Overview of energy storage methods

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Energy storage – At a glance

Purpose of energy storage

Energy storage is the storage of some form of energy that can be drawn upon at a later time to perform some useful operation. All forms of energy are either potential energy, chemical or gravitational energy:

- A wind up clock stores potential energy (in this case mechanical, in the spring tension);
- A battery stores readily convertible chemical energy to keep a clock chip in a computer running even when the computer is turned off; and
- A hydroelectric dam stores power in a reservoir as gravitational potential energy.

Energy storage became a dominant factor in economic development with the widespread introduction of electricity and refined chemical fuels, such as gasoline, kerosene and natural gas in the late 1800s. Unlike other common energy storage used in prior use, such as wood or coal, electricity must be used as it is generated.

Electricity is transmitted in a closed circuit, and for essentially any practical purpose cannot be stored as electrical energy. This meant that changes in demand could not be accommodated without either cutting supplies (e.g., blackouts) or arranging for a storage technique.

Paving the way for renewable base-load energy

Many renewable energy technologies such as solar and wind energy cannot be used for base-load power generation as their output is much more volatile and depends on the sun, water currents or winds. **Batteries and other energy storage technologies therefore become key enablers for any shift to these technologies.**

The power storage sector generally includes traditional batteries, but also covers hydrogen fuel cells and mechanical technologies like flywheels that are straight potential replacements for batteries. More and more research is also conducted in the field of nanotechnology as ultra-capacitors (high energy, high power density electrochemical devices that are easy to charge and discharge) and nano-materials could significantly increase the capacity and lifetime of batteries.

For more detailed information on nanotechnology and nanomaterials, you may consult the forthcoming research report by Mora Associates Ltd. "Nanotechnology in the cleantech sector".

Grid energy storage

Grid energy storage lets electric energy producers send excess electricity over the electricity transmission grid to temporary electricity storage sites that become energy producers when electricity demand is greater, optimizing the production by storing off-peak power for use during peak times. Also, photovoltaic and wind turbine users can avoid the necessity of having battery storage by connecting to the grid, which effectively becomes a giant battery.

Photovoltaic operations can store electricity for the night's use, and wind power can be stored for calm times. It is particularly likely that pumped storage hydropower will become especially important as a balance for very large-scale photovoltaic generation. [11]

For more information on this energy storage method, see: Pumped storage hydroelectricity.

Potential technologies for grid storage [10]

The use of underground reservoirs as lower dams has been investigated. Salt mines could be used, although ongoing and unwanted dissolution of salt could be a problem. If they prove affordable, underground systems could greatly expand the number of pumped storage sites. Saturated brine is about 20% more dense than fresh water.

A new concept in pumped storage is to utilise wind turbines to drive water pumps directly, in effect an *'Energy Storing Wind Dam'*. This could provide a more efficient process and usefully smooth out the variability of energy captured from the wind.

Other more mature grid storage methods include: Superconducting magnetic energy storage (SMES) and Compressed air energy storage (CAES).

Storage methods

Chemical energy storage

Chemical fuels have become the dominant form of energy storage, both in electrical generation and energy transportation. Chemical fuels in common use are processed coal, gasoline, diesel fuel, natural gas, liquefied petroleum gas (LPG), propane, butane, ethanol, biodiesel and hydrogen. All of these chemicals are readily converted to mechanical energy and then to electrical energy using heat engines that used for electrical power generation.

Liquid hydrocarbon fuels are the dominant forms of energy storage for use in transportation. Unfortunately, these produce greenhouse gases when used to power cars, trucks, trains, ships and aircraft. Carbon-free energy carriers, such as hydrogen and some forms of ethanol or biodiesel, are being sought in response to concerns about the consequences of greenhouse gas emissions.

Hydrogen

Hydrogen is a chemical energy carrier, just like gasoline, ethanol or natural gas. The unique characteristic of hydrogen is that it is the only carbon-free or zero-emission chemical energy carrier. Hydrogen is a widely used industrial chemical that can be produced from any primary energy source.

Hydrogen production in quantities sufficient to replace existing hydrocarbon fuels is not possible. Such production will require more energy than is currently being used, and require large capital investment in hydrogen production plants. Because of the increased costs, hydrogen is not yet in widespread use. If hydrogen production costs were to be reduced, hydrogen fuels may become more attractive commercially, providing clean, efficient power for our homes, businesses and vehicles.

Biofuels

Various biofuels such as biodiesel, straight vegetable oil, alcohol fuels, or biomass can be used to replace hydrocarbon fuels. Various chemical processes can convert the carbon and hydrogen in coal, natural gas, plant and animal biomass, and organic wastes into short hydrocarbons suitable as replacements for existing hydrocarbon fuels.

Electrochemical energy storage

An early solution to the problem of storing energy for electrical purposes was the development of the battery, an electrochemical storage device. It has been of limited use in electric power systems due to small capacity and high cost.

Batteries

A battery is a device that transforms chemical energy into electric energy. All batteries have three basic components in each cell – an anode, a cathode, and an electrolyte and their properties relate directly to their individual chemistries. Batteries are broadly classified into primary and secondary.

Primary batteries are the most common and are designed as single use batteries, to be discarded or recycled after they run out. They have very high impedance[1] which translates into long life energy storage for low current loads. The most frequently used batteries are carbon-zinc, alkaline, silver oxide, zinc air, and some lithium metal batteries.

[1] Impedance describes the opposition (resistance) to electrical flow. It is measured in *ohms*.

Secondary batteries are designed to be recharged and can be recharged up to 1,000 times depending on the usage and battery type. Very deep discharges result in a shorter cycle life, whereas shorter discharges result in long cycle life for most of these batteries. The charge time varies from 1 to 12 hours, depending upon battery condition other factors. Commonly available secondary batteries are nickel-cadmium (NiCad), lead-acid, nickel metal-hydride (NiMH) and lithium-ion (Li-Ion) batteries. Some of the limitations posed by secondary batteries are limited life, limited power capability, low energy-efficiency, and disposal concerns. [2]

According to Ron Pernick and Clint Wilder, "*whether military or civilian, a big key to successful portable energy technologies is energy storage. Very often that means batteries, which don't constitute clean tech in and of themselves – they've been round since the 19th century and can be extremely harmful to the environment. […] Advanced batteries on the market today and innovation tomorrow, however brings battery technology decisively into the realm of clean tech*." [22]

For more information on batteries, see: Electrochemical energy storage technologies.

Fuel cells

Fuel cells were invented about the same time as the battery. However, fuel cells were not well developed until the advent of spacecrafts when lightweight, non-thermal sources of electricity were required. Fuel cell development has increased in recent years to an attempt to increase conversion efficiency of chemical energy stored in hydrocarbon or hydrogen fuels into electricity.

Like a battery, a fuel cell uses stored chemical energy to generate power. Unlike batteries, its energy storage system is separate from the power generator. It produces electricity from an external fuel supply as opposed to the limited internal energy storage capacity of a battery. [2]

Electrical energy storage

Capacitor

Capacitors use physical charge separation between two electrodes to store charge. They store energy on the surfaces of metalized plastic film or metal electrodes.

When compared to batteries and supercapacitors, the energy density of capacitors is very low – less than 1% of a supercapacitor's, but the power density is very high, often higher than that of a supercapacitor. This means that capacitors are able to deliver or accept high currents, but only for extremely short periods, due to their relatively low capacitance. [2]

Supercapacitor

Supercapacitors are very high surface area activated carbon capacitors that use a molecule-thin layer of electrolyte, rather than a manufactured sheet of material, as the dielectric to separate charge. The supercapacitor resembles a regular capacitor except that it offers very high capacitance in a small package. Energy storage is by means of static charge rather than of an electrochemical process inherent to the battery. Supercapacitors rely on the separation of charge at an electrified interface that is measured in fractions of a nanometer, compared with micrometers for most polymer film capacitors.

The lifetime of supercapacitors is virtually indefinite and their energy efficiency rarely falls below 90% when they are kept within their design limits. Their power density is higher than that of batteries while their energy density is generally lower. However, unlike batteries, almost all of this energy is available in a reversible process. [2]

Superconducting magnetic energy storage (SMES)

In a SMES system, energy is stored within a magnet that is capable of releasing megawatts of power within a fraction of a cycle to replace a sudden loss in line power. It stores energy in the magnetic field created by the flow of direct current (DC) power in a coil of superconducting material that has been cryogenically cooled. [4]

The stored energy can be released back to the network by discharging the coil. The power conditioning system uses an inverter/rectifier to transform alternating current (AC) power to direct current or convert DC back to AC power. The inverter/rectifier accounts for about 2-3% energy loss in each direction. SMES loses the least amount of electricity in the energy storage process compared to other methods of storing energy. SMES systems are highly efficient; the round-trip efficiency is greater than 95%. [14]

Due to the energy requirements of refrigeration and the high cost of superconducting wire, SMES is currently used for short duration energy storage. These systems have been in use for several years to improve industrial power quality and to provide a high-quality service for individual customers vulnerable to voltage fluctuations.

SMES systems are typically installed on the exit of the power plants to stabilize output or on industrial sites where they can be used to accommodate peaks in energy consumption (e.g. steel plants or rapid transit railway). [15]

Mechanical energy storage

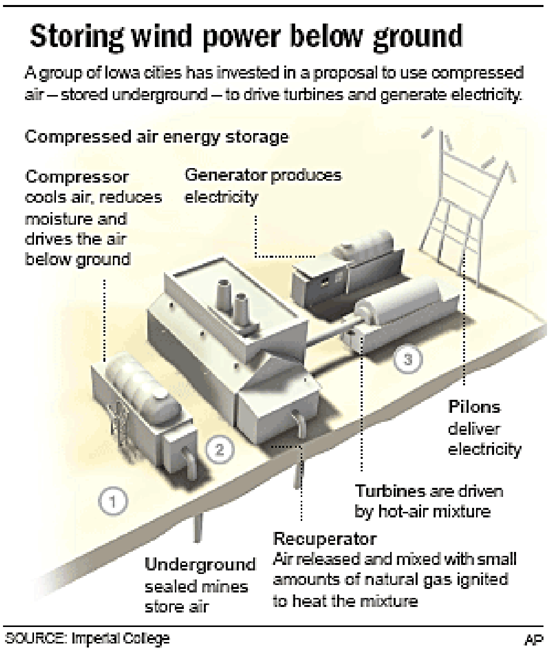
Compressed air energy storage (CAES)

CAES power plants use wind turbines to drive compressed air into underground aquifers. The air would be released to generate electricity when needed. It's a new twist on the idea of using wind energy in a way that removes the unreliability of nature.

"[…] *If you can use the compressed air as a storage medium, you get the certainty and the dispatchability that you need to make wind compete*" says Bob Haug, executive director of the Iowa Association of Municipal Utilities. [5]

At the moment, there are only two CAES plants in the world (one in the United States and one in Germany), and neither was built to make use of wind power. Instead, they are designed to take advantage of variations in the price of electricity. When power is cheap, it is used to run their compressors. When it is expensive, the valves are opened and the generators turn. [12]

According to The Economist, CAES plants are inefficient, and so they are commercially viable only in places where the price of power varies dramatically. But the intermittent nature of wind power can cause just that sort of variability. At any rate, a group of municipal power companies in the American Midwest reckon that building a wind-powered compressed-air plant to take advantage of the blustery Great Plains will be worthwhile. They have just selected a site in Iowa, and hope to be operational by 2011. BP, the British energy firm, is also looking into the concept. [12]



Flywheel energy storage

A flywheel is simply a device for storing energy or momentum in a rotating mass. The potter's wheel is often cited as the earliest use of a flywheel. Spacecrafts have long used the gyroscopic stability inherent in flywheels to control their altitude. [3]

Pumped storage hydroelectricity

Some areas of the world have used geographic features to store large quantities of water in elevated reservoirs, using excess electricity at times of low demand to pump water up to the reservoirs, then letting the water fall through turbine generators to retrieve the energy when demand peaks.

Pumped storage hydroelectricity was first used in Italy and Switzerland in the 1890's. By 1933 reversible pump-turbines with motor-generators were available. Adjustable speed machines are now being used to improve efficiency. Pumped storage hydro power is available at almost any scale with discharge times ranging from several hours to a few days. Their efficiency is in the 70% to 85% range.

For instance, pumping water up and down to store wind turbine energy brings efficiency around 20%, meaning that 80% of the electricity originally produced by the turbine is lost: clearly not mature.

There is over 90 GW of pumped storage in operation worldwide, which is about 3% of global generation capacity. Pumped storage plants are characterized by long construction times and high capital expenditure.

Pumped storage is the most widespread energy storage system in use on power networks. Its main applications are for energy management, frequency control and provision of reserve.

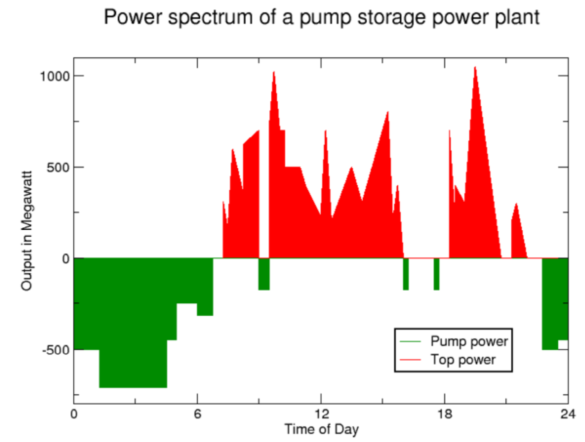


Figure 1 - Power spectrum of a pumped storage hydroelectricity power plant. Green represents power consumed in pumping and red is power generated.

Figure 2 - The upper reservoir (Llyn Stwlan) and dam of the Ffestiniog Pumped Storage Scheme in North Wales. The lower power station has four water turbines, which generate 360 MW of electricity within 60 seconds of the need arising. The size of the dam can be judged from the car parked below.

In 2000 the United States had 19.5 GW of pumped storage capacity, accounting for 2.5% of base-load generating capacity. In 1999 the EU had 32 GW capacity of pumped storage out of a total of 188 GW of hydropower and representing 5.5% of total electrical capacity in the EU.

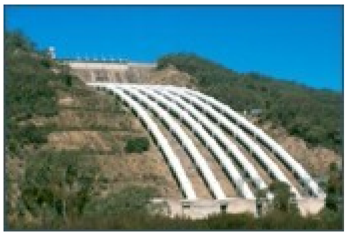
Examples of pumped hydroelectric power plants include:

- **China, Tianhuangping (1,800 MW)**
  The Tianhuangping pumped storage hydro power plant in China has a reservoir capacity of 8 million m^3 with a vertical distance of 600 metres. At 0.277 kWh per cubic meter per hundred vertical meters, that represents 13 million kWh of stored gravitational potential energy (convertible to electricity at about 80% efficiency), or only about 2% of China's daily electricity consumption.

- **United Kingdom, Dinorwig (1,728 MW)**
  Dinorwig power station is a pumped storage hydroelectric scheme on the edge of the Snowdonia national park in Gwynedd, North Wales. An important feature of Dinorwig is that it has been designed to assist restarting the National Grid on the occasion of a complete power failure. It includes diesel generators and large batteries which would allow the plant to restart even in the event of a complete shutdown of the grid. The plant runs on average at between 70 and 80% efficiency – i.e. it uses 20% more electricity than it actually produces.

- **United States, Raccoon Mountain (1,600 MW)**
  Raccoon Mountain Pumped-Storage Plant is a pumped-storage hydroelectric underground power station in Marion County, just west of Chattanooga in the U.S. state of Tennessee. The

facility is owned and operated by the Tennessee Valley Authority (TVA). Construction was started in 1970 and was completed in 1978. It takes 28 hours to fill the water reservoir. The plant has a capacity of 1,600 MW of electricity and can generate for up to 22 hours.

- **Australia, Snowy Mountains (4,500 MW, 7 sites)**
  
  Snowy Mountains hydroelectric scheme is one of the most complex integrated water and hydro-electric power schemes in the world and is listed as a "world-class civil engineering project" by the American Society of Civil Engineers. The scheme interlocks seven power stations and 16 major dams through 145 km of transmountain tunnels and 80 km of aqueducts. The scheme virtually reverses the flow of the Snowy River from its natural course toward the ocean and directs it inland. The Scheme is in an area of 5,124 km^2, almost entirely within the Kosciuszko National Park.

  The scheme took 25 years to build, from 1949 to 1974, at the historical cost of AUD$800 million, a dollar value equivalent in 1999 and 2004 to AUD$6bn. The scheme is the largest renewable energy generator in mainland Australia and plays a pivotal role in the operation of the national electricity market, generating approximately 3.5% of the mainland grid's power and providing additional water for an irrigated agriculture industry worth about $5bn per annum.

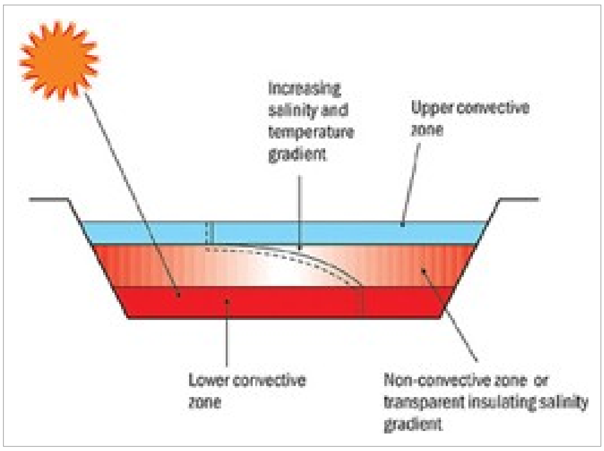
Thermal energy storage

Molten salt batteries

Molten salt batteries are a class of primary cell and secondary cell high temperature electric battery that use molten salts as an electrolyte. They offer both a higher energy density through the proper selection of reactant pairs as well as a higher power density by means of a high conductivity molten salt electrolyte. They are used in services where high energy density and high power density are required. These features make rechargeable molten salt batteries a promising technology for powering electric vehicles. Operating temperatures of 400°C to 700°C however bring problems of thermal management and safety and places more stringent requirements on the rest of the battery components.

Solar pond

A solar pond is simply a pool of water, which collects and stores solar energy. It contains layers of salt solutions with increasing concentration (and therefore density) to a certain depth, below which the solution has a uniform high salt concentration.



When sunlight is absorbed, the density gradient prevents heat in the lower layers from moving upwards by convection and leaving the pond. This means that the temperature at the bottom of the pond will rise to over 90°C while the temperature at the top of the pond is usually around 30°C. The heat trapped in the salty bottom layer can be used for many different purposes, such as the heating of buildings or industrial hot water or to drive a turbine for generating electricity.

Examples of solar pond installations include:

- **Ormat Turbines (1980)**
  150kW solar pond built in Israel at *En Boqeq* on the Dead Sea in 1980.

- **University of Texas (1986)**
  Salinity gradient solar pond at El Paso, United States.

- **Bhuj solar pond in India (1993)**
  Completed in 1993 after a sustained collaborative effort by TERI, the Gujarat Energy Development Agency, and the GDDC (Gujarat Dairy Development Corporation Ltd). The solar pond functioned effortlessly till the year 2000 when severe financial losses crippled GDDC. [19]

- **RMIT University, Geo-Eng Australia Pty Ltd and Pyramid Salt Pty Ltd (2001)**
  The demonstration solar pond and associated heating system at Pyramid Hill began supplying heat for commercial salt production in June 2001. To date results have been promising. An economic assessment of this demonstration facility, and of potential commercial solar pond industrial process heating systems is being conducted. [18]

Seasonal thermal store / Heat pumps

Seasonal thermal storage can be divided into two broad categories:

- Low-temperature systems use the soil adjoining the building as a low-temperature seasonal heat store (reaching temperatures similar to average annual air temperature), drawing upon the stored heat for space heating. Such systems can also be seen as an extension to the building design (normally passive solar building design).

- High-temperature seasonal heat stores are essentially an extension of the building's HVAC and water heating systems. Water is normally the storage medium, stored in tanks at temperatures that can approach boiling point.

In both cases, very effective insulation of the building structure is required to minimize heat-loss from the building, and hence the amount of heat that needs to be stored and used for space heating.

Electrochemical energy storage technologies

The nickel-cadmium battery (1899)

In 1899, a Swedish scientist Waldmar Jungner invented the nickel-cadmium (NiCd) battery, a rechargeable battery that had nickel and cadmium electrodes in a potassium hydroxide solution – the first battery to use an alkaline electrolyte. The first models were robust and had significantly better energy density than lead-acid batteries, but were much more expensive.

The common alkaline battery (1955)

Up until the late 1950s the zinc-carbon battery continued to be a popular primary cell battery, but its relatively low battery life hampered sales. In 1955, Eveready (now known as Energizer) wanted to find a way to extend the life of zinc-carbon batteries, but engineers at Eveready believed alkaline batteries (very expensive at that time) held more promise. They came up with a new alkaline battery that consisted of a manganese dioxide cathode and a powdered zinc anode with an alkaline electrolyte. Using powdered zinc gave the anode a greater surface area. These batteries hit the market in 1959.

The nickel metal-hydride battery (1980s)

Near the end of the 1980s, Stanford R. Ovshinsky invented the nickel metal-hydride (NiMH) battery, a variant of the NiCd, which replaced the cadmium electrode with one made of a hydrogen-absorbing alloy. NiMH batteries tend to have longer lifespans than NiCd batteries (and their lifespans continue to increase as manufacturers experiment with new alloys) and, since cadmium is toxic, NiMH batteries are less damaging to the environment.

The lithium and lithium-ion batteries (1970s and 1990s)

Lithium is the metal with lowest density and has the greatest electrochemical potential and energy-to-weight ratio, so in theory it would be an ideal material with which to make batteries. Experimentation with lithium batteries began in 1912, and in the 1970s the first lithium batteries were sold.

In the 1980s, an American chemist John B. Goodenough lead a research team at Sony that would produce the lithium-ion (Li-Ion) battery, a rechargeable and more stable version of the lithium battery; the first ones were sold in 1991.

In 1996, the lithium-ion polymer battery was released. These batteries hold their electrolyte in a solid polymer composite instead of a liquid solvent, and the electrodes and separators are laminated to each other. The latter difference allows the battery to be encased in a flexible wrapping instead of a rigid metal casing, which means such batteries can be specifically shaped to fit a particular device. They also have a higher energy density than normal lithium ion batteries. These advantages have made it a choice battery for portable electronics such as mobile phones and PDAs, as they allow for more flexible and compact design.

Characteristics of NiCd, NiMH, Li-Ion (Polymer) batteries

Characteristics / Battery	NiCd	NiMH	Li-Ion	Li-Ion Polymer
Energy/weight	40–60 Wh/kg	30–80 Wh/kg	160 Wh/kg	130–200 Wh/kg
Energy/size	50–150 Wh/L	140–300 Wh/L	270 Wh/L	300 Wh/L
Power/weight	150W/kg	250–1000 W/kg	1800 W/kg	up to 2800 W/kg
Charge/discharge efficiency	70%–90%	66%	99.90%	99.80%
Energy/consumer-price		1.37 Wh/US$	2.8-5 Wh/US$	2.8-5 Wh/US$
Self-discharge rate	10%/month	30%/month (temperature dependant)	5%-10%/month	5%/month
Time durability			24-36 months	24-36 months
Cycle durability	2000 cycles	500–1000 cycles	1200 cycles	>1000 cycles
Nominal Cell Voltage	1.2 V	1.2 V	3.6 / 3.7 V	3.7 V

Table 1 – Summary of battery energy characteristics (Source: PowerStream, Battery University)

Fuel cell technologies

Common fuel cell applications [23]

Fuel cells are very useful as power sources in remote locations, such as spacecraft, remote weather stations, large parks, rural locations, and in certain military applications. A fuel cell system running on hydrogen can be compact, lightweight and has no major moving parts. Because fuel cells have no moving parts, and do not involve combustion, in ideal conditions they can achieve up to 99.9999% reliability. This equates to less than one minute of down time in a six-year period.

Suggested applications include base-load power plants, electric and hybrid vehicles, off-grid power supply and notebook computers.

Characteristics of fuel cells

Fuel cell	Electrolyte	Qualified power (watts)	Status
Metal hydride fuel cell	Aqueous alkaline solution	?	Commercial/Research
Electro-galvanic fuel cell	Aqueous alkaline solution	?	Commercial/Research
Direct formic acid fuel cell (DFAFC)	Polymer membrane (ionomer)	to 50 W	Commercial/Research
Zinc-air battery	Aqueous alkaline solution	?	Mass production
Microbial fuel cell	Polymer membrane or humic acid	?	Research
Upflow microbial fuel cell (UMFC)		?	Research
Reversible fuel cell	Polymer membrane (ionomer)	?	Commercial/Research
Direct borohydride fuel cell	Aqueous alkaline solution	?	Commercial

Alkaline fuel cell	Aqueous alkaline solution	10 kW to 100 kW	Commercial/Research
Direct methanol fuel cell	Polymer membrane (ionomer)	100 kW to 1 mW	Commercial/Research
Reformed methanol fuel cell	Polymer membrane (ionomer)	5 W to 100 kW	Commercial/Research
Direct-ethanol fuel cell	Polymer membrane (ionomer)	up to 140 mW/cm²	Research
Formic acid fuel cell	Polymer membrane (ionomer)	?	Research
Proton exchange membrane fuel cell	Polymer membrane (ionomer)	100 W to 500 kW	Commercial/Research
RFC - Redox	Liquid electrolytes with redox shuttle & polymer membrane (Ionomer)	1 kW to 10 MW	Research
Phosphoric acid fuel cell	Molten phosphoric acid (H_3PO_4)	up to 10 MW	Commercial/Research
Molten carbonate fuel cell	Molten alkaline carbonate (e.g., sodium bicarbonate $NaHCO_3$)	100 MW	Commercial/Research
Tubular solid oxide fuel cell (TSOFC)			Research
Protonic ceramic fuel cell	H^+-conducting ceramic oxide	?	Research
Direct carbon fuel cell	Several different electrolytes	?	Commercial/Research
Solid oxide fuel cell	O^{2-}-conducting ceramic oxide (e.g., zirconium dioxide, ZrO_2)	up to 100 MW	Commercial/Research

Table 2 – Summary of fuel cell energy characteristics (Source: PowerStream, Battery University)

Comparison of energy densities [2]

Energy storage devices may be broadly characterized by their energy density (energy stored per unit volume or mass) and by their power (how fast that energy can be delivered from the device).

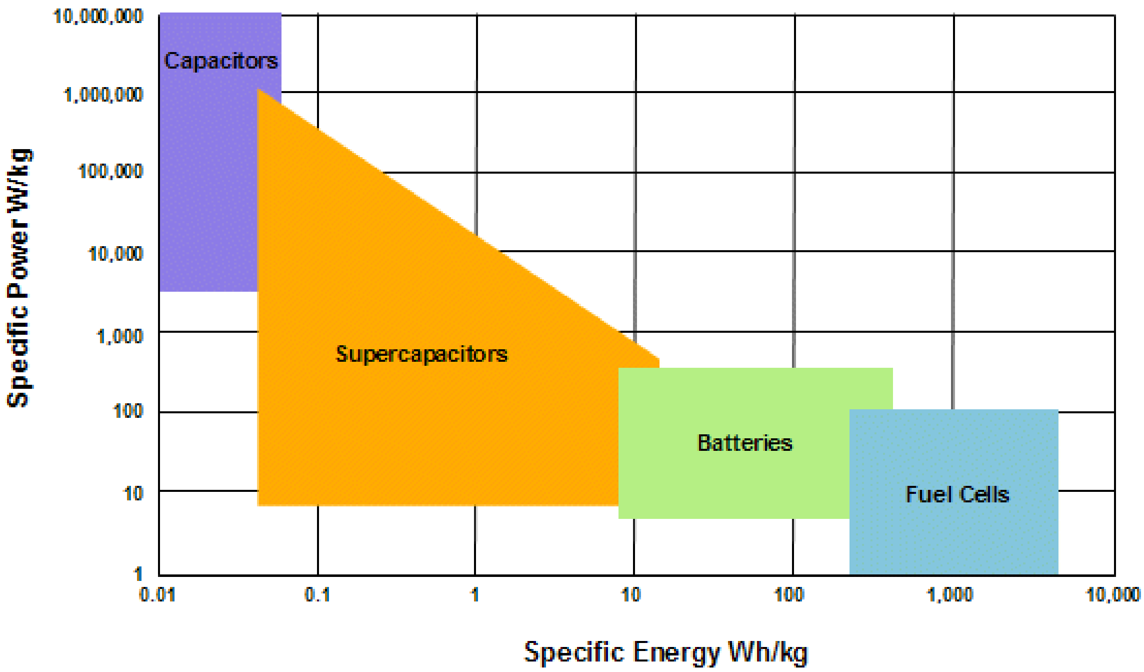


Figure 3 – Power vs. Energy (Source: CAP-XX Ltd.)

Major key differences in electrical and electrochemical energy storage methods are outlined here:

- **Batteries** can store lots of energy but take a long time to charge up or discharge, which means they have low power.
- **Conventional capacitors** have enormous power but store only tiny amounts of energy.
- **Supercapacitors** offer a unique combination of high power and high-energy properties, bridging the gap between batteries and capacitors.
- **Fuel cells** operate most efficiently over a narrow range of performance parameters and at elevated temperature, rapidly becoming inefficient under high power demands. They can be used in tandem with either batteries or supercapacitors to provide a high-energy, high-power combination.

Looking ahead

SmartGrid Newsletter, July 5th, 2007
By Mark Fitzgerald, a consultant and Contributing Editor at GlobalSmartEnergy. [17]

Storage drivers

According to Electricity Storage Association chairman Jim McDowall, installation of electricity storage is accelerating. Demonstrations are popping up around the country and confidence is building. Some of the benefits of electricity storage include:

- Protection from long outages, voltage sags, and surges
- Effective on-site generation for peak shaving customers
- Streamlining supply during peak periods by coalescing storage capabilities with renewable resources
- Complementary optimization of photovoltaic and wind-generated electricity
- Favorable life-cycle cost, including capital and installation cost, operation and maintenance cost, and disposal cost
- Versatility for transitioning to micro-grids and decentralization

Storage blockers

The storage industry has been working work with governments, regulators, utilities, and operators to address and attempt to overcome the challenges to the proliferation of electricity storage. Some of these include:

- A lack of government subsidies and incentives to encourage investment
- Regulatory constraints and limitations
- The uncertainty of selling electricity storage systems at a price that will allow both developers and customers to profit
- Political will

Recent activity in the energy storage sector

Research and development in Li-Ion batteries [20]

In February 2005, Altairnano, US-based developer of ceramic nanomaterials, announced a nano-sized titanate electrode material for lithium-ion batteries. It is claimed the prototype battery has three times the power output of existing batteries and can be fully charged in six minutes. However, the energy capacity is about half that of normal Li-Ion cells. The company also says the battery can handle approximately 20,000 recharging cycles, so durability and battery life are much longer, estimated to be around 20 years or four times longer than regular lithium-ion batteries.

In March 2005, Toshiba announced another fast charging Li-Ion battery, based on new nano-material technology that provides even faster charge times, greater capacity, and a longer life cycle.

In November 2005, A123Systems announced a new Li-Ion battery system based on research licensed from MIT. While the battery has a lower energy density that othesr competing Li-Ion technologies, a 2-Ah cell can provide a peak of 70 Amps without damage, and operate at temperatures above 60°C.

In April 2006, scientists at MIT announced a process, which uses viruses to form nano-sized wires. These can be used to build ultra-thin Li-Ion batteries with three times the normal energy density.

As of June 2006, researchers in France have created nano-structured battery electrodes with several times the energy capacity, by weight and volume, of conventional electrodes.

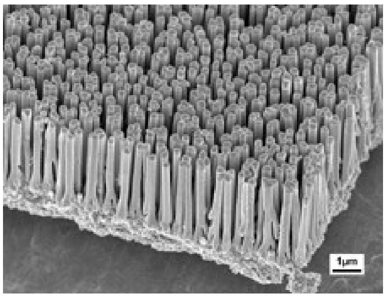


Figure 3 – A forest of copper rods about 100 nanometres in diameter create much more surface area for high-capacity battery electrodes. [21]

All these technological advances involve new electrodes. By increasing the effective electrode area – thus decreasing the internal resistance of the battery – the current can be increased during both use and charging. This is similar to developments in supercapacitors. Therefore, the battery is capable of delivering more power (watts); however, the battery's capacity (ampere-hours) is increased only slightly.

Research and development in fuel cells [23]

In August 2005, Georgia Institute of Technology researchers use triazole to raise the operating temperature of PEM fuel cells from below 100°C to over 120°C, claiming this will require less carbon-monoxide purification of the hydrogen fuel.

In September 2005, Technical University of Denmark (DTU) scientists announced in September 2005 a method of storing hydrogen in the form of ammonia saturated into a salt tablet. They claim it will be an inexpensive and safe storage method.

In January 2006, Virent Energy Systems is working on developing a low-cost method for producing hydrogen on demand - from certain sugar/water mixtures (using one of glycerol, sorbitol, or hydrogenated glucose derivatives).

In 2006, Staxon introduced an inexpensive OEM fuel cell module for system integration. In 2006, Angstrom Power began commercial sales of portable devices using proprietary hydrogen fuel cell technology, trademarked as "*micro hydrogen*."

In May 2007, Purdue University researchers have developed a method that uses aluminum and gallium alloy to extract hydrogen from water. According to the researchers "*the hydrogen is generated on demand, so you only produce as much as you need when you need it.*"

Venture capital deals in energy storage sector

According to David Ehrlich (Cleantech Venture Network), the three firms listed below raised finance from VC firms. [13]

- **A123Systems**, developer and producer of Li-Ion batteries, completed its fourth round of funding with $30 million. The new cash is expected to boost production capacity at the company, which makes batteries for hybrid electric, plug-in hybrid and extended range electric vehicles.
- **HelioVolt** also took in some fresh financing, increasing its Series B round to $101 million with some extra cash from new investors. The thin-film startup plans to build its first plant and begin volume production in 2009.

- **Planar Energy Devices**, power storage startup, secured $4 million in Series A financing from Battelle Ventures. The company, which is developing thin film batteries, is a spinout of the U.S. Department of Energy's National Renewable Energy Laboratory (NREL). Planar received $1.3 million, with another $2.7 million committed in milestone payments.

- **International Battery of Oakland** raised $25 million in financing from Digital Power Capital, an affiliate of Wexford Capital. The company manufactures large-format lithium-ion rechargeable cells and batteries for use in hybrid and electric vehicles.

Bibliography

1. "*Energy storage*" published by Wikipedia. Retrieved on November 7th, 2007 from http://en.wikipedia.org/wiki/Energy_storage

2. "*Energy Storage Technologies: A Comparison*" published by CAP-XX Ltd. Retrieved on November 7th, 2007 from http://www.cap-xx.com/resources/reviews/strge_cmprsn.htm

3. "*NASA P&PO: Aerospace Flywheel Development: Technical Details*" published by NASA. Retrieved on November 16th, 2007 from http://space-power.grc.nasa.gov/ppo/projects/flywheel/techdet.html

4. "*What is SMES?"* published by Ecole Polytechnique Fédérale de Lausanne. Retrieved on November 16th, 2007 from http://lanoswww.epfl.ch/studinfo/courses/cours_supra/smes/whatsmes.htm

5. "*Cities to Store Wind Power for Later Use*" published by MSNBC on January 4th, 2006. Retrieved on November 23rd, 2007 from http://www.msnbc.msn.com/id/10695864/

6. "*Solar pond*" published by Wikipedia. Retrieved on November 7th, 2007 from http://en.wikipedia.org/wiki/Solar_pond

7. "*History of the battery*" published by Wikipedia. Retrieved on December 3rd, 2007 from http://en.wikipedia.org/wiki/History_of_the_battery

8. "*How to charge Nickel Metal Hydride batteries?*" published by PowerStream. Retrieved on December 3rd, 2007 from http://www.powerstream.com/NiMH.htm

9. "*Charging nickel-based batteries*" published by Battery University. Retrieved on December 3rd, 2007 from http://www.batteryuniversity.com/partone-11.htm

10. "*Pumped-storage hydroelectricity - Wikipedia, the free encyclopaedia*" published by Wikipedia. Retrieved on December 3rd, 2007 from http://en.wikipedia.org/wiki/Pumped-storage_hydroelectricity

11. "*Summary Energy from the Desert: Practical Proposals for Very Large Scale Photovoltaic Power Generation (VLS-PV) Systems*" published by Earthscan. Retrieved on December 3rd, 2007 from http://www.iea-pvps.org/products/rep8_02s.htm

12. "*Power storage: Trapped Energy*" article published by The Economist on July 26th, 2007. Retrieved on December 3rd, 2007 from http://www.economist.com/science/displaystory.cfm?story_id=9539806

13. "*Batteries charge up with VC cash | Cleantech.com*" published by Cleantech Venture Network LLC on October 25th, 2007. Retrieved on December 3rd, 2007 from http://media.cleantech.com/1982/batteries-charge-up-with-vc-cash

14. Cheung K.Y.C, Cheung S.T.H, Navin De Silvia R.G, Juvonen M.P.T, Singh R, Woo J.J. *Large-Scale Energy Storage Systems*. Imperial College London: ISE2, 2002/2003.

15. "*Concerning the Start of the Verification Tests of the SMES (Superconducting Magnetic Energy Storage) For the Electric Power System Control*" published by Chubu Electric Power on June 15th, 2007. Retrieved on December 3rd, 2007 from http://www.chuden.co.jp/english/corporate/press2007/0615_1.html

16. "*Large Scale Electricity Storage. - EE/RE Investing*" published by Tom Konrad, PhD on October 8th, 2006. Retrieved on December 3rd, 2007 http://tomkonrad.wordpress.com/2006/10/08/large-scale-energy-storage/

17. "I*s Grid-Scale Storage Finally for Real?*" published by GridPoint. Retrieved on December 3rd, 2007 from http://www.gridpoint.com/news/industry/07052007.aspx

18. "*RMIT - Solar Pond Project*" published by The Royal Melbourne Institute of Technology (RMIT). Retrieved on December 3rd, 2007 from http://www.rmit.edu.au/browse;ID=905wa9169827

19. "*TERIIN.org – Salt gradient solar ponds*" published by TERIIN. Retrieved on December 3rd, 2007 from http://www.teriin.org/tech_solarponds.php

20. "*Lithium-ion battery - Wikipedia, the free encyclopaedia*" published by Wikipedia. Retrieved on December 4th, 2007 from http://en.wikipedia.org/wiki/Lithium_ion_battery

21. "*Technology Review: Higher-Capacity Lithium-Ion Batteries*" published by MIT. Retrieved on December 4th, 2007 from http://www.technologyreview.com/read_article.aspx?ch=nanotech&sc=&id=17017&pg=1

22. "The Clean Tech Revolution: The Next Big Growth and Investment Opportunity" by Ron Pernick and Clint Wilder (pp. 193-194). Published by HarperCollins in 2007.

23. *"Fuel cell - Wikipedia, the free encyclopaedia*" published by Wikipedia. Retrieved on December 4th, 2007 from http://en.wikipedia.org/wiki/Fuel_cell

Appendix I: Comparison of different storage technologies

Storage Technologies	Main Advantages (relative)	Disadvantages (Relative)	Power Application	Energy Application
Pumped Storage	High Capacity, Low Cost	Special Site Requirement		●
CAES	High Capacity, Low Cost	Special Site Requirement, Need Gas Fuel		●
Flow Batteries: PSB VRB ZnBr	High Capacity, Independent Power and Energy Ratings	Low Energy Density	◑	●
Metal-Air	Very High Energy Density	Electric Charging is Difficult		●
NaS	High Power & Energy Densities, High Efficiency	Production Cost, Safety Concerns (addressed in design)	●	●
Li-ion	High Power & Energy Densities, High Efficiency	High Production Cost, Requires Special Charging Circuit	●	○
Ni-Cd	High Power & Energy Densities, Efficiency		●	◑
Other Advanced Batteries	High Power & Energy Densities, High Efficiency	High Production Cost	●	○
Lead-Acid	Low Capital Cost	Limited Cycle Life when Deeply Discharged	●	○
Flywheels	High Power	Low Energy density	●	○
SMES, DSMES	High Power	Low Energy Density, High Production Cost	●	
E.C. Capacitors	Long Cycle Life, High Efficiency	Low Energy Density	●	◑

● Fully capable and reasonable ◑ Reasonable for this application ○ Feasable but not quite practical or economical None Not feasable or economical

Source: Electricity Storage Association (www.electricitystorage.org)

Appendix II: Pumped storage hydro installations with > 1,000MW

Location	Plant Name	On-Line Date	Hydraulic Head (m)	Max Total Rating (MW)	Hours of Discharge	Plant Cost
Australia	Tumut 3	1973		1690		
China	Tianhuangping	2001	590	1800		$1080 M
	Guangzhu	2000	554	2400		
France	Grand Maison	1987	955	1800		
Germany	Markersbach	1981		1050		
	Goldisthal	2002		1060		$ 700 M
Iran	Siah Bisheh	1996		1140		
Italy	Piastra Edolo	1982	1260	1020		
	Chiotas	1981	1070	1184		
	Presenzano	1992		1000		
	Lago Delio	1971		1040		
Japan	Imaichi	1991	524	1050	7.2	
	Okuyoshino	1978	505	1240		
	Kazunogowa	2001	714	1600	8.2	$3200 M
	Matanogawa	1999	489	1200		
	Ohkawachi	1995	411	1280	6	
	Okukiyotsu	1982	470	1040		
	Okumino	1995	485	1036		
	Okutataragi	1998	387	1240		
	Shimogo	1991	387	1040		
	Shin Takesagawa	1981	229	1280	7	
	Shin Toyne	1973	203	1150		
	Tamahara	1986	518	1200	13	
Luxembourg	Vianden	1964	287	1096		
Russia	Zagorsk	1994	539	1200		
	Kaishador	1993		1600		
	Dneister	1996		2268		
South Africa	Drakensbergs	1983	473	1200		
Taiwan	Minghu	1985	310	1008		$ 866 M
	Mingtan	1994	380	1620		$ 1338 M
U.K./Wales	Dinorwig	1984	545	1890	5	$ 310 M
USA / CA	Castaic	1978	350	1566	10	
USA / CA	Helms	1984	520	1212	153	$ 416 M
USA / MA	Northfield Mt	1973	240	1080	10	$ 685 M
USA / MI	Ludington	1973	110	1980	9	$ 327 M
USA / NY	Blenheim-Gilboa	1973	340	1200	12	$ 212 M
USA / NY	Lewiston (Niagara)	1961	33	2880	20	
USA / SC	Bad Creek	1991	370	1065	24	$ 652 M
USA / TN	Racoon Mt	1979	310	1900	21	$ 288 M
USA / VA	Bath County	1985	380	2700	11	$1650 M

Source: Electricity Storage Association (www.electricitystorage.org)