructure* which require medium to large scale energy storage (at least 0.1MW);

c. *Building management/ renewable energy smoothing* with small to medium scale energy storage (1kW to 100 kW). *See Figure 4.*

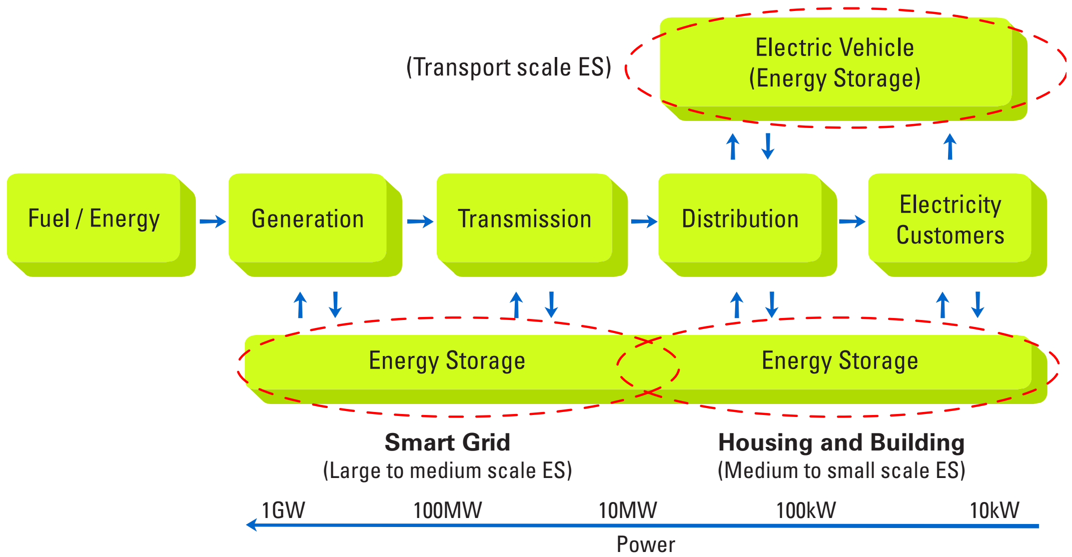

Figure 4: Electricity Value Chain

8 Source: StrateGen and CESA research. Excludes pumped hydro capacity, estimated at ~123GW.

Energy storage technologies that are applicable to these applications consist of mainly battery-based technologies, as well as Flywheels, Hydrogen Storage, Supercapacitor, Pumped Hydroelectricity, Compressed Air Energy Storage (CAES), Superconducting Magnetic Energy Storage (SMES) and Thermal Energy Storage. A summary of the relevant energy storage technologies are shown in *Figure 5*.

Applications	Energy Storage Technologies
E-Mobility	• Lead-Acid Batteries • Li-ion Batteries • Metal Air Batteries • NiCd Batteries • Fuel Cell* • Supercapacitor
Smart Grid	• NaS Batteries • Lead-Acid Batteries • Li-ion Batteries • Metal Air Batteries • NiCd Batteries • High Power Flywheels • Micro SMES • Large SMES • Pumped-hydroelectricity • CAES • Thermal • Super-capacitor • Fuel Cell* • Flow ZnBr • Flow VRB
Housing & Building	• Lead-Acid Batteries • Li-ion Batteries • Metal Air Batteries • Thermal • Fuel Cell*

Figure 5: Energy storage technologies and their applications

* Utilises Chemical energy from Hydrogen storage.

ENERGY STORAGE FOR TRANSPORT APPLICATION IN SINGAPORE

Electric Vehicles (EVs) are seen as the future sustainable mode of transport worldwide as they offer the following advantages over internal combustion engine cars:

a. *Energy Efficient.* The electric motors convert 75% of the chemical energy from the batteries to power the wheels. This is unlike internal combustion engines that only convert 20% of the energy stored in the gasoline.

b. *Environmental friendliness.* Current well-to-wheel emission estimates from Original Equipment manufacturers (OEMs) show about 66% reduction in carbon emissions when switching from a gasoline car to an equivalent-size EV.[9] This reduces pollution in traffics, although the same tailpipe pollutants will be present at fossil-fuel based power plant that produces the needed electricity. There will be no air pollutant for electricity produced from renewable energy sources (e.g. wind, solar, hydro etc.)

[9] "Renault-Nissan Alliance Partners with Singapore Government for Zero-Emission Mobility" (accessed 29 April 2011). http://www.nissan-global.com/EN/NEWS/2009/_STORY/090507-05-e.html

The authors assess that in Singapore, battery is the major mean of energy storage to provide electricity to the vehicle and one of the key technologies for vehicle electrification. However, EVs face significant battery-related challenges. ***Among the current battery options, the authors recommend that lithium-ion batteries are the most promising***, as they hold more than 5 times the specific energy and 10 times of specific power compared to the conventional lead acid batteries - promising a viable form of energy storage. However, the technology still faces the following key hurdles for effective deployment:

a. *Long charging time.* Lithium-ion batteries are not suited for fast charging. Unlike current re-fueling which takes around 5-10mins at petrol station, a full recharge of lithium-ion batteries can take 2 to 8 hours[10]. Even "quick charging" technologies to 80% capacity can take 30 minutes and can be detrimental to the battery lifecycle.

b. *Lower energy storage capacity compared to gasoline.* The commuting range of a fully charged battery pack depends very much on the capacity of the batteries, the type of routes traveled, whether air-conditioning (uses a lot of electric power) is turned on and also driver habits. Current battery technology on a full charge would allow a range of between 90 km to 160 km[5]. This is much lower than the typical range of gasoline that goes above 400 km on a full tank. This calls for more frequent recharge.

c. *Battery Cost.* Current battery packs for EVs are expensive. The current expected cost is around USD400-USD800/kWh. This is expected to reduce to USD300-USD500/kWh by 2020[11]. IEA estimated battery costs for Plug-in Hybrid EVs (PHEVs) and EVs must drop towards USD 300/kWh to bring EVs cost to competitive levels.

d. *Lower safety level.* Under high stress operation conditions, large lithium-ion battery packs may undergo a thermal runaway, which eventually results in the battery catching fire and exploding. This risk is higher as batteries become "older" but can be alleviated by using advanced battery management systems (BMS).

E-MOBILITY PROJECTS IN SINGAPORE

An EV task force, chaired by the Energy Marketing Authority (EMA) and the Land Transport Authority (LTA) has been set up with representatives from government agencies to lead tests and research into the introduction of EVs in Singapore from 2010.[9, 12] S$20 million of funding was set aside to support infrastructure development and to analyse the robustness, cost-effectiveness and environmental impact of electric-powered vehicles in a tropical climate and automakers, such as Renault and Nissan[13], have been involved in these studies.

The EV test-bed was launched in June 2011 and will last till end 2013. The test-bed will focus on gathering data and insights to guide the planning for the future deployment of EVs, including the optimal ratio of charging stations to

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[10] "Factsheet on Electric Vehicles (EVs)", EMA.

[11] "Electric Plug-In Hybrid Vehicle Roadmap", IEA (2010).

[12] "EMA leads study to put electric vehicles on Singapore roads" (accessed 17 April 2011). http://www.channelnewsasia.com/stories/ singaporelocalnews/view/427272/1/.html

vehicles. For the convenience of the test-bed participants, charging stations have been designed to automatically collect data on the EV users' charging patterns. Participants of this test-bed scheme can apply for the tax incentive scheme, Enhanced Technology Innovation and Development Scheme (TIDES-PLUS) which waives all vehicle taxes such as Additional Registration Fees (ARF), Certificate of of Entitlement (COE), road tax and excise duty, for the purposes of R&D and test-bedding of transport technologies[14].

In Jan 2011, the Technische Universitat Munchen (TUM) teamed up with the Nanyang Technological University (NTU) to set up the *TUM-CREATE Centre of Electromobility* to study how e-mobility would work in megacities in Asia, and the technology infrastructure needed to support this effort. The centre is a project under the National Research Foundation's (NRF) CREATE[15] programme, for research on sustainability of electric vehicle[16].

In the National University of Singapore (NUS), several researchers have conducted R&D on energy storage for EV applications. Details of such R&D projects are described in *Appendix B*.

ENERGY STORAGE FOR SMART GRID APPLICATIONS IN SINGAPORE

Smart grids are digitally-enhanced versions of the conventional electricity grid, and a key enabler for energy security and reliability and integration of renewable energy resources. The key differences in the characteristics of smart grids and conventional grids are summarised in *Figure 6*. In particular, unlike smart grids, conventional grids operate with little or no energy storage[17]. *Energy storage technologies play an important role in facilitating the integration and storage of electricity from renewable energy resources into smart grids.* Energy storage applications in smart grids include the ramping up and smoothing of power supply, and distributed energy storage.

Characteristic	Conventional Grid	Smart Grid
Consumer participation	Consumers are under-informed and non-participative with power system	Informed, involved and active consumers- demand response and distributed energy resources
Integrating generation and storage	Dominated by central generation. Many obstacles exist for integrating distributed energy resources	Many distributed energy resources with plug-and-play convenience, focus on renewables
Market evolution	Limited wholesale markets, not well integrated. Limited opportunities for consumers	Mature, well-integrated wholesale markets, growth of new electricity markets for consumers
Resiliency	Vulnerable to natural disasters and malicious acts of terror	Resilient to attacks and natural disasters with rapid restoration capabilities

Figure 6: Smart Grid versus. Conventional Grid Characteristics

[14] Press release "Launch of Singapore's Electric Vehicle Test-bed", (25 Jun 2011).
[15] CREATE - Campus for Research Excellence and Technological Enterprise.
[16] "One electric car, two universities, 100 researchers", The Straits Times, (22 Jan 2011).
[17] Dr Dennis Gross, Cleantech Magazine (July / August 2010.

The electricity grid in Singapore is considered reliable and robust. Network losses are reported to be only around 3%. *The authors for the "Smart Grid Primer: A Summary" have recommended that a possible area of R&D for Singapore is the integration of distributed generation and renewables into the grid, which requires the support of energy storage technologies.* See "Smart Grid Primer: A Summary" for more information.

For large-scale energy storage purposes, pumped hydroelectricity and CAES are technologies which are typically adopted. However, Singapore is geologically disadvantaged to implement these technologies due to our land constraint. There is no suitable above ground site for conventional pumped hydroelectricity. Similarly, the deployment of CAES faces challenge in Singapore due to a lack of suitable sites. To the best knowledge of the authors, Singapore has no sealed underground air pockets or abandoned mines which are required for the implementation of CAES.

The authors recommend that mid-scale distributed energy storage may be more suitable in Singapore for the following applications:

a. Integration of distributed renewable energy generation such as solar photovoltaics;
b. Ancillary services such as frequency regulation, i.e. Regulation of the instantaneous frequency of the Alternate Current supply in Singapore to be stabilized at 50 Hz, to prevent load-shedding and blackouts.
c. Application of renewable energy for off-grid island application.

Singapore has plans to include renewable energy in its urban landscape.[18] Moreover, there is potential for mid-scale energy storage to play a role in off-grid island application in Singapore (e.g. Semakau Landfill, Pulau Ubin, Lighthouses, etc).

The authors assess that suitable energy storage technologies for renewable energy generation integration and off-grid island application include lithium-ion batteries, flow batteries, sodium sulfur batteries and advanced lead-acid batteries. For power applications such as frequency regulation, on the other hand, lithium-ion batteries, advanced lead-acid batteries and flywheels may be applicable.

ENERGY STORAGE FOR HOUSING AND BUILDING APPLICATIONS IN SINGAPORE

Energy storage technologies can be part of future plans to incorporate higher amounts of energy from renewable energy sources, such as solar photovoltaics. Examples include thermal energy storage which can potentially be applied for major energy usage (e.g. thermal energy storage system for cooling application in Republic Polytechnic and Resort World Sentosa) in Singapore, fuel cell in primary or backup power system, and battery systems for storage of energy from renewable sources such as solar and wind energy. An example of energy storage application for housing application can be seen in the "Smart Houses" concept explored in Japan.[19]

[18] Report of the Economic Strategies Committee (February 2010), Economic Strategies Committee. Available from: http://app.mof.gov.sg/data/cmsresource/ESC%20Full%20Report.pdf

[19] Andy Bae, "Smart House in Japan", available from: http://www.pikeresearch.com/blog/articles/smart-house-in-japan. (accessed 1 May 2011).

Three forms of energy storage are suitable for housing and building applications – (i) batteries; (ii) thermal energy storage; and (iii) fuel cell. *(See Figure 5.)* ***The energy storage for housing and building in discussion is mainly thermal energy storage (TES), which is a mature technology.*** This, however, takes up valuable land area, which is scarce in Singapore. As such, applications at the consumer side usually target electric bill reduction, via either Demand Charges or Time-of-use Pricing.

Typically, the single biggest component of utility costs is the electric bill for air-conditioning, which can be as high as 50%.[20] The deployment of a TES system is thus an attractive option as it can help to store cooling energy during off-peak hours (when utility cost is cheaper) and use it during the peak load at day time. This helps the building owner to save up to 40% of electricity bill (e.g. $380,000 per annum for Republic Polytechnic) and provides energy savings of 10-20% depending on the type of TES system (e.g. Air/Water/Phase Change Materials).

POSSIBLE R&D AREAS FOR SINGAPORE

There are several fundamental and applied research projects in the area of energy storage being carried out at institutes such as NUS and NTU. Some of the research projects and programmes currently underway at these institutes are described in *Appendix C*.

In the Singapore context, taking into account the available research and R&D institutions and competencies, ***the authors have identified batteries as the main technological opportunity for energy storage for the next two decades.*** To realise the potential of battery technologies, Singapore's R&D efforts should be focused on solutions to the current drawbacks as follows:

a. ***Lead Acid, Nickel-based and Redox Flow batteries:*** toxic materials;
b. ***Nickel Metal-hydride (NiMH) batteries:*** Self-discharge issues; Performance is also sensitive to temperature conditions;
c. ***Lithium-ion batteries:*** Charge storage capacity needs lead to high cost for EVs; Safety issues;
d. ***Sodium-based batteries:*** Corrosion due to molten sulfur; and
e. ***Flywheels:*** Limited to Stationary Utility Energy Storage (SUES) applications; high costs.

R&D for some of these types of batteries will require more in-depth research to solve the problems of charging/ discharging/ depth of charge/ self-discharge losses.

[20] Singapore's Second National Communication: Under the United Nations Framework Convention on Climate Change, (November 2010) NEA.

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APPENDIX A

MAIN ENERGY STORAGE TECHNOLOGIES

Lead-acid battery

Lead-acid battery technology is one of the oldest and most developed battery technologies *(See Figure A1)*. They come in two basic forms: flooded lead acid batteries, which are considered a well proven and robust design, and valve regulated lead acid (VRLA, or "maintenance free batteries") batteries. These batteries are also used in traction for lifts, golf carts, Uninterruptible Power Supply (UPS), mines etc. Lead-acid batteries have some known drawbacks and limitations. They are heavy, giving rise to very poor energy-to-weight and power-to-weight ratios that limit their applications. The lead content and the sulfuric acid electrolyte make the battery environmentally unfriendly (although approximately 98%[21] of lead-acid batteries are recycled). They have short cycle-life and long recharge times. They can only accommodate a small number of full ("deep") discharges and cannot be stored in a discharged condition without service life failure.

Relatively low self-discharge rate of lead-acid batteries makes them a common choice for standby stationary energy storage such as uninterruptible power supplies (UPS). Lead-acid batteries have been used for utility applications such as peak shaving. However, the economics and life-cycle requirements do not work out well for lead-acid batteries. They are therefore not the dominant provider of Stationery Utility Energy Storage (SUES) applications. Their popularity is expected to decline as advances in other technologies occur with the exception of Starting, Lighting and Ignition (SLI) applications.

Figure A1: Lead-Acid Car Battery

According to the Energy Advisory Council (EAC), the market for Lead-Acid batteries is estimated to be approximately $3 billion and growing in excess of 8% per year.

[21] Excluding Brazil, Russia, India and China.

Nickel Based Batteries

There are two types of nickel batteries, the older, nickel-cadmium (NiCd) batteries, and the newer, nickel metal-hydride (NiMH) batteries, both are rechargeable.

Nickel-Cadmium (NiCd) Batteries use nickel oxy-hydroxide and metallic cadmium as the electrodes. They come in two designs: sealed and vented. NiCd are relatively inexpensive, able to sustain deep discharge, recharge quickly, and have a long cycle life. NiCd can also endure very high discharge rates with no damage or loss of capacity. Hence they are common among power tools.

However, NiCd are extremely environmentally unfriendly because of the use of toxic cadmium. They have relatively low energy density and relatively high self-discharge rates, which require recharge after relatively short storage periods. The charging rates are very sensitive to hot and cold temperature conditions. There are also known memory effects that shorten the battery shelf life. They compare unfavorably in terms of availability and energy density with the Nickel Metal Hydride (NiMH) and Li-ion batteries.

There have been a few demonstrations of large-scale *SUES* applications, such as the system installed by the Golden Valley Electric Association Inc. (GVEA) in Fairbanks, Alaska. The system consists of 13,760 cells and can provide 40 MW of power for up to seven minutes. *(See Figure A2)* However, the inherent disadvantages of NiCd relative to other emerging battery technologies and environmental considerations have largely relegated Ni-Cd to the backburner. There is little, if any, anticipated growth for NiCd in SUES applications.

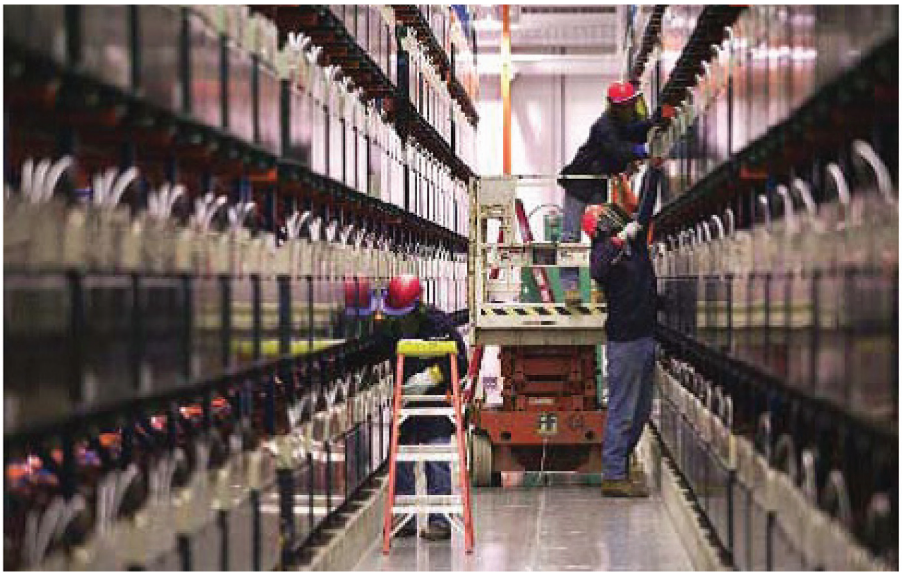

Figure A2: Golden Valley Electric Association (GVEA) located in Fairbanks, Ala, 13760 Saft SBH 920 high performance rechargeable nickel-cadmium cells[22]

[22] http://www.batterypoweronline.com/images/PDFs_articles_whitepaper_appros/AppProBESS.pdf

Nickel metal-hydride (NiMH) batteries are another alkaline Nickel-based battery technology that has replaced NiCd in many applications. NiMH batteries provide 30 to 40% more energy capacity and power capabilities compared to the same size NiCd cell. NiMH is able to meet the high power requirements in hybrid electric vehicles (HEV); and as such has been the dominant battery technology powering today's HEVs such as the Toyota Prius. NiMH batteries are considerably more environmentally friendly compared with lead acid and NiCd batteries. They can be charged in about 3 hours, although, like NiCd, charging rates are sensitive to both hot and cold temperature conditions. While NiMH batteries are capable of high power discharge, consistent use in high-current conditions can limit the battery's life.

The NiMH's self-discharge [23] rate is quite high, up to 400% greater than that of a lead-air battery. The most significant operational challenge with NiMH relates to recharge safety. The temperature and internal pressure of a NiMH battery cell rises significantly as it reaches 100% state of charge. To prevent thermal runaway, complex cell-monitoring electronics and sophisticated charging algorithms must be designed into the battery system. With NiMH technology gaining prominence in the electric and hybrid electric vehicle markets industry participants believe there are looming pressures on nickel supplies, which is one significant factor that may limit the technologies' ability to scale.

The general sense among the industry is that other technologies offer a more favorable energy density and cost profile for utility-scale energy storage applications.

Redox Flow Batteries

Zinc-bromine flow battery is a type of hybrid flow battery with nominal cell voltage ~1.8 V and energy density 16–39 W•h/L or 34–54 W•h/kg, although higher values have been reported. *(See Figure A3)* The battery systems have the potential to provide energy storage solutions at a lower overall cost than other energy storage systems such as lead-acid, vanadium redox, sodium-sulfur, lithium-ion and others.

Figure A3: RedFlow ZBM zinc-bromine battery: 5kWh and 10kWh.

Vanadium redox-flow battery (VRB) is one of the mostly studied rechargeable flow batteries, in which only one electroactive element -- vanadium -- in four different oxidation states is used. The open circuit voltage of VRB is ~1.41 V and energy density ~25 Wh/kg. The extremely large capacities possible from vanadium redox batteries make them well-suited to use in large power storage applications.

[23] Self-discharge rate refers to the rate of energy capacity loss due to the internal leakage between a battery's metal plates over time.

A VRB battery can be recharged simply by replacing the electrolyte if no power source is available to charge it. The main disadvantages with vanadium redox technology are a relatively poor energy-to-volume ratio, and the system complexity, in comparison with standard storage batteries. Large systems with power of 200kW - 1.5 MW have been installed.

Li-ion Batteries

Li-ion batteries - the most successful electrochemical devices – were first commercialized in 1990 based on the extensive knowledge gained in intercalation chemistry by inorganic and solid state chemists during the 1970's to 1980's. The first generation of such batteries allowed storing more than twice the energy compared to nickel or lead batteries of the same size and mass. Today, the lithium-ion batteries offer the promise of high energy, high power, high efficiency, longer life, and easier state-of-charge control at lower weight, volume, and reasonable cost.

Commercially available Li-ion batteries ($LiCoO_2$ versus graphite) have many advantages, such as high open circuit voltage (~ 4 V), excellent cyclic performance (up to 3000) and are highly reversible (>99% coulombic efficiency), but limited lithium storage capacity. However, both existing and new emerging applications demand even better performance in terms of energy density, power, safety, price and environmental impact. As a consequence, there is a great interest to increase the storage capacity of both the cathode as well as anode materials of a Li-ion battery. See *Figure A4* on the schematic of a Li-ion battery.

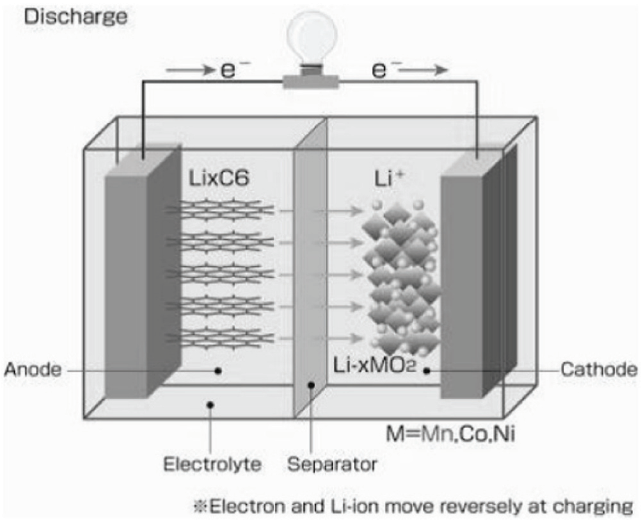

Figure A4: Schematic of a Lithium Ion Battery

Among the existing cathodes used in Li-ion batteries, phosphate-based cathode ($LiFePO_4$) offers high rate performance, excellent cyclability, relatively safe operation and low cost. However, combining $LiFePO_4$ with conventional graphitic anode in a full cell poses a serious limitation for fast charging and subsequent safety of the system. Thus, there is a need to look for anode materials that operate at slightly higher potential for safety reasons. Lithium titanate ($Li_4Ti_5O_{12}$) and titania (TiO_2) are being considered as high potential anode materials with negligible volume expansion and very high cyclic performance (15,000 cycles compared to graphite having 5,000 cycles).

Metal-air Batteries

Metal-air batteries are the most compact and, potentially, the least expensive batteries available and are environmentally benign. The anodes in these batteries are commonly available metals with high energy density like aluminum or zinc that release electrons when oxidized. The cathodes or air electrodes are often made of a porous carbon structure or a metal mesh covered with proper catalysts. The electrolytes are often a good OH^- ion conductor such as KOH. The electrolyte may be in liquid form or a solid polymer membrane saturated with KOH. The main disadvantage is that electrical recharging of these batteries is very difficult and inefficient.[24]

Zinc-air batteries

Zinc-air batteries are electro-chemical batteries powered by oxidizing zinc with oxygen from air. Zinc-air delivers the highest energy density of any commercially available battery system, and at a lower operating cost. This advantage is due to the use of atmospheric oxygen as the cathode reactant. It allows more zinc to be used to fill the zinc-air cell. Typically, batteries contain approximately the same amount of anode and cathode material, thus their service life is limited by the material that is consumed first. Thus, the increase in amount of anode material of the zinc-air battery offers up to 5 times more capacity (gravimetric energy density of up to 442 Wh/kg, volumetric energy density of up to 1673 Wh/l) than regular zinc-anode systems which must additionally house the oxidant within the cell[25]. These batteries are already commercially available and range in size from small button cells for hearing aids to very large batteries for electrical vehicle propulsion.

Zinc-air batteries have some properties of fuel cells, as well as batteries, thus making it a contender to power electric vehicles. Another advantage of the zinc-air system is that it is relatively safe as it does not require volatile material and is thus not prone to catching fire, and it has a long shelf life, indefinite in fact, if stored in a dry state but are best used within three years of manufacture[26].

However, this battery cannot be used in a sealed battery holder as air must be come in. Some other disadvantages of the zinc-air battery is that zinc corrosion can produce hydrogen which could build-up in enclosed areas, short-circuiting the cell and deep discharge below 0.5V/cell may result in electrode leakage.

Li-S batteries

Li-S batteries, due to their light weight (practical energy densities > 600 Wh/kg, 2.5 – 1.7 V) and the safe, abundant low-cost cathode material, constitute a promising technology for future mobile applications. Its outstanding potential has e.g. been demonstrated as the night time power source on the longest solar-powered airplane flight in 2008. The Li-S battery consists of a Li metal anode, an organic liquid electrolyte and a cathode made of a composite of sulfur and mesoporous carbon. During discharge, lithium dissolves from the anode and reacts with sulfur of the anode to form Lithium polysulfides, $S_8 \rightarrow Li_2S_8 \rightarrow Li_2S_6 \rightarrow Li_2S_4 \rightarrow Li_2S_3$, and finally to Lithium sulfide.

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[24] http://www.electricitystorage.org/ESA/technologies/

[25] http://www1.duracell.com/oem/primary/Zinc/zinc_air_tech.asp

[26] http://www.technologyreview.com/business/23812/

On charging, Li_2S as well as the polysulfides are reduced again and Li is plated on the anode. Despite its inherent advantages, Li-S battery technology requires further progress in the coming decades to overcome challenges in terms of cycle-life, cycle-efficiency, self-discharging etc. mostly related to the solubility of Li polysulfides in the available electrolytes. The problems can be mitigated by electrolyte additives, Li anodes protected by solid electrolyte separators and coating of cathodes by hydrophilic layers. Another approach is to keep the sulfur accessible to electrons and lithium by immobilizing it in carbon nanostructures.

Sodium-based Batteries

In the ***sodium-sulfur (NaS) battery*** (2.08V, ~120Wh/kg), Na^+ ions from a molten sodium metal anode pass at 300-350°C through the ceramic Na^+ ion electrolyte β-alumina and react with the molten sulfur of the cathode to form sodium (poly)sulfides (see *Figure 13*). As sulfur is an insulator, it is combined with a porous carbon-sponge matrix has to be used to ensure electronic conductivity. The high temperature, corrosive nature of Na, and the potential for catastrophic failure limit applications to large-scale stationary systems. NaS battery technology was demonstrated at over 200 sites (By NGK Insulators, Ltd. / Japan) with installations up to 245 MWh (34 MW) unit e.g. for the stabilization of the power output from wind parks. See *Figure A5* on the schematic representation of NaS battery.

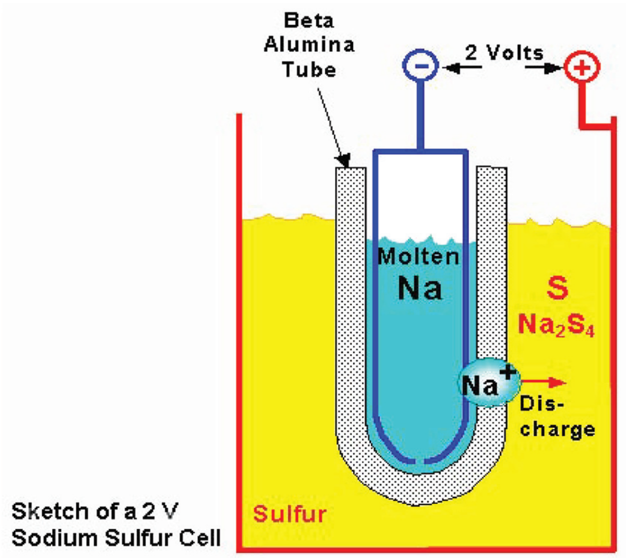

Figure A5: Schematic representation of NaS battery

Research for a safe alternative with a long cycle life sparked the development of the ***Na-$NiCl_2$ or ZEBRA*** (invented by the **Ze**olite **B**attery **R**esearch **A**frica Project (ZEBRA) at Council for Scientific and Industrial Research (CSIR) labs / South Africa) **battery** (2.58V, 90 W/kg, ~140 W/kg) and **similar Na-metal halide batteries.** The Na-$NiCl_2$ battery has been tested in various electric vehicles (Th!nk, Daimler), a significant drawback is however that the battery has to be stored in molten charged state. Once the NaAlCl4 solidifies (below 157°C in the discharged state), a non-destructive restart takes several days. See *Figure A6*.

Figure A6: ZEBRA battery[27]

Flywheels

Flywheels are one of the oldest known systems for energy storage and for rotating machines' speed regulation. In modern flywheels, kinetic energy is stored owing to the very high speed spinning of a weighted cylinder (rotor) and is eventually converted to electric energy through a motor-generator system (stator). The kinetic-electric energy conversion is highly efficient. However, flywheels can only be used for a relatively short time of electric energy generation, up to a few minutes. See *Figure A7*.

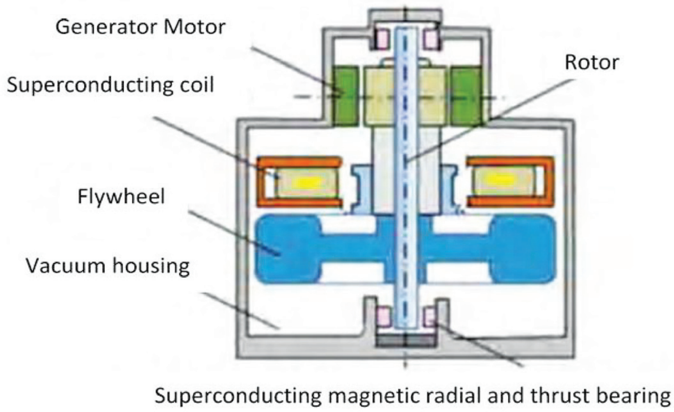

Figure A7: Schematic of a flywheel structure[28]

Hydrogen Storage

Hydrogen storage has been conventionally realized via high pressure compression (500-600 bars) or low temperature liquefaction (-253°C). At the current technology level, hydrogen is stored in gaseous or liquid form, or in material-based storage units. The status in terms of weight, volume, and cost of various hydrogen storage technologies is shown below. See *Figure A8*.

[27] http://www.metricmind.com/ac_honda/battery.htm

[28] Prospects of Large-Scale Energy Storage in Decarbonised Power Grids (2009), IEA. www.iea.org/papers/2009/energy_storage.pdf

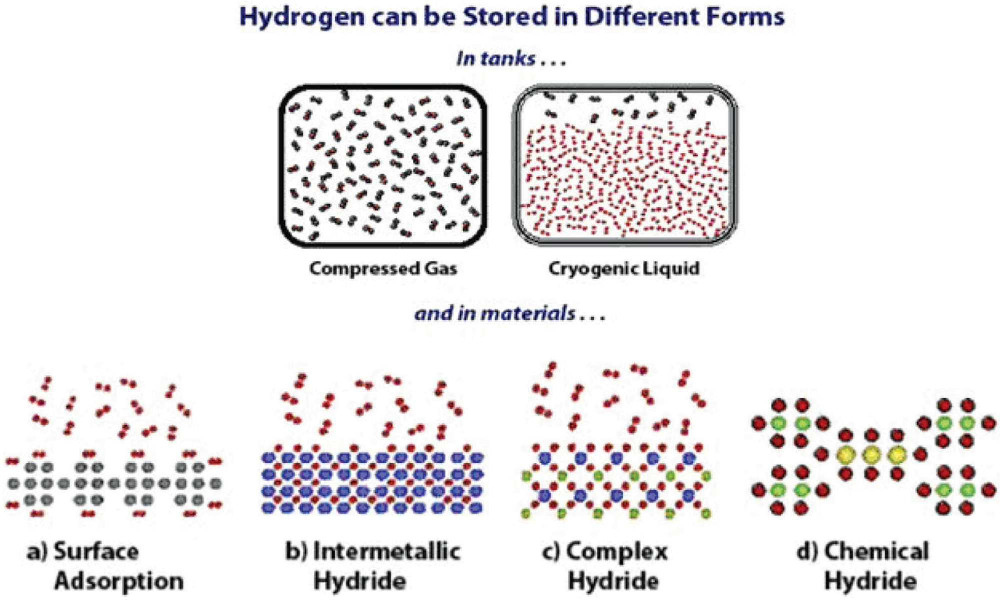

Figure A8: Different storage forms of hydrogen[29]

Supercapacitors

Supercapacitors are devices that are capable of storing and releasing electric charge, Q. While batteries store energy chemically, supercapacitors stores the energy in an electrostatic field created between a pair of electrodes, separated by an electronically insulating yet ionically conducting material called a dielectric as shown in *Figure A9*. The charge, Q, stored is associated with capacitance and voltage, V, of the dielectric constant, ε, of material between the two electrodes and the voltage, V, applied to the two electrodes through the relation $Q = (A\varepsilon V / 4\pi d)$ where A is the area of an electrode. Since the amount of charge that can be stored is proportional to the surface area, supercapacitors utilize highly porous materials and/or nano-technology to create super large specific areas to increase its capacitance.

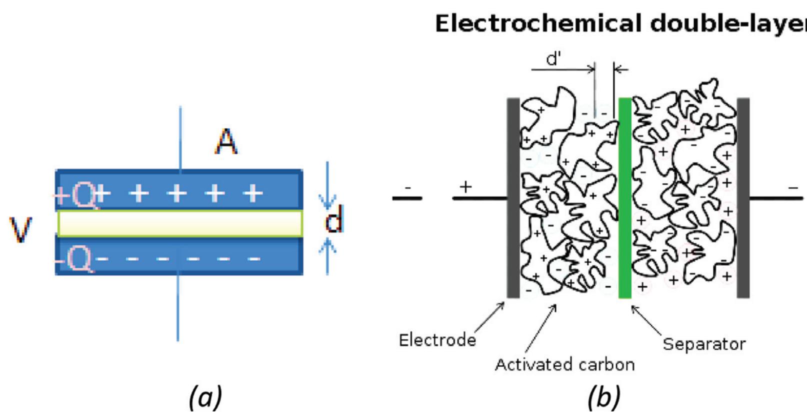

Figure A9: Schematic configuration of (a) a conventional parallel plates capacitor and (b) a supercapacitor.

[29] http://www1.eere.energy.gov/hydrogenandfuelcells/storage/images/modified_storage_cartoon.gif

Nonlinear dielectric capacitors with large electric polarization possess outstandingly high power density with the fast discharge rate. See *Figure A10*.

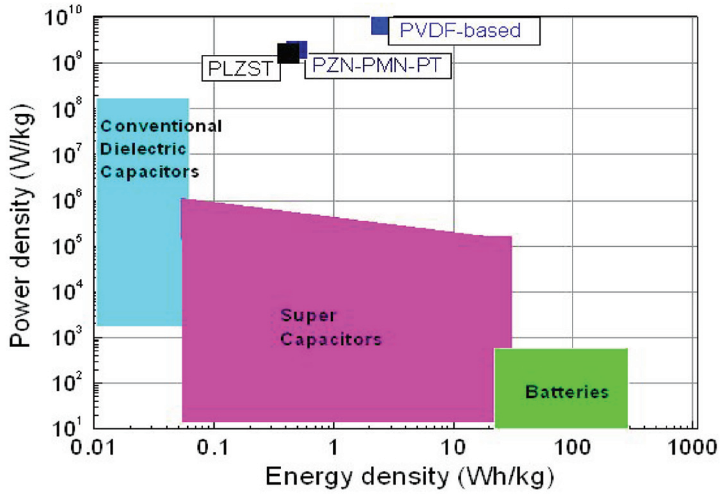

Figure A10: Power density and energy density for the PLZST, PZN-PMN-PT, and PVDF-based polymer blend thin films produced at IMRE, in comparison with the commercial dielectric capacitors, electrochemical capacitors and batteries

Superconducting Magnetic Energy Storage (SMES)

SMES systems store energy in a magnetic field produced by current flowing through a superconducting coil. SMES technology is based on inductive energy storage produced from the magnetic field by current that flows through a superconducting coil. SMES devices offer high power and quick recharge characteristics. (See *Figure A11*.) However, the technology is in many cases prohibitively expensive, energy density is relatively low and there can be large parasitic losses. The DC current is converted to three-phase AC output using a solid-state power conditioning system.

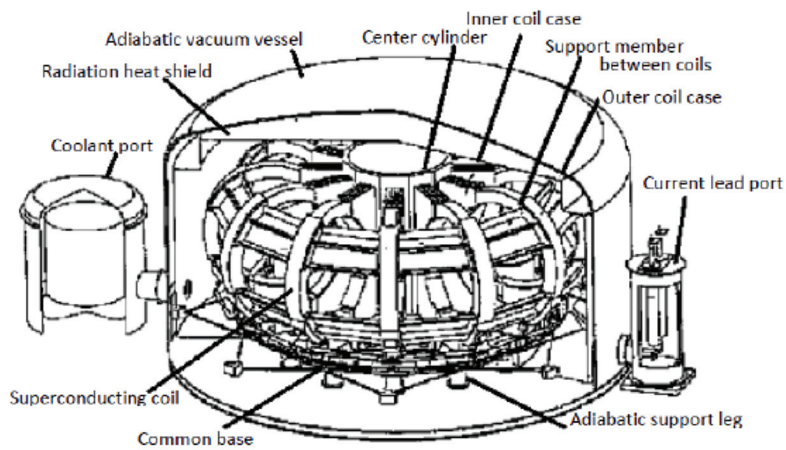

Figure A11: Schematic of Superconducting Magnetic Energy Storage[30]

[30] A. Gonzalez, B. Ó Gallachóir, E. McKeogh, K. Lynch; Study of Electricity Storage Technologies and Their Potential to Address Wind Energy Intermittency in Ireland, Cork: University College, Cork, pp. 20.

Pumped Storage Hydropower

The pumped storage principle is explained in *Figure A12*. The pump turbine is the key device. In periods of discharging (usually during daytime), the system generates power just like a conventional hydropower plant. In periods of charging (usually during night), water is pumped from a lower reservoir to an upper reservoir. In some designs, a single machine operates as a turbine and as a pump; in other cases, two separate machines are installed. Key elements of a pumped hydro system include turbine/generator equipment, a waterway, an upper reservoir, and a lower reservoir. The turbine/generator is similar to equipment used for normal hydroelectric power plants that do not incorporate storage.

Pumped hydro systems store energy by operating the turbine/generator in reserve to pump water uphill or into an elevated vessel when inexpensive energy is available. The water is later released when energy is more valuable. When the water is released, it goes through the turbine which turns the generator to produce electric power.

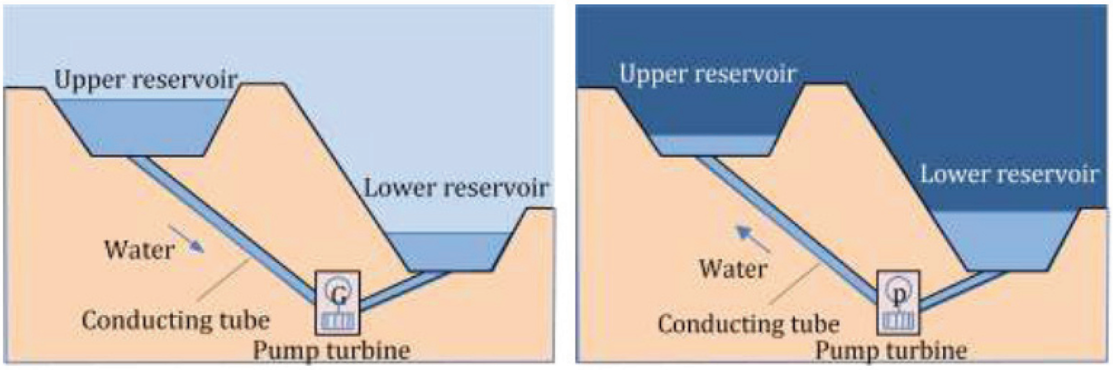

Figure A12: Prospects for Large-Scale Energy Storage in Decarbonised Power Grids[28]

Compressed Air Energy Storage

Compressed air energy storage (CAES) converts excess off-peak generated electricity into compressed air through the use of a generator. The compressed air is stored in sealed underground air pockets or caverns, and some industry participants are considering above-ground storage containers.

When electricity is required, the system returns the compressed air to the surface. The air is then heated with natural gas and put through expanders to power a generator which then produces electricity. See *Figure A13*.

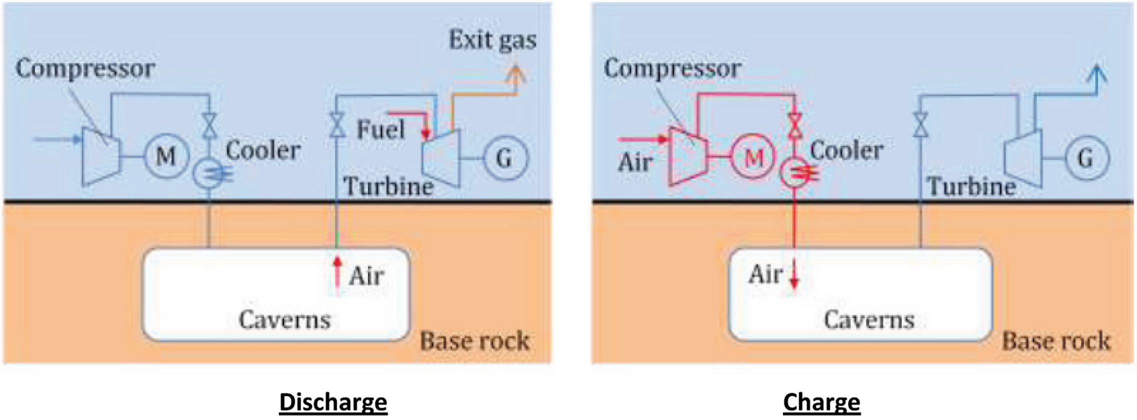

Figure A13: Schematics of the operational principle of Compressed air energy storage system [28]

Thermal Energy Storage

Refrigerating storage houses can be effectively used to skim off superabundant electrical power when they are implemented into smart grids. This is possible because the temperature in cold storage houses can be accepted to vary within certain margins. Once the temperature has been lowered during periods of superabundant electricity, the load can quickly be reduced if other consumers are claiming demand. Refrigerating storage houses may thus act as effective thermal energy storage units. This possibility is currently explored in the Netherlands, where cold storage houses of the food industry measurably contribute to the overall power demands of the country. See *Figure A14*.

Figure A14: Thermal Energy Storage System Tanks

APPENDIX B

R&D PROJECTS FOR ELECTRIC VEHICLES

The R&D projects for electric vehicles at NUS are listed below.

- Performance evaluation and studies of EVs in Singapore
- Electric vehicle platform for evaluation and testing of hybrid power plant
- Fabrication of high performance Li rechargeable batteries with superfast charge rate and ultra high power density
- Development of phosphate/borate/silicate based cathode materials with superior storage capacity at high rate operation
- Development of Novel Mesoporous TiO_2 Anode based Li-ion Battery for Electric Vehicle Application
- Setting up of 18650 Li-ion battery fabrication line funded by NUS
- Fabrication of 18650 type advanced Li-ion battery using several IP rights arising out of R&D on energy storage
- Development of an intelligent high-performance battery system for electric vehicles
- Theoretical and experimental investigations on electric energy storage by super-capacitors
- Investigation of deploying hybrid ultra-capacitor electric buses in Singapore

APPENDIX C

ON-GOING RESEARCH PROJECTS AND PROGRAMMES IN SINGAPORE

Research Projects @ Singapore Institutes	Objectives
Design and development of cathode, anode and electrolyte materials for advanced Li-ion batteries @ NUS, NTU & IMRE	• High storage capacity • High rate performance • High voltage (cathode) • Enhanced tap density • Long cycle life and storage life • Low irreversibility losses • Flame retarding electrolyte • Cost reduction • Safety at high rate applications • Scalable production • Morphology engineering for processability • Multifunction (e.g. photoactive + storage)
Laminate Sheet Battery (LSB) prototype fabrication @ NTU	• Fabricate assemble and test lithium ion based LSB packs for e-mobility applications • Enhance battery safety and cycle life • Optimized design of high energy and high power density batteries
Design of battery systems @ NUS	• Design of battery models • Ageing prediction • Battery fabrications for HEVs, EVs and PEVs
Redox flow lithium batteries @ NUS	• New operating mode compatible with current fuel refilling technology for EV applications • Cost reduction • Improved energy density • Simpler maintenance of large battery stacks • Safety improvement
Redox Additives for Advanced Lithium Ion Batteries @ NUS	• Enhanced energy density • High safety • Long cyclic performance
Theoretical and experimental investigations on supercapacitor electrical energy storage systems @ ICES & NUS	• High specific capacitance • High energy density and High power density • Long cyclic performance • Inexpensive • Safe and fast rate operation

Research Projects @ Singapore Institutes	Objectives
Lithium-air batteries @ NUS	• Passivation of Li anode to improve rechargeability • Design of cathode structure • Aqueous Li-air systems
Functional mechanisms in ferroelectrics for energy harvesting and storage @ IMRE	• Materials with outstanding power density and competitive energy density • Materials with both energy harvesting and energy storage functions • Energy storage for device applications
Development of functionalized metal-organic frameworks (MOFs) hybrid materials via engineering coordination space @ IMRE	• MOF storage materials with high porosity
• Printed Li-ion battery technology o Plastic-metal substrate o Roll-to-roll process • High voltage cathode and metal substrate materials • Lithium-air batteries Refillable batteries @ NTU	• Increase energy density • Flexible form factor, • Combined solar & storage cells • Increase power density and cycle life • Cleaner and cheaper batteries • Shorter charging time
All solid state Lithium batteries @ NUS	• Design solid electrolytes with high conductivity and stability vs. electrodes • Reduce electrode electrolyte transfer resistance • All-Solid-State Battery fabrication