Technologies and Operational Concepts for Energy Storages

Jan-Hendrik Psola[1], Wolf-Rüdiger Canders[1], Markus Henke[1]

Energy Storage Systems

With higher amount of fluctuating energy generation within a power grid new concepts are required to maintain a reliable energy supply which is essential for the economy. Grid enlargement is always an option; however a long time process is necessary with a lot of political implications. Electrical energy storages offer here an alternative. This paper gives an overview about possible energy storage concepts for electrical energy. Several operational concepts will be discussed and the suitability for each technology will be shown.

1. Demand for Energy Storages

In the last decade the electrical energy generation in Germany has been changing form a centralized, top-to-bottom system with conventional power plants to a decentralized generation where the power is fed into the grid on low voltage levels. Moreover this generation is volatile, leading to challenges for a stable grid operation:

1) The energy generation becomes more volatile and less predictable;
2) More generation takes place in lower grid levels;
3) The energy generation from renewable energies takes place far away from the areas of high energy demand.

The EEG (renewable energy act) in Germany is the main driver for the fast growth in installed renewable energy systems. Production of environmentally friendly energy is one key reason, the other is to gain or maintain energy independency. Germany has, except lignite, no large natural energy resources and depends on energy imports. Especially the amount of natural gas consumption has been rising over the past year. Natural gas is used in high efficient combined cycle power plant; furthermore it is used for heating as well as in the mobility sector.

At the moment with a renewable energy generation about 20% grid enlargement offers the best solution to maintain a reliable power grid. The construction of new power lines is though a time consuming process and many interests need to be considered. Therefore other solutions might be applicable in future.

A research study (VDE 2012) has shown that with an installed capacity of renewable energies higher then 40% storage systems will be needed.

Within this conversion process sooner or later energy storages are indispensable. And in some cases storages are already required today. Often renewable generation has to be stopped due to the grid condition, thus this not generated energy has to be paid for.

[1] Institute for Electrical Machines, Traction and Drives; Technische Universität Braunschweig, Hans-Sommer-Str. 66, 38106 Braunschweig, Germany; j.psola@tu-bs.de, w.canders@tu-bs.de, markus.henke@tu-bs.de; Tel: +49 531 391-3913, FAX: +49 531 391-5767

2. Energy Storage Technologies

In the following different types of energy storage concepts will be described. Potential operation modes for the storages are described and the usability for each storage system is assigned. The general cost structures of theses concepts will be shown and other restriction will be pointed out. In general electrical energy storage systems can be divided into three main groups which are based on the physical principles in which the electrical energy is stored. These types are mechanical, electrical and chemical energy. It can bee seen that, in most cases, the electrical energy is converted into another energy form, either mechanical, or chemical.

2.1 Energy Storages Requirements

In order to evaluate different storage systems the important requirements need to be identified. Some of these are generally important whereas others depend on how the storage will be used. For different types of application the significance of these parameters varies. Therefore in order to find the best solution these parameters need to be weighted. E.g. energy density per weight is for electrical vehicles an important requirement whereas it becomes for stationary storage systems nearly insignificant (Canders 2009).
Energy storage requirements:

- Cycle efficiency
- Life time
- Self-discharge
- Capacity
- Rated power
- Response time
- Geographical restrictions
- Power density (gravimetric/volumetric)
- Energy density (gravimetric/volumetric)
- Cycle stability

Many energy storages have to be connected to the grid by an inverter to adopt output frequency and voltage to grid conditions. In these cases the properties of the inverter dominate the storage performance data (e.g. overload, short circuit current, etc.).

2.2 Mechanical Energy Storages

2.2.1 Pumped-Storage Plant

Pumped-storage plants are a long developed storage system that uses the potential energy of water that is pumped between two reservoirs. If energy needs to be stored water is pumped from the lower reservoir to the upper. If electricity is submitted to the grid water from the upper reservoir is used for propulsion of a water turbine combined with a synchronous machine that is connected to the grid. For pumped-storages strict geographical restrictions exist which are suitable geographical height differences and a water source.

2.2.2 Compressed Air Energy Storage

Compressed air energy storages (CAES) use the pressure potential of compressed air. The air is later expanded in a gas turbine. With the purpose to store a large amount of air often salt caverns are used. However to maintain stability of theses caverns temperatures over 70°C are not allowed. Therefore the air, which has an increased temperature after compressing, needs to be cooled before storage. The two existing plants of this type (Huntorf, Germany; McIntosh, USA) are working diabatic where the heat energy from compression is not further stored. Diabatic compressed energy storages require natural gas for the heating of the air in a combustion chamber before expansion in the turbine.

To increase the efficiency of this technology adiabatic systems are under research, which are bound to store all the heat from compression within a separate heat storage on the surface. This heat later is used for the expansion process in order to avoid additional energy demand as natural gas, as it is the case in diabatic systems.
Currently an advanced compressed air energy storage is under construction in Staßfurt, Germany (RWE 2010). The advantage of CAES technology is that many conventional components are used which have a long life time and a high cycle durability. However one strict restriction is to have a suitable cavern.

2.2.3 Flywheel Energy Storage

Within a Flywheel kinetic energy is stored by a rotating mass which is typically connected with the rotor of an electrical machine. To reduce friction losses the mass is rotating in vacuum and contactless bearing are preferred. There are also concepts to use superconducting magnetic bearing as a vacuum is already applied that favours thermal insulation (Canders 2006). Usually the electrical machine is connected to the grid by an inverter.

2.3 Electrical Energy Storages

2.3.1 Supercapacitor Energy Storage

Supercapacitors store energy in the electric field. They are DC sources and require an inverter to be connected with the energy grid. Moreover a voltage balance system is required if many cells are connected to a stack (Guetif 2012). This results in increase of volume and energy losses.

2.3.2 Superconducting Magnetic Energy Storages

Superconducting Magnetic Energy Storages (SMES) store the energy in the magnetic field by generating a current in a superconducting coil. As there is no resistance the current is constant. However this concept has not achieved marketability due to high consumption of cooling power.

2.4 Chemical Energy Storages

This group also could be subdivided into battery storages (2.4.1 – 2.4.4) and chemical substances (2.4.5 – 2.4.7). Within the battery storages the energy is concentrated and stored at a specific place, the battery. As the battery systems deliver a DC voltage they are connected by an inverter with the energy grid.
If the energy is stored in chemical substances, which can be easily transported, the in- and output place of electrical energy must not be the same. This fact leads to additional degrees of freedom. Another advantage of chemical substances is that these can be used in other fields of energy conversation e.g. heat generation, mobility and industry. The conversion can be done by conventional combustion processs with generators or in fuel cells.

2.4.1 Lead-acid Battery Storage

The lead-acid (Pb) battery is a long developed technology, most popular as starter battery in vehicles. Advantages are the low cost and the availability of the materials. The disadvantage of low gravimetric energy density does not apply for stationary storage systems, but volumetric energy density is low as well.

2.4.2 Sodium-Sulfer Battery Storage

Sodium-sulfer batteries (NaS) have high temperature cells with operational temperatures 300-350°C. Furthermore due to the risk of reacting of sodium with water special safety arrangements are necessary. Besides that they are comparable with lead-acid batteries. But there is no self-discharge and additionally the cheap and good available basic materials are an advantage.

2.4.3 Lithium-Ion Battery Storage

Due to its high power density the lithium-ion battery is the preferred technology for hybrid and electrical vehicles. In this context the vehicle-to-grid (V2G) concept shows high potential as energy storage solution. There are several sub types of chemistry which can be distinguished e.g. Li-Ion, Li-polymer, $LiFePO_4$. The cost for the Li-Ion battery is still higher than other battery technologies, but it can be assumed that the prices will decrease due to volume effects in automotive mass production.

2.4.4 Redox-Flow Battery Storage

The redox-flow battery is different to the other battery technologies (Psola 2013). The energy is released by the reaction of two solutions. The reaction takes place in a cell stack, and the solutions are stored in tanks. Due to this behaviour the rated power and the capacity are independent. There are several subtypes based on the reactants, e.g. vanadium salts or zink-bromide.

2.4.5 Hydrogen

Hydrogen (H_2) is produced by electrolysis. The main principles are the alkaline electrolysis and the electrolysis with proton exchange membrane cells (PEM). The conversion to electrical energy can be done by combustion or in fuel cells. It is approved to mix up to 5% of hydrogen into the national gas grid, up to 15% is technical possible.

2.4.6 Methane

Methane (CH_4) that has been generated form Hydrogen and carbon dioxide is also referred to substitute natural gas (SNG). The volumetric energy density from methane is much higher than hydrogen, which makes it more valuable. However for the production hydrogen as well as a carbon dioxide source is needed. Due to that the cycle efficiency is reduced. The cost for SNG is actually about three times higher than for fossil methane. But there is an existing infrastructure for methane with huge storage capacities in the pipeline grid and the storage caverns.

2.4.7 Methanol

Methanol (CH_4O) has an even higher volumetric energy density than methane and it is in liquid state under normal conditions. It can be handled as gasoline or diesel in unpressurized stores. If the hydrogen is generated by electricity the process is similar to SNG, which means hydrogen and carbon dioxide are source materials. The fact that methanol, other than methane, does not exist in natural resources reduces the cost difference between conventional and sustainable production. Making sustainable methanol will be about two times more expensive.

	Cycle efficiency	Rated power	Capacity	Self-discharge	Lifetime
Pumped-Storage	70 – 85 %	10 – 1000 MW	up to 8000 MWh	neglectable	70 years
CAES	diabatic 30-54 % adiabatic 60-70%	10 – 600 MW	500 - 5000 MWh	-	30 years
Flywheel	90 – 95 %	5 kW – 5 MW	up to 2 MWh	up to 20%/ hour	20 years
SuperCaps	90 – 95 %	up to 200 kW	up to 50 kWh	0.5%/hour	*
SMES	90 – 95 %	10 kW -100 MW	up to 30 kWh	10-15%/day	30 years
Lead-acid	70 – 85 %	up to 20 MW	up to 10 MWh	5%/month	10-15 years
Sodium-sulfer	75 –90 %	up to 20 MW	up to 10 MWh	-	15-20 years
Lithium-ion	85 – 95 %	1 kW -1 MW	up to 1 MWh	5-10%/month	10-15 years
Redox-Flow	70-80 %	10 kW -10 MW	up to 100 MWh	neglectable	10 years
Hydrogen	20-40 %	kW - GW	GWh	neglectable	20 years
Methane	30-40%	kW - GW	GWh	-	20 years
Methanol	20-35%	kW - GW	GWh	-	20 years

Table 1
Energy Storage Data

3. Operational Concepts

3.1 Real Power Market Arbitrage

One Operational concept for energy storages is to gain arbitrage at energy markets. This means basically to store the electrical energy when the price is low (i.e. during off-peak hour) and to deliver electrical energy to the market during peak hours. However, self-discharge rate and cycle efficiency need to be considered, i.e. for per kWh stored only a certain amount can be delivered to the grid again.
It must be mentioned that under certain grid conditions (i.e. high generation by renewables and low demand) the price for energy at the market could be negative which is advantageous for arbitrage.
Storage requirements:

- High cycle efficiency
- Low self-discharge
- High capacity
- High rated power

3.2 Ancillary Services

Ancillary services do have requirements that need to be fulfilled in order to take part in this market. These services are subdivided into primary and secondary response reserve and replacement reserve.
For primary response reserve the full power has to be delivered within 30 seconds for up to 15 minutes. Therefore a fast response time is essential. The minimum rated power that can be offered is 1 MW.
As for secondary response reserve has to be delivered with full power at maximum after 5 minutes and the minimal offer is 5 MW.
And for replacement reserve the maximum power must be delivered 15 minute after the order. The minimal offer is also 5 MW

It can be seen that for the different ancillary services the minimum rated power is large and therefore some storage technologies are not appropriate. However these market segments offer much higher reimbursement for the energy then the normal energy market.
Storage requirements:

- High rated power
- High capacity
- Fast response time
- Low self-discharge

	Real Power Market Arbitrage	Ancillary Services		
		Primary	Secondary	Replacement
Pumped-Storage	X		X	X
CAES	X			X
Flywheel	X	X		
SuperCaps		X		
SMES		X		
Lead-acid	X	X		
Sodium-sulfer	X	X		
Lithium-ion	X	X		
Redox-Flow	X	X		
Hydrogen	X		X	X
Methane	X		X	X
Methanol	X		X	X

Table 2
Operational Concepts for Energy Storages

4. Conclusion

It can be seen that all energy storage technologies have specific operational behaviour according to which the operational concept has to be chosen. However to choose the right storage for a specific scenario a weighted parameter structure needs to be established for that case in order to classify the technologies. For example some technologies might not be possible due to geographical restrictions.
The chemical substances hydrogen, methane and methanol have very low cycle efficiency and their production by electrical energy is 2-4 times more expensive than by fossil sources. However theses substances have high volumetric energy densities and vast amounts of energy can be stored. Moreover they offer the possibility to be used for heating, the mobility sector as well as for industrial processes.
If renewable energy will reach 50% or more of the overall electricity production theses substances will be indispensable. Yet today battery storages offer the best support for the grid. These systems have free scalability, no geographical restrictions and can be used for ancillary services as well as to balance the local energy demand.

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