1. EUSUSTEL WP3 Report [Storage]

Björn Bolund, Urban Lundin and Mats Leijon
Department of Engineering
Uppsala University
Sweden
Bjorn.bolund@angstrom.uu.se
Urban.Lundin@angstrom.uu.se
Mats.Leijon@angstrom.uu.se

Table of Contents

1.1 Introduction

There are many kinds of different energy forms: electric energy, chemical energy, kinetic and potential energy, mechanical energy, etc. Energy is continuously converted from one form to another.

Unlike chemical energy, which can easily be stored and used when desired, electric energy is difficult to store and is ideally produced and consumed simultaneously. In a country's electric grid that is often the case and the electricity production is closely matched to the consumption. Nowadays, when emphasis on developing renewable sources for production of electricity increases, the intermittent nature of most renewables will create a discrepancy in correlation between production and consumption. To handle such a situation, the produced electricity can be stored intermediately. At present, there is no universal large-scale technology for energy storage, although there are several promising techniques such as, pumped hydro, CAES (Compressed Air Energy Storage), SMES (Superconducting Magnetic Energy Storage), batteries, and flywheels. Pumped hydro is a commercial technique used on a few places world over. However it needs geologically special sites and has some degree of environmental impact. CAES can be used in combination with gas turbines (yields a clean and efficient operation). Large scale battery based storages of electricity is today two to tree times more expensive than Pumped hydro and CAES. The other techniques are currently not viable for large-scale installations. Apart from these large-scale electric networks required to maintain a working infrastructure, energy storage is also crucial for the growing area of small electrical devices. The growing need for electric vehicles also constitutes a huge potential market. The storing unit has to possess different attributes, depending on the application. Properties that need to be optimized are energy density, power density, working efficiency, response time and lifetime.

1.2 General Issues on [Storage] Technologies

Many of the existing electricity markets are based on grids with very little large scale storage. A clear effect is the drive to install distributed generation, problems with insufficient transmission, some of the problems regarding market deregulation as well as the extreme variations in electricity pricing. Take for instance fig 1 which shows the sales of electricity in Nordpools spot market during October 2006. A market that is not regulated by any type of energy storage and the sales is therefore closely matched to the consumption. The daily variation in electricity demand can bee clearly seen and without any means for storing energy the production must follow the same pattern.

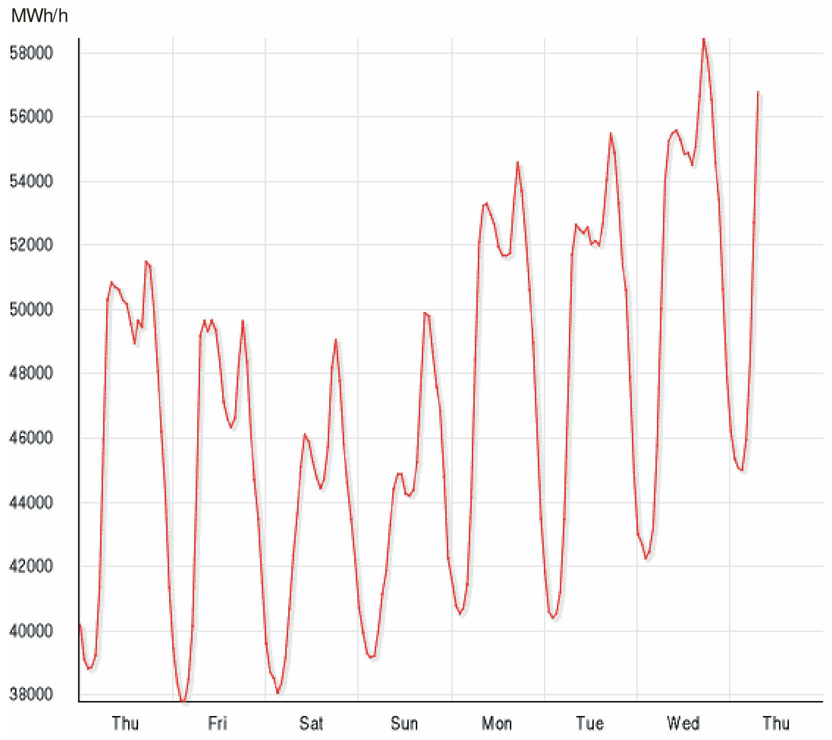

Fig 1. Consumption of electricity (MWh/h) on the Nordpool spotmaket v43-44 2006.

Many conventional technologies favor a plant with constant operation. Regulation of energy production on short timescales is normally done in the following ways:

- Limit and regulate the power output from the power plants. This means an installed overcapacity and a poor use of the energy supply.
- Use hydropower, gas-turbines or diesel plants for regulation. This will correlate the production to the consumption in an efficient way.
- Use a large scale energy storage to regulate the power output. This is a viable solution that however is associated with some degree of losses.

Different types of energy storage use different techniques to store energy. Depending on the form in which the energy is intermediately stored, the following categorization can be made:

Mechanic:
- Pumped Hydropower
- Compressed Air Energy Storage (CAES)
- Flywheel Storage

Magnetic:
- Superconducting Magnetic Energy Storage (SMES)

Chemical:
- Supercapacitors
- Utility Battery Storage
- Fuel cell technology

1.3 Description of Pumped hydro

Pumped hydroelectric storage is the most effective of all large scale energy storage methods. It can store large amounts of energy as well as having a high power capacity, several current installations exceed 2000 MW/plant with the largest beeing the 2700 MW plant at Kannagawa, Japan. Pumped hydro can store energy for long periods, up to six months depending on climate, is has a quick response time making it useful as a large scale back-up system. Pumped hydro plants have been in operation woldwide for more than 70 years

1.3.1 Present Pumped Hydro Market

Fig 2 shows the buildup of a Pumped Hydro plant,

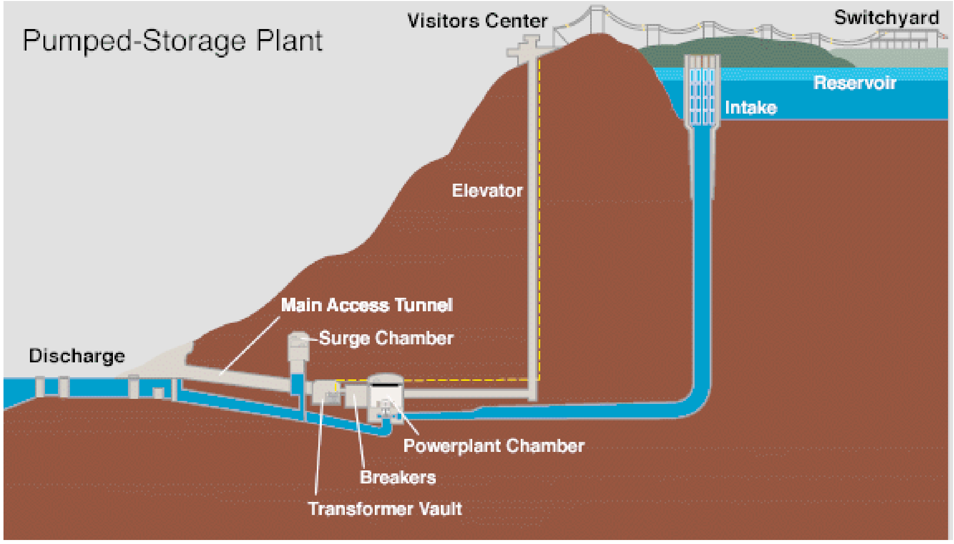

Fig 2. Skematic of a pumped hydro plant from http://www.mirror.org/people/maria.oryan/raccview.htm.

A pumped hydro plant needs two large volume reservoirs located at different heights. When storing energy, water is pumped from the lower reservoir to the higher reservoir. When generating electricity, water is released from the high reservoir through a turbine to the lower reservoir, just like a hydropower plant. The power capacity is set by the difference in height between the reservoirs, called the "head" and the flow rate, m^3/s, called the "flow" A high head plant can be quickly adjusted to meet electrical demand surge. The "head" and The "flow" are not interchangeable. A low head plant would require a very high "flow" for a high power output making it very expensive or impossible to make. A good quality for pumped hydro is the quick response time, the turbines can be brought to full power within 10 seconds if it is initially spinning in air and starting from a complete standstill takes only one minute.

A high "head pumped hydro plant requires specific geological formations, were two large reservoirs are located with a sufficient difference in height. Unfortunately such places are often on remote locations in the mountains, making construction and power grid connections an issue.

The operation cost of pumped hydro is cheap although the initial capital cost of construction is substantial, about \$1000/kW-\$3000/kW. The high initial cost combined with ecological impact and disturbances of the local habitat that the construction of dams has, pumped hydro plants are large (in the 1000-MW to 3000-MW range). On the other hand it produces no or very little pollution and waste.

Nowadays plants are constructed using a bi-directional turbine connected to a generator that can be used both as a generator and a motor. This gives an easier construction and offer round trip efficiencies in the range of 70-80%, depending on plant size, penstock diameter, turbines and the head.

1.3.2 Future development

In 1997, 290 pumped hydro plants where in operation worldwide with a maximum installed capacity of 82.8 GW. IEA has projected the pumped hydro capacity to increase to 94 GW to year 2030, se table 1. Development and new construction of pumped hydro plants is expected to be mainly in Asian countries (Korea, Vietnam, China), some development is expected in Europe, while very little construction is expected in north american countries maily due to lack of new good sites sutable for pumped hydro.

Table 1. IEA projections of pumped hydro capacity to the year 2030.

Year	1990	2010	2020	2030
Pumped hydro Capacity (GW)	84	88	92	94

Underground pumped hydro systems are being developed that uses caverns up to 300m under ground. These systems are designed to be isolated from the outside and incorporate very low losses and EPRI and DOE RD have shown this to be a technically feasible approach. Another possibility is to use the sea as the lower reservoir. One such station exists in Japan, however ecological problems and technical issues such as corrosion are under discussion.

1.4 Description of Compressed Air Energy Storage

In compressed air energy storage (CAES) air is compressed and stored under pressure in an underground reservoir or surface vessel/piping system. To produce electricity the pressurise air is released, heated via combustion in combination with a fuel, goes through an expansion turbine which drives a generator. A popular fuel is natural gas which, in cogeneration with CAES burn about on third of the premium fuel of a conventional simple cycle combustion turbine and hence produce one third as much pollutants. The most important part of the CAES plant is the storage facility for compressed air. Possible storage facilities are man-made rock caverns, salt caverns, porous rock either created by water-bearing aquifers or as a result of depleted natural gas fields. Aquifers in particular can be very attractive as storage media because the compressed air will displace water, setting up a constant pressure storage system. The pressure in the alternative systems will vary when adding or releasing air.

1.4.1 Present CAES Market

The two first large CAES plants in operation in the world are the 290 MW plant belonging to E.N Kraftwerk in Huntorf, Germany, and a 110 MW plant of Alabama Electric Corporation in McIntosh, Alabama, USA, commissioned in 1991.Tests on smaller plants have peen performed in several countries.
The Huntorf plant has operated for 10 years with 90% availability and 99% reliability.

The annual investment costs for a CAES are estimated between \$90/kW/yr and \$120/kW/yr, i.e. uniform cash flow, depending on air storage type (EESAT 1998). With a 9% discount rate and a 10-year life cycle, these correspond to necessary initial investments between \$580/kW and \$770/kW.
As with pumped storage capacity, the development of large-scale CAES is limited by the availability of suitable sites. As a result, current research is focused on the development of systems with man-made storage tanks.

1.4.2 Future CAES development

During the last years a number of advanced CAES cycles have been developed and evaluated by EPRI. Studies in the US shows that three quarters of their geology are suited for reliable underground energy storage. There are now a number of interesting CAES alternatives suitable for many different needs. Several plans for constructing new CAES plants are still actively pursued, most notably of which is a project Norton, Ohio, USA, with a turbine capacity of 2700 MW.

1.5 Description of SMES

In 1971 research which lead to the first SMES began in the US. A SMES is a relatively simple concept. Electric energy is stored in a magnetic field generated by a DC current flowing through a coiled wire. The wire is made of a superconducting material. When storing energy a converter is used to go from AC to DC power and when energy is needed a DC-AC converter is used. The vast potential for SMES:s are improved system reliability, dynamic stability, enhanced power quality and transmission capacity enhancement. For short term spinning reserve the utility industry requires SMES technology in the range of 50 to 200 MW and 50 to 3000 MJ.

1.5.1 Present SMES Market

In a larger scale SMES can be used to provide energy storage for flexible AC transmission System devices (FACTS). It can provide greater real power in addition to better reactive power control. Frequency stabilisation can also be enhanced. A SMES unit discharges DC power with efficiencies of 98 % and can switch between charging and discharging within 17 milliseconds.

SMES costs can be broken down into three main components: Coil (including containment, leads, bus and external support), Cryogenic system (including refigerator and vacuum Vessel) and power conversion system (including monitoring). Estimated costs for the coil components are \$70-100 kJ. Corresponding cost of a cryostat system is in the range of \$15-25 kJ, whereas the power conversion system at present are estimated at \$150-250 kW. The overall system cost is shown in fig 3.

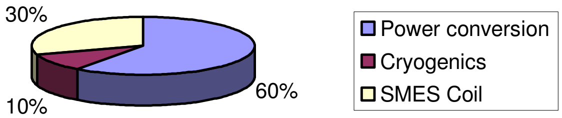

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Fig 3. Cost distribution for a SMES storage system.

1.5.2 Future SMES Development

Some research groups have achieved SMES capabilities of hundreds of MW, but only for second timescales. Theoretically, a coil of around 150-500 m radius would be able to store 5000 MWh, and support a load at 1000 MW; depending on the peak field and ratio of the coil's height and diameter.

So far, SMES have only operated on a relatively small scale. However, projects have been started with SMES on a much commercially larger scale. This is very beneficial, as the unit cost of SMES facilities will decrease as the size increases.

SMES systems are able to store energy with a loss of only 0.1% per hour (this is required for the cooling system),

A common superconductor is a niobium-titanium alloy which needs to be kept at liquid helium temperature in order to super conduct. High-temperature superconductors, those that operate at liquid nitrogen temperature or above, are not as technically advanced at this point to be considered for a large-scale application. Once SMES has established a foothold in the utility market based on conventional superconductors, high-temperature superconductors can be introduced to reduce capital and operating costs once their physical characteristics have improved, and the manufacturing processes are more mature.

The power converter system constitute a large part of the overall cost. Ongoing progress within the power converter area indicate better and cheaper power electronics with less losses. Future introduction with for instance diamond based rectifiers can drastically improve the SMES technology.

1.6 Description of Flywheel Energy Storage

The basic principle of storing energy in a flywheel is that a rotating wheel represents stored kinetic energy. More than a hundred years ago pure mechanical flywheels where used solely to keep machines running smoothly from cycle to cycle, thereby rendering the industrial revolution possible. During that time, several shapes and designs where implemented, but it took until the early 20th century before flywheel rotor shapes and rotational stress were thoroughly analyzed. Later, in the 1970s, flywheel energy storage was proposed as a primary objective for electric vehicles and stationary power backup. At the same time fiber composite rotors where built, and in the 1980s magnetic bearings started to appear.

One of the key issues for making flywheel energy storage units a competitive energy and power storage, are the recent improvements in material, magnetic bearings and power electronics. Progress in power electronics, IGBTs and FETs, makes it possible to operate flywheel at high power, with a power electronics unit comparable in size to the flywheel itself or smaller. The use of composite materials enables high rotational velocity, with power densities comparable to that of chemical batteries. Experimental tests of the energy density for different rotor configurations shows energy storage capabilities (in the flywheel only) of 79-244 Wh/kg. Magnetic bearings offer very low friction and high stiffness, enabling low internal losses during long-term storage.

1.6.1 Present Flywheel Market

Some of the primary attributes that make flywheels useful for applications where other storing units are currently being used include high power density, large number of repetitive deep discharge cycles without capacity degradation, virtually maintenance free and environmentally friendly materials. The ability to handle high power levels is one of the major advantages of flywheels and is a desirable quality in e.g. a vehicle, where a large peak power is necessary during acceleration. Two other interesting application areas for flywheels are as uninterruptible power supplies (UPS) and in space applications. Individual flywheels are so far capable of storing more than 1 GJ and peak power ranges from kilowatts to hundreds of megawatts, with the higher powers aimed at pulsed power applications.
These have been several tests and technical evaluations of flywheels interacting with intermittent energy sources, such as wind and photovoltaic with good and promising results.

The roundtrip efficiency of flywheel modules is in the 80-85 % range, but is highly dependent on bearing loss, winding loss and cycle time.

1.6.2 Future Flywheel Development

Although some flywheels are already available commercially, much work must be done to improve the design. One of the main features to consider is idling loss i.e. the energy lost when a spinning flywheel is on standby. These losses are due to external forces, like gravity. Hence there is a need to push the flywheel once in a while to maintain its speed. In commercial applications, the idling loss is usually less than 2%/h. Some companies have made flywheels with almost zero idling losses, but they spin at low speeds. These flywheels only produce 5-10 kW of power. Size is a factor that the general public takes very seriously. At the moment a "`consumer-size" flywheel in the market costs about $10,000 and spins at 50,000 rpm. The flywheel is about the size of a cabinet and occupies about a square metre of floor space.

1.7 Description of Battery Storage

Batteries have been around for a long time. They have the advantage of being modular, quiet, low polluting and easy to install. Quick response time, down to 20 milliseconds is another advantage. Roundtrip efficiency depend on charge time, discharge time, power level and type of electrochemistry but is normally in the 60-80% range. A number of battery systems have been built and used successfully for load leveling, VAR, frequency and spinning reserve in the grid. EPRI and the U.S. Department of Energy are developing battery systems with different electrochemistry.

1.7.1 Present Battery Market

Fig 4 shows the energy density with respect to mass and volume for different battery technologies.

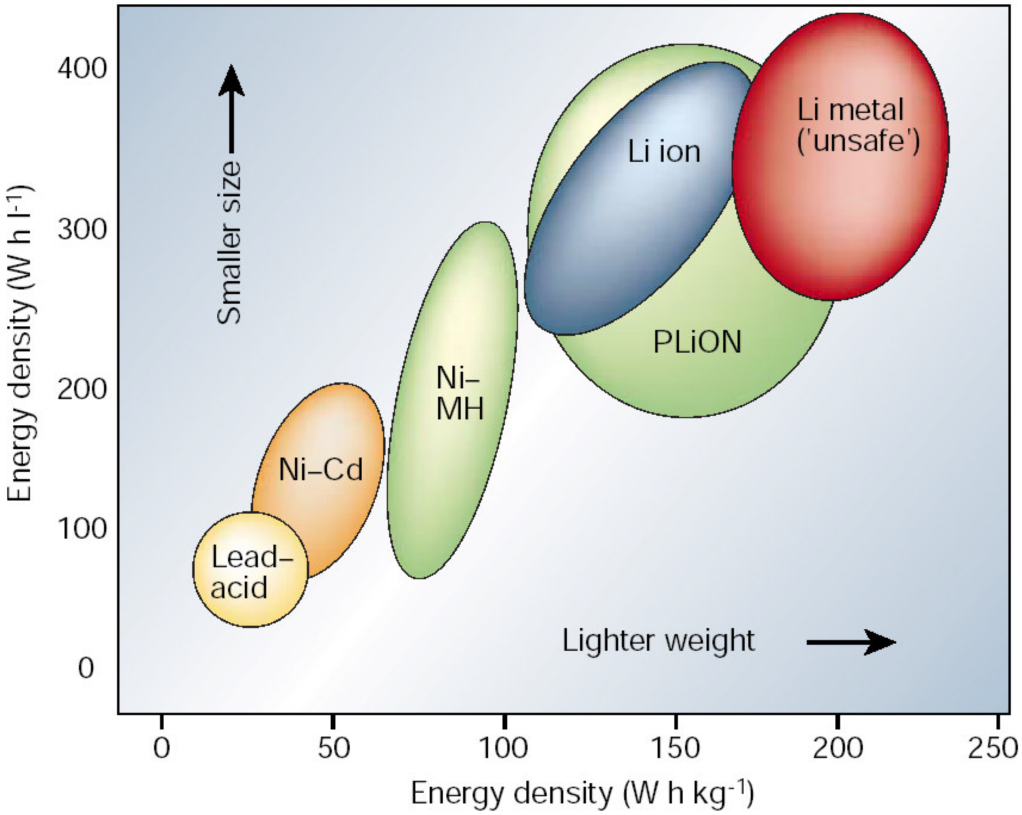

Fig 4. Energy densities for different battery storage electrochemistry.

The lifetime of batteries is also an issue. The number of cycles is heavily dependent on depth of discharge(DOD). Depending on technology and DOD the standard no of cycles are 1000-4000 before the battery is used up.

1.7.2 Future Battery Development

The largest battery bank constructed (the Columbus) constitute of two tanks 10m tall and 20m in diameter. The price is $2,000 per kilowatt, to build the Columbus battery. To reach economic viability the capital cost needs to go below $1,000 per kilowatt. The area of Redox flow batteries is becoming increasingly attractive, mainly because of its robustness the costs are there estimated to $40-260 Wh/kg and $130-900 W/kg

1.8 Future Storage Development

The choice of storage technology must be determined by the prerequisites given by the grid and by the geometrical surroundings. The cost for different storage methods is given in table 2. It is clearly seen that pumped hydro and large scale batteries holds the most beneficial cost scheme.

Table 2: Estimates of power capacity cost and energy capacity cost for different storage systems. Annual costs assume a discount rate of 9% and a 10-year life cycle.

Electricity storage system	**Power capacity costs [US$/kW/a]**	**Energy capacity costs [US$/kWh/a]**
Compressed air energy storage in tanks	120	100-1500
Underground compressed air energy storage	90	5-100
Large scale batteries	70	10-700
Pumped storage hydropower	50	3-90
Super-conducting magnetic energy storage	40	9-150
Flywheel energy storage	30	80-1200

Source: EESAT. "Proceedings of the International Conference of Electrical Energy Storage Systems: Applications and Technologies." International conference Electrical Energy Storage Systems, Chester, UK, 323.

Fig. 5 shows several energy storage technologies arrayed across three types of applications and plotted in terms of typical system sizes and maximum discharge times. As shown in the figure, CAES, Pumped hydro, and flow batteries are the primary technologies suitable for energy management applications, in addition to conventional lead acid batteries. Sodium sulfur batteries may also be an option for energy storage. These batteries are potentially low cost, but are expensive at present and have disadvantages associated with their high-temperature operation.

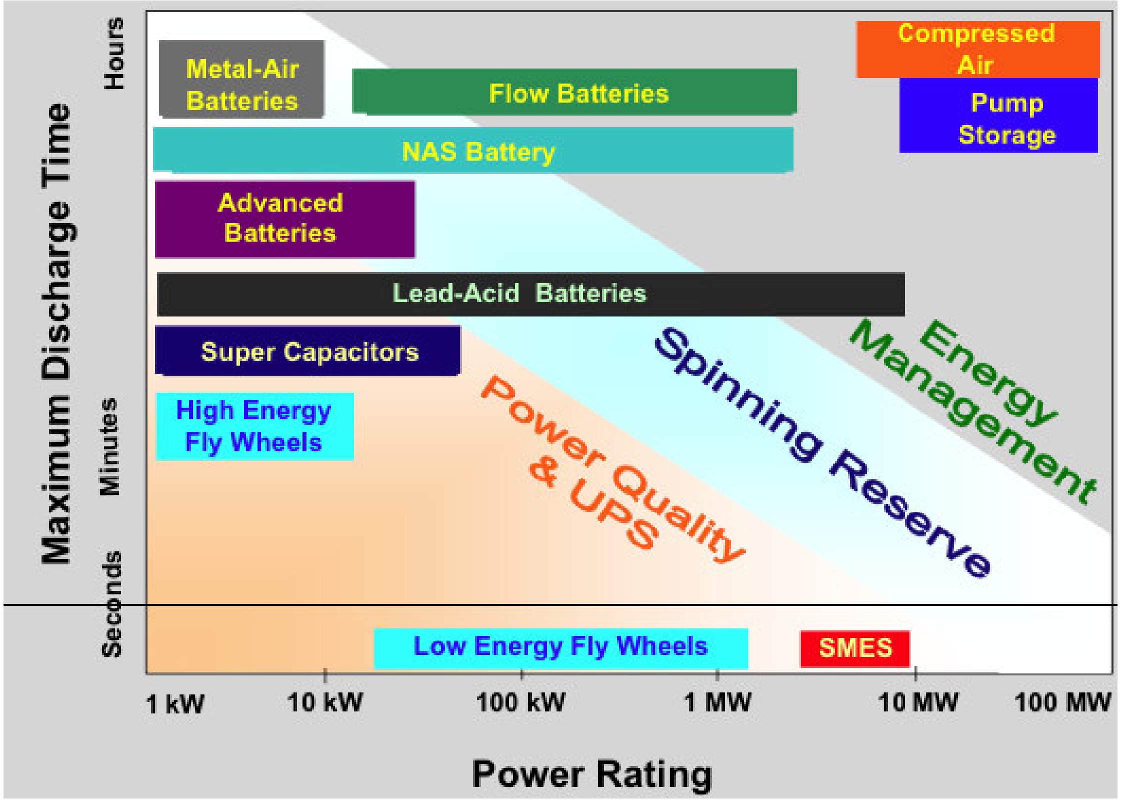

Fig 5: Comparison of different storage types. *Source: Gyuk 2002* Note: NAS = sodium sulfur; SMES = superconducting magnetic energy storage; UPS = uninterruptible power supply.

One of the most important issues is the possibilities given by the local surroundings. Pumped hydro and CAES requires special surrounding conditions, whereas Flywheel, SMES and batteries are more versatile in their placing.

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