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SWOT analysis of utility-side energy storage technologies

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Abstract: - New developments in the grid, notably the connection of unpredictable renewables, which make higher demands upon the transmission network, and the trade in liberalized markets create excellent opportunities for energy storage. The importance of energy storage is reflected in recent technical developments. Traditionally, electric energy was converted to another primary energy source for storage. Two relatively new technologies, SMES and supercapacitors, contradict the adage that electric energy is non-storable, by storing electric energy directly. This paper assesses the strengths, weaknesses, opportunities and threats (SWOT) of various energy storage systems and discusses their applications on the generation and transportation level.

Key-Words: - Energy storage, Pumped storage, Compressed air energy storage, Battery storage, Superconducting magnet energy storage, Capacitive energy storage, Mechanical energy storage.

1 INTRODUCTION

The physics of electricity makes the characteristics of the product electricity different from those of other products [1]. The electric grid has no substantial storage capacity, so there has to be an instantaneous balance between generated electric power and stochastic demand. This balancing is difficult because a modern grid has thousands of power plants and millions of consumers and has to be rebalanced every few seconds[1]. The lack of storage capacity makes electricity delivery a just-in-time process at its extreme [2]. Electrical energy storage can relieve the stringent balancing requirement. Although electrical energy is regarded as economically non-storable, recent developments have provided some new opportunities. Supercapacitors and Superconducting Magnetic Energy Storage (SMES) are two examples of these new developments which can provide new possibilities for electrical energy storage. Both are in a far state of development. Section 2 gives a general introduction to energy storage applications. In sections 3 to 8, various energy storage technologies are discussed: pumped hydro, compressed air energy storage, battery storage, flywheels, superconducting magnetic energy storage, and supercapacitors.

2 APPLICATIONS OF ENERGY STORAGE

Many scientific publications have been written on the application of energy storage on distribution and consumer level (UPS,…). This paper focuses on the production and transmission level.

2.1 Production

The production of electrical energy has to equal the demand, including transportation losses and auto consumption, at any time. In a liberalized market, grid users try to balance their portfolios and the grid operator balances the system real time [3],[4]. Both face a difficult balancing task because of three problems.

The first one is the unpredictability of supply. This is especially important for the emerging renewable energy sources, e.g. wind and solar power, which are neither controllable nor reliable. A storage facility can store energy at off-peak and inject energy at peak demand. This practice, load leveling, allows for less capacity and less (expensive) peaking generators, thus lowering the overall production cost. An additional advantage of using less peak generation is the reduction of greenhouse gas emissions.

Secondly, demand for electrical energy is not constant. A flattening of the demand diagram is advantageous because less production capacity is needed for the same electrical energy consumption and the production units can operate at a higher efficiency. The methods to reduce the discrepancies between peak and off-peak demand are referred to as ‘load management’, one of the aspects of demand side management (DSM). Examples are the different tarrification for day and night and high fees for high demand peaks. This creates an incentive for the customer to take measures such as peak-shaving and load shifting. Because of the losses of energy storage, load management is economically more interesting than load leveling. Of course, it is not possible to obtain a loadfactor equal to unity.

Thirdly, not only is the demand not constant, it also has a stochastic nature, meaning having limited predictability. In order to be able to react on fast deviations from the expected demand, enough reserve capacity has to be available. The more uncertainty, the more need for reserve capacity. It is thus advantageous to reduce the uncertainty of the demand curve. This last problem can also be alleviated by energy storage.

Although the most important one, balancing of supply and demand is not the only application of energy storage. Some energy storage facilities have blackstart capability, rendering them extremely important for restoring power after a blackout. Energy storage can furthermore be used as long term reserve, standby reserve or spinning reserve.

2.2 Transmission

In the transmission grid, energy storage can be used to improve power quality by correcting voltage sags, flicker and surges. It can also provide line stability and Power Oscillation Damping (POD). At the transmission level, the dynamic behaviour of the energy storage facilities is more important than at generation level. The first column of table 1 gives an overview of some common utility-side energy storage applications. The remaining columns list the technical characteristics that are required for these applications.

To assess whether a certain technology is suited for a certain application, the characteristics of the technology should be compared with the requirements of the application.

Table 1: Technical requirements of storage applications

		Power [MW]	Back-up time	Cycles/ year	Response time
Operating reserve	Generation	100	hours	20-50	secs → 10 min
Load leveling		100	hours	250	mins
Blackstart		100	hours	seldom	< 1 min
Power quality	Transmission	< 1	minutes	< 100	~ cycles
Transmission line stability		100	seconds	100	~ cycles
POD		< 1	seconds	100	~ cycles

3 PUMPED HYDRO

Electrical energy is used to pump water from a low reservoir to a higher one. The energy is stored as potential energy. Water from the high reservoir flows to the lower one through a turbine, which drives a generator.

3.1 Strengths

The operating cost of pumped hydro is low; it is reliable and has a long lifetime. This storage method can have large power ratings and a fairly fast response time for its size; typically the time to go from full load pumping to full load generation is in the order of minutes. The efficiency is approximately 75%.

3.2 Weaknesses

A serious disadvantage is the dependence of the design on specific geological formations. Mostly, these geological constraints cause difficult construction. The investment cost of a pumped hydro installation is, as a result, high. There are furthermore environmental concerns: large pumped hydro installations can be disruptive to the ecosystem. Issues include changed river flows, water quality and threatened species protection.

3.3 Opportunities

The development of new, high head pumps increases the number of useable geological formations. Moreover, if the reservoirs are higher, they can be smaller in size, thereby reducing environmental impact. A second opportunity is the use of variable speed drives, which ameliorate efficiency and dynamic behaviour. A new concept, wind-pumped hydro storage, uses excess wind energy to fill a reservoir.

3.4 Threats

There is rising public opposition because of environmental damage. Partially due to this opposition, partly due to geological constraints, there is limited prospect for new projects. Other storage technologies, notably CAES, have been developed that are less taxing to the environment, less dependent on geological formations and that can compete with pumped hydro with respect to parameters such as storage capacity and cost.

3.5 Facts and figures

Table 2 lists a few technical characteristics of pumped hydro storage.

Table 2: Pumped hydro: technical characteristics

Power	Back-up time	Response time	Efficiency	Lifetime
200 MW → 2 GW	hours	~ 12 min	~ 75%	~ 50 y

4 CAES

An alternative of pumped hydro storage is

Compressed Air Energy Storage (CAES). A compressor train compresses air, which is then stored in an underground cavern. When electric energy is needed, the air runs through an expander train, which drives an electric generator. A conventional CAES facility uses fossil fuel before expansion. Therefore, CAES storage is, more often than other technologies, regarded as a production plant (gas turbine) instead of a storage facility.

4.1 Strengths

Compressed air energy storage facilities can be very large: a 2700 MW CAES plant is developed in phases of 300 MW in Norton, Ohio [5]. The storing losses are very small; energy can be stored for more than a year. The start-up time is approximately 12 minutes, faster than conventional generation plants.

4.2 Weaknesses

The main drawback is the need for suitable geological structures. Compared to pumped hydro, however, there are less geographical restrictions. Although it is possible to construct artificial caverns, this is not recommended because of the high cost.

4.3 Opportunities

Advanced Adiabatic Compressed Air Energy Storage (AA-CAES) is a further development of conventional, diabatic CAES with higher cycle efficiency. During compression, a conventional CAES facility loses heat, which must be regenerated, using fossil fuel, before expansion. AA-CAES plants have a separate thermal energy store that is used during expansion, eliminating the use of fuel. An advantageous result is zero emissions [6].

4.4 Threats

The costs of fuel are likely to rise with time. Conventional CAES requires natural gas or distillate oil to operate. In the long term, these fuels will probably become less attractive for electricity generation.

4.5 Facts and figures

Some characteristics of a CAES system are listed in Table 3.

Table 3: CAES technical characteristics

Power	Back-up time	Response time	Efficiency	Lifetime
25 MW → 2.7 GW	hours	~ 12 min	~ 70%	< 50 y

5 BATTERIES

A Battery Energy Storage (BES) system stores energy by using an electrochemical reaction. They can be found in many sizes and power ratings. Many different types have been developed, but the main principle behind all batteries is the same.

5.1 Strengths

The use of BES systems for load leveling alone is not cost effective. However, batteries cover an extremely wide range, making them suitable for almost all energy storage applications. Therefore one installation can be used for multiple applications, which can render its use cost effective. An example is the BES system in Puerto Rico (20 MW, 14 MWh), providing spinning reserve as well as voltage and frequency control. Batteries have a fast response time. While a gas turbine needs up to 30 minutes to start, a BES system needs only a few seconds. The standby losses are low and both energy efficiency and density are high.

Furthermore, as the first battery was created in 1800, there is much experience with batteries.

5.2 Weaknesses

BES systems have a limited lifetime; batteries have to be replaced periodically. Also, maintenance requirements are generally higher than competing technologies. The energy storage capacities of pumped hydro and CAES can currently not be attained and the storage capacity in terms of hours of storage is less as well.

Batteries are very sensitive to heat: service life can be reduced considerably if operated above rated temperature. Battery life depends also on cycle-depth. New types of batteries do not suffer from these drawbacks as much: they are more robust and not that sensitive to heat or charge abuse. The investment cost is, however, higher.

5.3 Opportunities

Large scale distributed generation and the connection of renewables to the grid will create the need for additional energy storage.

A new evolution in battery technology is the flow battery. The principle of energy storage is different from the one of classical batteries. Electrical energy is stored or released by a reversible, ion exchanging, electrochemical reaction between two salt solutions, the electrolytes, that are pumped through two separate circuits. A continuous flow of the electrolytes has to be assured [7],[9]. Flow batteries have numerous advantages over their conventional counterparts: high discharge depth, high cycle life, high capacity and reduced maintenance requirements. Furthermore, they can decouple power, which is determined by the size and number of cells and energy, which is determined by the volume of electrolyte. Energy density and efficiency, however, are lower.

5.4 Threats

There is concern about possible ecological damage caused by batteries. Batteries contain toxic materials that can weigh hard on the environment. Much research about reducing environmental impact is going on and special care must be taken when disposing of batteries.

Other technologies can already compete with batteries in certain applications. These technologies are relatively young, and substantial technical breakthroughs are to be expected, which will render their use even more attractive, compared to batteries.

5.5 Facts and figures

Some characteristics of a lead-acid battery system are listed in table 4. By using batteries of a new type, the efficiency can be higher and the lifetime longer. The cost of these new batteries is, however, significantly higher.

Table 4: Batteries: technical characteristics

Power	Back-up time	Response time	Efficiency	Lifetime
KW's → 50 MW	hours	seconds	~ 80%	< 10 y

6 FLYWHEELS

A flywheel is a mass spinning around an axis. Flywheels store energy mechanically in the form of kinetic energy. Kinetic energy increases proportional to mass and quadratic to speed. It is therefore more interesting to use low density, high tensile strength materials, which can spin extremely fast, than high-density materials.

6.1 Strengths

The conversion process from electrical to mechanical energy and back is very efficient. Friction can be significantly reduced by installation in a sealed vacuum chamber and by magnetic suspension. Flywheels typically have a long lifetime and high energy density. With respect to the environment, Flywheel Energy Storage (FES) systems are less potentially damaging than for instance BES systems. The charge/discharge rate is limited only by the motor/generator and can therefore be very fast; several charge and discharge cycles within a few minutes are possible.

6.2 Weaknesses

Being mechanical devices, flywheels require quite a lot of maintenance. Flywheels have a fairly low specific energy and the cost is too high to compete effectively with batteries for any application above the 10 minutes range. For high speeds, a converter is necessary.

6.3 Opportunities

In the last years, much progress has been made in the development of materials technology. New composite materials with great tensile strength and lower production costs are beneficial to flywheels.

6.4 Threats

Especially with regards to safety, it is difficult to use flywheels on a large scale. Due to danger of flywheel explosion, containment vessels are needed, which negatively contribute to cost, weight, and size of the installation [8].

6.5 Facts and figures

Some characteristics of flywheels are listed in table 5.

Table 5: Flywheels: technical characteristics

Power	Back-up time	Response time	Efficiency	Lifetime
5 kW → 3 MW	mins	~ 12 min	< 95%	~ 20 y

7 SMES

Superconducting Magnetic Energy Storage (SMES) stores electric energy in the magnetic field generated by a current flowing through a coil. While the coil is in superconducting state, it has virtually no electrical resistance, thus allowing the coil to carry currents with practically no ohmic loss.

7.1 Strengths

SMES stores electric energy directly, so efficiency is very high. There are no moving parts in a SMES system; it requires little maintenance and the cycle life is virtually unlimited. The dynamic performance is far superior to earlier discussed storage technology; response times are in the order of milliseconds. The technology is environmentally friendly.

7.2 Weaknesses

A major drawback is price. A cost breakdown structure was made in [9], showing that the power converter represents the largest cost. The ongoing fast evolution in power electronics will cause a reduction in cost, but cryogenics will remain an important cost factor. Stability is still a major issue in superconductor technology: a SMES always has a risk of the sudden appearance of normal conducting zones. The loss of superconductivity may damage the coil severely.

7.3 Opportunities

The use of high temperature superconducting (HTS) materials allows higher operating temperatures, thus reducing the cryogenics in terms of cost and power consumption. The HTS material that is currently available is, however, not suited for SMES because of problems concerning the stability of the field. Second generation HTS material, which does not suffer from this problem, will be available soon [10]

7.4 Threats

There is a rising public concern about the health effects of electromagnetic fields. Clearly there are health risks associated to the huge magnetic fields created. Special measures (shielding) have to be taken to substantially diminish the magnetic fields.

7.5 Facts and figures

Technical data of a commercial small-scale SMES device are shown in table 6.

Table 6: SMES: technical characteristics

Power	Back-up time	Response time	Efficiency	Lifetime
10 kW → 3 MW	seconds	millisecs	~ 95%	~ 30 y

8 SUPERCAPACITORS

Another method of storing electrical energy directly is by using supercapacitors (or ultracapacitors). Supercapacitors store electrical energy in the electric field between two electrodes by applying DC voltage. The operating principle of supercapacitors is not new. The technology is enhanced by using modern materials. These new materials have higher dielectric constants, thus providing much higher energy storage capacity. While conventional capacitors have high power and low energy, supercapacitors have high power as well as high energy. The back-up time is generally limited to a few seconds at most.

8.1 Strengths

Supercapacitors have a very fast charge and discharge rate. Because of this fast discharge rate, supercapacitors are safe.

The cycle life is virtually infinite and no maintenance is required. Furthermore, supercapacitors are environmentally friendly.

8.2 Weaknesses

The DC voltage requires a converter, which negatively influences efficiency and cost. The cost of supercapacitors is high.

8.3 Opportunities

Supercapacitors have a number of distinctive advantages over batteries. They can be recharged much faster than batteries and supercapacitors have lower weight and a longer lifetime, which renders them particularly suitable for transportation applications. Furthermore, the energy storage capacity does not diminish after time. Supercapacitors can advantageously replace batteries in some applications. Another possibility is to combine supercapacitors and batteries in one application. This is well suited to provide power to loads that require a pulsed and variable energy consumption.

8.4 Threats

For utility-side application of energy storage, other technologies are more mature and cost-effective than supercapacitors.

8.5 Facts and figures

Table 7 gives the values of some key parameters.

Table 7: Supercapacitors: technical characteristics

Power	Back-up time	Response time	Efficiency	Lifetime
< 150 kW	seconds	millisecs	< 95%	> 10 y

9 CONCLUSIONS

To use energy storage at generation level, bulk storage is necessary. At present only pumped hydro, CAES and BES are technically as well as economically viable.

Pumped hydro is only suited for large-scale energy storage applications. It is excellent for load leveling, providing blackstart capability, and as operating reserve. Due to the limited prospect for new pumped hydro projects, there is certainly room for other large-scale energy storage systems.

CAES facilities become more and more interesting options when planning a large-scale energy storage facility. Due to geological constraints, the construction of new CAES, and particularly of new pumped hydro, is, however, limited. This will benefit BES systems, which have few geological requirements. BES systems can be used for all energy storage applications. Battery systems are technically feasible for bulk energy storage but are less economic than pumped hydro and CAES. In the small-scale range, BES systems have to compete with newer technologies, such as SMES and supercapacitors. Many applications are cost-effective with battery storage technologies. The cost-effectiveness is enhanced if several applications are combined, for instance the combination of load leveling and stability.

Small-scale energy storage can be used on transmission and distribution level. BES, SMES, supercapacitors and flywheels are possible. The choice of an energy storage system depends on the requirements of the application. Generally, BES systems are the best choice, because no other system can compete in terms of cost. However, in applications where battery systems begin to reach their limits, other solutions like SMES, supercapacitors or flywheels become advantageous.

Flywheels are proven for a number of applications, notably motion smoothing and the providing of ride-through power for power disturbances. A possible application is the coupling of flywheels with wind turbines to dampen voltage fluctuations.

Currently, the application of SMES devices is limited to a few niche markets although theoretically, SMES systems could be used for all utility-side applications of energy storage. Large and medium-scale SMES systems are exceptional. Today only small-scale SMES systems are economical efficient. This is reflected in the R&D efforts that are almost solely focused on small-scale SMES systems in applications that benefit the most from the specific characteristics of SMES systems, notably fast response [11],[12],[13].

The supercapacitor releases its energy in quick bursts; it does not deliver a steady stream of power for hours at a time. Although supercapacitors clearly have numerous applications, for instance in telecommunications and in vehicles, they are not suitable for utility-side energy storage at first sight. Apart from the combination with Statcom or SSSC, there are not a lot of utility-level applications. However, in the future, they could have a role in protecting the grid. By using large banks of supercapacitors as a buffer between systems, a complete blackout can be avoided. Obviously, a lot of technical developments would be necessary before supercapacitors could be used for this purpose.

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