Energy Storage Technologies & Their Role in Renewable Integration

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Andreas Oberhofer
Research Associate, Global Energy Network Institute (GENI)
andreasoberhofer@gmx.de

Under the supervision of and editing by
Peter Meisen
President, Global Energy Network Institute (GENI)
http://www.geni.org
peter@geni.org (619) 595-0139

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1 Abstract

Today's world is at a turning point. Resources are running low, pollution is increasing and the climate is changing. As we are about to run out of fossil fuels in the next few decades, we are keen to find substitutes that will guarantee our acquired wealth and further growth on a long term basis. Modern technology is already providing us with such alternatives like wind turbines, photovoltaic cells, biomass plants and more. But these technologies have flaws. Compared to traditional power plants they produce much smaller amounts of electricity and even more problematic is the inconsistency of the production. The global demand for electricity is huge, and it's growing by approximately 3.6 percent annually[1], but the sun isn't always shining nor is the wind always blowing. For technical reasons, however, the amount of electricity fed into the power grid must always remain on the same level as demanded by the consumers to prevent blackouts and damage to the grid. It leads to situations where the production is higher than the consumption or vice versa. This is where storage technologies come into play — they are the key element to balance out these flaws.

With the growing importance of renewable energy sources, scientist and engineers are anxious to enhance efficiencies and to lower the costs of these technologies. Yet, there seems to be only a handful of technologies available that are efficient enough and also economical. Storing energy isn't an easy task, as most of us know. Our smartphone battery only lasts for about a day laptops only a few hours; the range for electric cars is limited to only little more than a 100 kilometers; and these are only examples for comparatively small devices. Now imagine the problem of storing energy at the level of hundreds to thousands of wind turbines and photovoltaic cells.

The way we handle the fluctuating energy demand today works fine – for now. But, as we approach the point of peak oil faster and faster, and as we are trying hard to replace these conventional plants with regenerative energy sources, the grid changes, whereas the demand will remain about the same. With renewable energy, the production is fluctuating in a way that is hardly predictable. We may be able to predict the weather for the next few days, but as we all know, the weather forecast isn't always right and even then, a few days isn't enough to calculate in the context of a national or even transnational power grid to guarantee a secure energy supply. Also, when the wind stops, it stops, foreseeing it won't change the fact that wind turbines won't produce the energy we need. So, there is a need to find ways to compensate for this fluctuation, to save the energy in times of sunny and

[1] http://www.engineeringnews.co.za/article/electricity-consumption-to-increase-to-over-30-116-b-kwh-globally-in-2030-2009-04-17

windy days and use it for cloudy and windless days. Technology to do so exists, and we even use them today, but its capacity is not enough by a long shot – not if we're planning to go green and sustainable. The problem emerging is that we can't just simply build more of the existing storage technologies as each technology has its own flaws. For example, pumped hydro storage, the most reliable and so far only economical storage technology available, is extremely limited by few potential sites and strict laws on nature conservation.

In the following chapters I'll be introducing some basic knowledge of power grids, the most important storage technologies so far, as well as a critical observation of their benefits, problems and possible impacts in the future; and a small glance at promising technologies still in their development and pilot phases.

2 The Electric Grid

Power Generation

Electrical power usually starts at power plants. Although it may be coal, gas or even nuclear power, almost every conventional plant produces electrical energy through steam powered turbines. The fossil fuels are burned in order to make water boil and turn into steam which then enters the turbine and pushes against blades to turn the generator shaft to create electric current. Right after the turbine, the steam is usually cooled down and turned into liquid form again in order to increase efficiency.

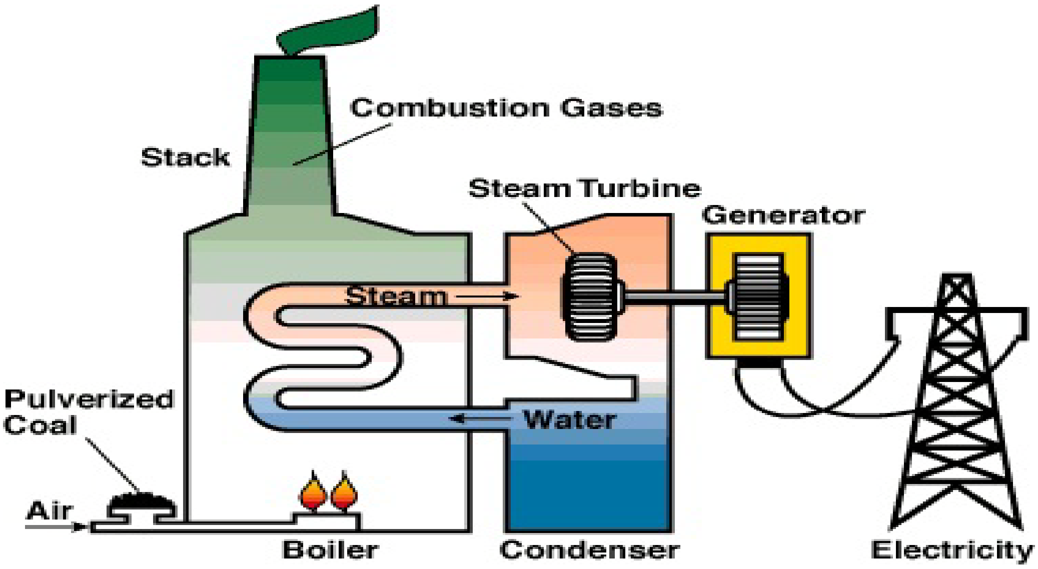

Figure 1: Steam powered power plant

Source: http://www.oncor.com/community/knowledgecollege/energy_library/generating/generating01.aspx

Transmission and Distribution

Power plants aren't located right next to your house, they tend to have sites where noise and emissions aren't disturbing issues for the population and near rivers for cooling purposes. So, in order to transport the electricity from the plants to the demanding locations an electrical grid is needed. To minimize dissipation over long distance and to guarantee safety and functionality, different transmission grid types exist using different voltages. The closer the power gets to the consumer, the more the voltage decreases in the following order:

- **Extra High Voltage Grid**: Electricity is transformed into voltages higher than 220 kilovolts (kV) in order to keep energy losses to a minimum when transporting over long distances. These lines can run hundreds to thousands of kilometers and deliver the power into the common grid but are also used for transnational exchange.

- **High Voltage Grid**: Transformer stations transform the power to lower voltages, usually between 60 and 220 kV. These lines are supposed to carry the electricity into different regional areas with high population density or bigger industrial areas.

- **Distribution Grid**: Voltages rank between 6 kV – 60 kV. Its main task is to provide major institutions like facilities, schools or hospital and the transformer stations responsible for low voltage grids delivering to private households.

- **Low Voltage Grid**: Often referred to as the "last mile". Voltages between 110V – 400V are common. The low voltage grid is the last station of the transmission and provides private households with power to use for everyday electronic devices.

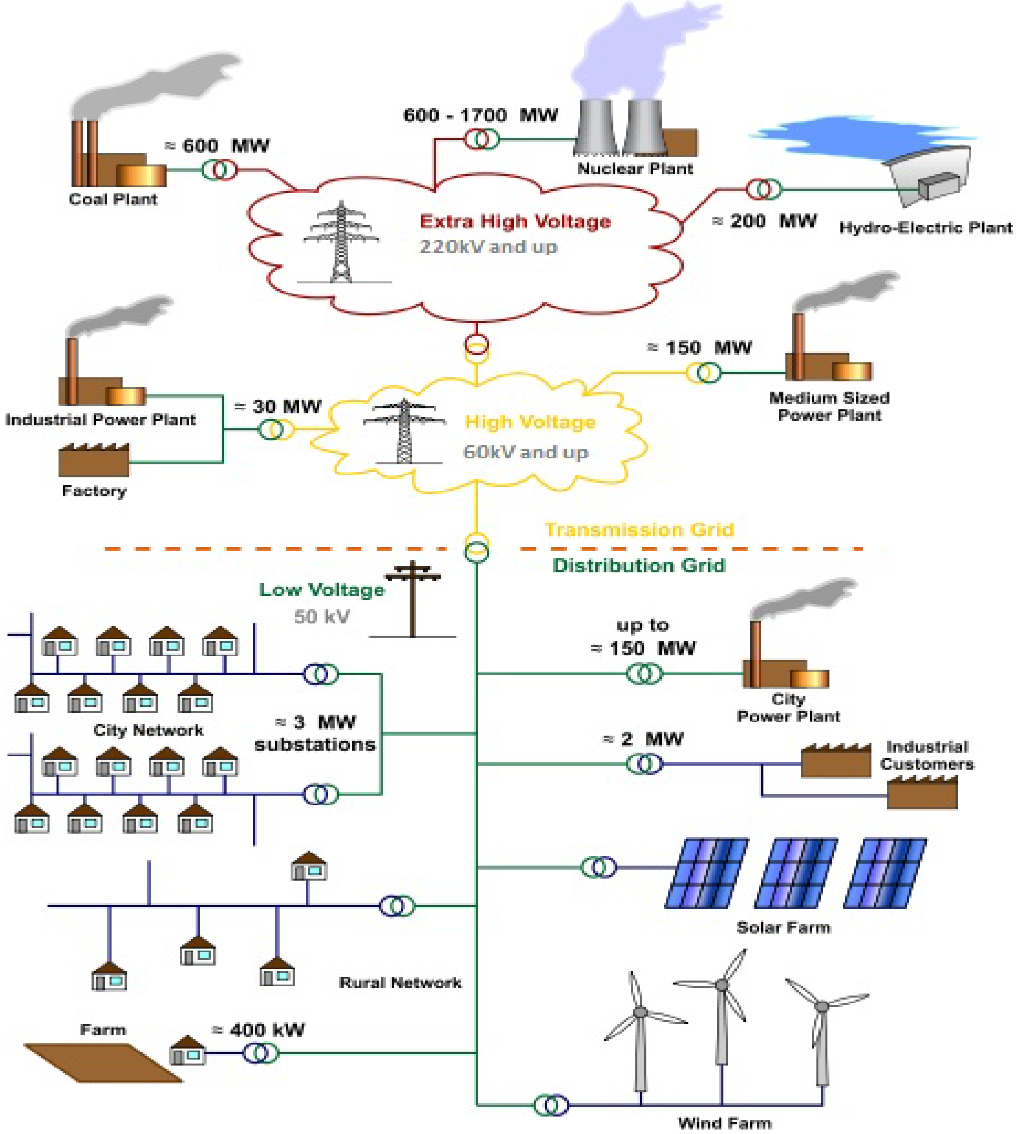

Figure 2: Schematic of a transmission grid

Source: Modified from http://en.wikipedia.org/wiki/Electrical_grid

Load Management

As mentioned before, it is necessary to produce the almost exact amount of electricity that is demanded by customers. In order to maintain grid stability, a frequency of 50 or 60 hertz (Hz) (depending on the country's standard) must be generated. Higher deviations (± 2.5 Hz) will result in causing damage to the generators.

The curve progression varies over the day; but, behavior is usually steady and pretty well known for each day and is used as a road map for production along general lines. For example, the need for electricity during the night is low whereas at noon, when everybody starts cooking, it is at its peak.

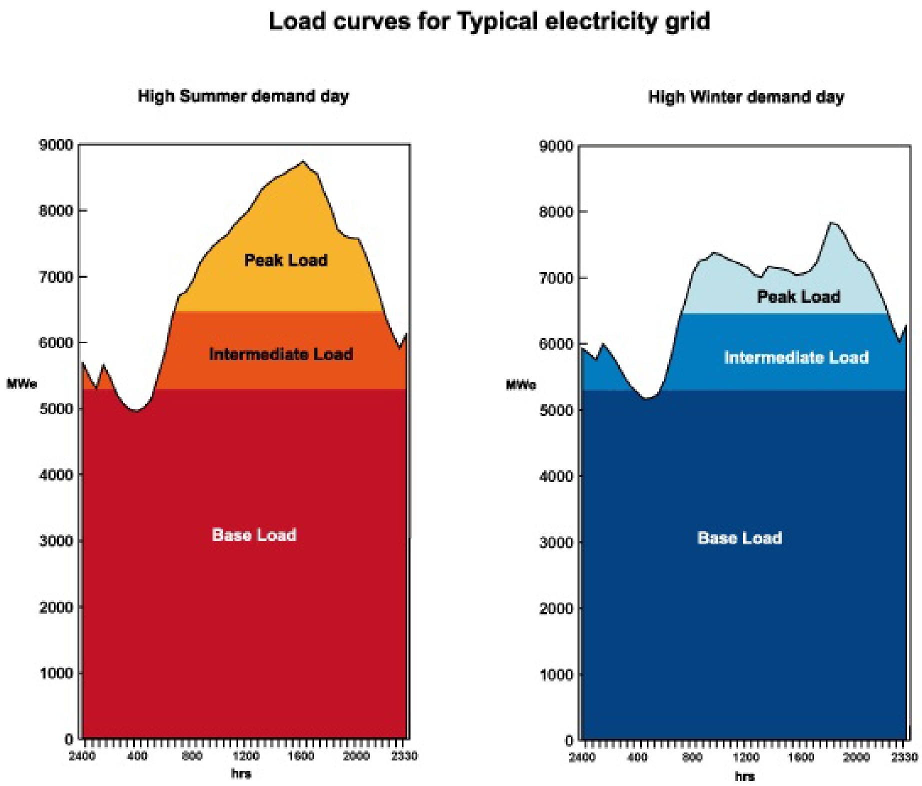

Figure 3: Load curves for typical electricity grid

Source: http://www.world-nuclear.org/info/inf10.html

The figure above shows the concept of a load management which is separated into three different types:

- **Base Load**: This is the amount of electricity that is demanded and produced at any time. Nuclear, hydroelectric power or brown coal plants are known and common to use as base load plants due to the long startup time and/or the low operating and fuel costs.

- **Intermediate Load**: Power plants that are easier and faster to regulate are used for the task of middle load. These plants are capable of working within minutes to an hour and have moderate operating costs. Black coal or wind plants are typical of middle loads.
- **Peak Load**: Peak load is the power demand outside of the daily "road map." Different events like unexpected hot and sunny days can lead to an extended use of air conditioners and therefore a higher electricity demand. Peak load plants have a fast response time, which means they're operational within seconds to a few minutes. A typical example would be gas turbine power plants or pumped-storage hydroelectricity.

Hydroelectric power plants are technically qualified for peak load but are used for base load instead because not using the already flowing water would be a waste.

Middle load plants can be and are also used for this task, when not operated under full load they bear reserves. In some countries like Germany, it is statutory that a certain amount of power plants must have these reserves for supply security reasons. Operating power plants on lower degrees however is to be avoided if possible as the efficiency of the turbines decreases.

3 Types of Storage Technologies

3.1 Flywheels

Concept

The functionality of a flywheel system is quite simple and you may have even played with it when you were kid. Remember the toy cars that kept going after spinning their wheels? Those were powered by a flywheel. So, basically a flywheel is a disk with a certain amount of mass that spins, holding kinetic energy.

Modern high-tech flywheels are built with the disk attached to a rotor in upright position to prevent gravity influence. They are charged by a simple electric motor that simultaneously acts as a generator in the process of discharging.

When dealing with efficiency however it gets more complicated, as stated by the rules of physics, they will eventually have to deal with friction during operation. Therefore, the challenge to increase that efficiency is to minimize friction. This is mainly accomplished by two measures: the first one is to let the disk spin in a vacuum, so there will be no air friction; and the second one is to bear the spinning rotor on permanent and electromagnetic bearings so it basically floats. The spinning speed for a modern single flywheel reaches up to 16.000 rpm and offers a capacity up to 25kilowatt hours (kWh), which can be absorbed and injected almost instantly.

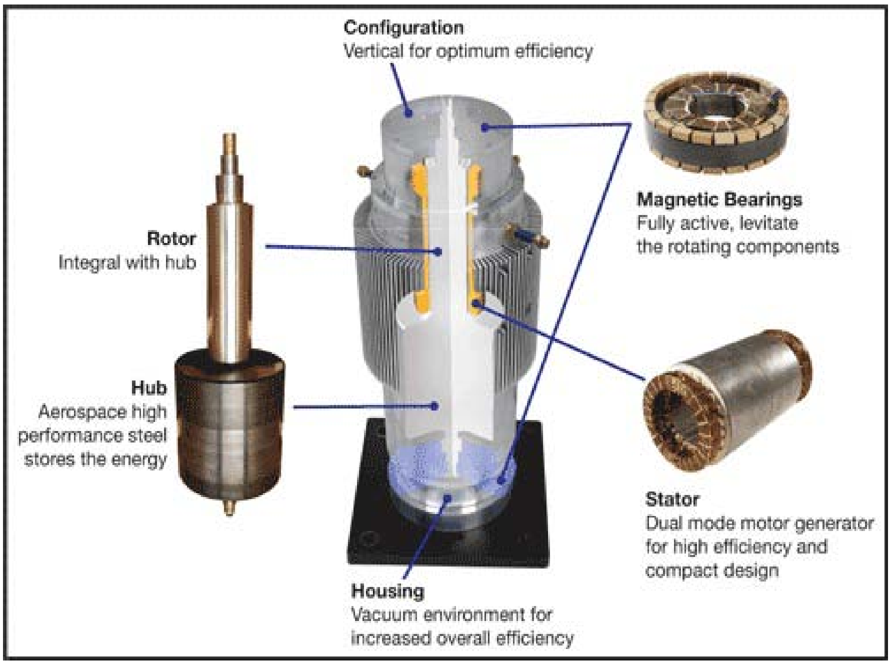

Figure 4: Inside of a flywheel

Source: http://www.acsystems.com/vycon/

Pros and Cons

- ✚ Low maintenance and long lifespan: up to 20 years
- ✚ Almost no carbon emissions
- ✚ Fast response times
- ✚ No toxic components
- ▬ High acquisition costs
- ▬ Low storage capacity
- ▬ High self-discharge (3 –20 percent per hour)

Future Prospects

Stephentown, New York is successfully operating the largest and latest flywheel energy storage system since July, 2011. The facility is capable of storing up to 5 megawatt-hours (MWh) with its 200 flywheels for several hours and required a budget of roughly $60-million[2]. This storage system has several advantages compared to others, most notable the low maintenance costs, the fast access to the stored energy and the fact that you don't need any toxic resources as well as almost no carbon emissions. On the downside stands the low capacity compared to systems like the pumped hydro storage and the high acquisition costs, though compensated by the low maintenance and duration of up to 20 years[2]. The project in Stephentown will show if flywheels are as good and economical as promised. Due to the high costs and low capacity however it is likely that the flywheel technology will remain a niche market that requires fast response times as the high storage needs can-not be met by them.

On a side note: In lower terms, flywheels could be used in the transport sector to make vehicles more efficient by using their kinetic energy to charge them and therefore lower the need for energy through fuel. The Formula 1 is currently successfully making use of this technology (kinetic energy recovery system –KERS) but to improve power, not efficiency.

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2 http://investors.beaconpower.com/releasedetail.cfm?ReleaseID=593208

3.2 Superconducting Magnetic Energy Storage (SMES)

Concept

The system consists of three major components: the coil, the power conditioning system (PCS) and a cooling system. The idea is to store energy in the form of an electromagnetic field surrounding the coil, which is made of a superconductor. At very low temperatures, some materials lose every electric resistance and thus become superconducting. The superconducting magnetic storage system (SMES) makes use of this phenomenon and – in theory – stores energy without almost any energy loss (practically 90 – 95 percent efficiency).

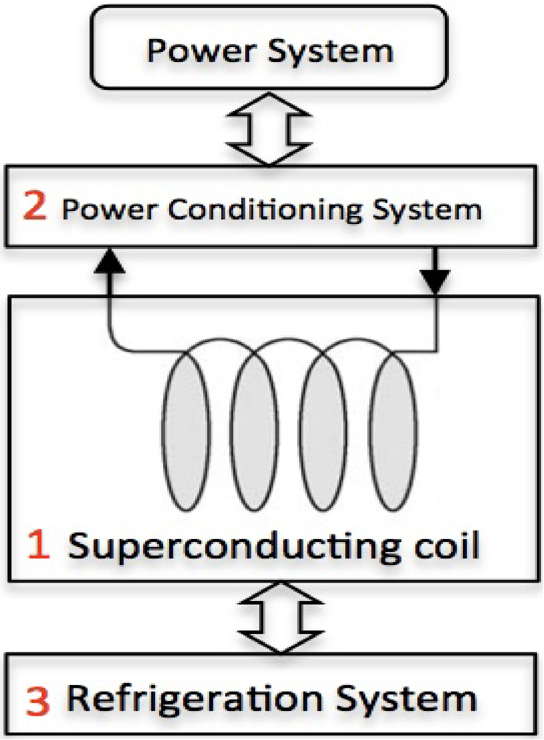

Figure 5: Components of a SMES system

Source:http://www.lowcarbonfutures.org/assets/media/SMES final.pdf

However, since relevant superconducting materials are only known to work below -253° centigrade (C) (20° kelvin [K]) (e.g. niobium-titanium -264° C [9° K], niobium-tin -255°C [18 K]) a system to cool the components down to those temperatures is required. This can be accomplished by liquefying helium; but, it is very expensive and the process lowers the efficiency, especially in stand-by mode. New high-temperature superconductors have been in development since 1986 reaching the state of superconductivity already at −163°C (110° K), allowing them to be cooled by liquid nitrogen and thereby lowering the costs by a factor of 10 –20. Known production methods for these materials however make them very brittle and difficult and expensive to process.

The PCS is the interface between the SMES coil and the power system. Its task is to convert alternating current (AC) into direct current (DC) and vice versa since the coil is only capable of storing and releasing the energy in the form of DC.

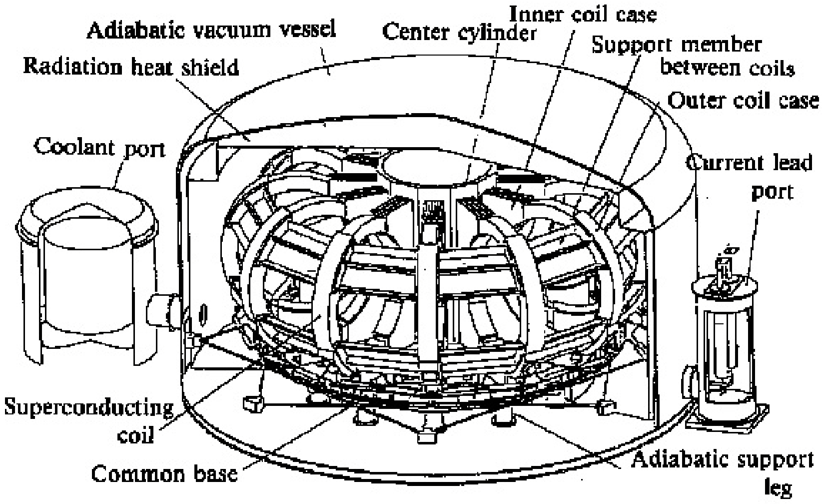

Figure 6: Conceptual design of a superconducting coil

Source: http://www.wtec.org/loyola/scpa/02_06.htm

Pros and Cons

- ✚ Fast respond times
- ✚ Capable of partial and deep discharges
- ✚ No environmental hazard
- − High energy losses (~12 percent per day)
- − Very expensive in production and maintenance
- − Reduced efficiency due to the required cooling process

Future Prospects

Future prospects are difficult to determine because they depend on further development in superconducting materials. The discovery of a suitable material with these properties on room-temperature would change nearly anything (hence, the consideration for being the Holy Grail of physics) and would make energy storage and transmission easy, safe and cheap. However, it is uncertain if such a material even exists.

Right now, SMES systems are pretty much like flywheels, considered a niche market, requiring fast response times. Because of the difficult and expensive procedure to process high-temperature superconductors, it is expected that low-temperature materials will come to action in short and medium terms. Right now, the development focus lies on micro-SMES systems with capacities up to 10 kWh, applied mainly for power quality and uninterrupted power sources (UPS) and therefore of no relevant significance for renewable energies right now. Further technological improvements and achievements in processing high-temperature superconductors could change the course and make SMES systems more economical and relevant for energy storage in the future though.

3.3 Batteries

A battery is a device that produces electrical energy from chemical reactions. There are different kinds of batteries with different chemicals. The idea behind them is that the two different chemicals within a battery cell have different loads and are connected with a negative (cathode) and the other with a positive electrode (anode). When connected to an appliance the negative electrode supplies a current of electrons that flow through the appliance and are accepted by the positive electrode. For the use of storing energy produced by renewable energy sources only rechargeable batteries are relevant and will be considered.

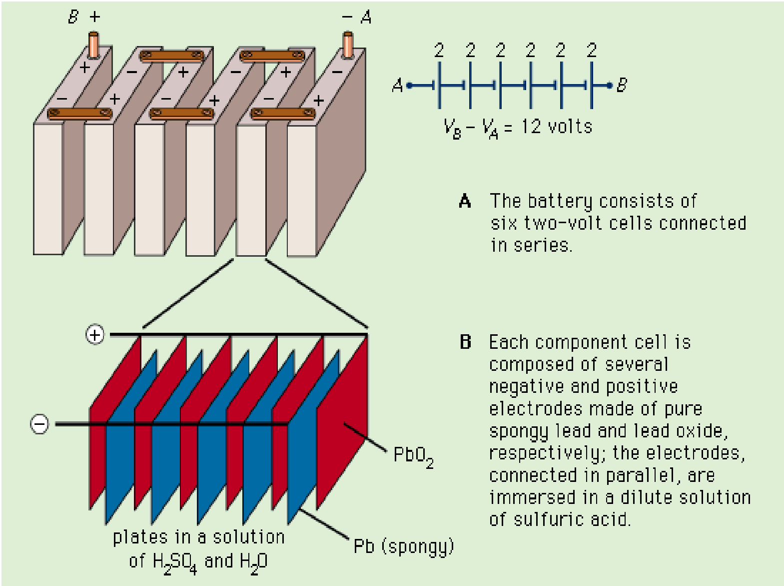

Figure 7: The inside of a lead-acid battery

Source: http://www.wholesale-electrical-electronics.com/p-solar-battery-np12-200ah-12v-200ah-855419.html

3.3.1 Lead-Acid Batteries

The lead-acid battery is the oldest known type of rechargeable battery and was invented in 1859 by the French physicist Gaston Planté. Even though the concept is over 150 years old the lead-acid battery is still known for its cost-effectiveness today. They are often used in cars (as starter batteries, known as SLI batteries), wheelchairs or golf carts.

Concept

A lead-acid battery usually has several in-series connected cells, each delivering 2 volts (V) and each consisting several spongy pure lead cathodes, positive loaded lead oxide anodes and a 20 –40 percent solution of sulfuric acid that acts as an electrolyte. When discharged, both the anode and the cathode undergo a chemical reaction with the electrolyte that progressively changes them into lead sulfate that releases electrical energy in the process. This reaction can be almost completely reversed by supplying the electrodes with electricity, which is the reason a lead-acid battery can be recharged.

The cycle life and the ability to tolerate deep discharges depend on the type. Starting-lighting-ignition (SLI) batteries used in cars are not designed to be discharged to more than 50 percent as they have thinner lead plates. Doing so on a regular base will damage them and shorten their cycle life dramatically, whereas deep cycle batteries with thicker plates can handle this much better but are as a result heavier and bulkier.

Pros and Cons

- ✚ Easy and therefore cheap to produce
- ✚ Mature technology, more than 150 years of experience and development
- ✚ Very high surge-to-weight-ratio; capable of delivering a high jolt of electricity at once, which is why they are so suitable as car starters
- ✚ Easily recyclable
- ▬ Very heavy and bulky
- ▬ Rather short lived
- ▬ Environmental concerns: although pretty safe, lead is very toxic and exposure can cause severe damage to people and animals
- ▬ Corrosion caused by the chemical reactions

Future Prospects

Lead-acid batteries have pretty much reached the end of the rope in terms of development. It is clear that no significant improvements can be made in capacity, density or weight. Therefore, resources on future development should concentrate on other battery technologies with higher potentials.

Nonetheless because of the cost-effectiveness, lead-acid batteries are an important part of today's technology systems that can't be denied. Until other battery technologies emerge, they will remain first choice for many applications; however, grid storage is unlikely to be one of them simply because these batteries are not capable of storing huge amount of energy compared to other systems like a Pumped Storage Hydroelectricity plant (PSH), while staying cost effective as the energy density is just too low. It is possible to integrate battery banks for few smaller decentralized systems (like photovoltaic [PV] systems on rooftops); but, it can't be used as a definite solution, just for the simple reason that the amount of resources are not available for the required capacity scale. Also, these batteries have a limited life cycle of a few years; and therefore, have to be replaced by new ones.

Future prospects and outlooks for other battery technologies and development indicate that lead-acid based batteries will probably play the role of a inexpensive transitory technology.

3.3.2 Lithium-Ion Batteries

Concept

Lithium is the lightest metal with the highest potential due to its very reactive behavior, which, in theory, makes it very fitting as a compound for batteries. Just as the lead-acid and most other batteries the Lithium-Ion battery by definition uses chemical reactions to release electricity. Although all are called lithium-ion batteries, there's a variety of types with slightly different chemical compounds. The construction looks somehow similar to a capacitor, using three different layers curled up in order to minimize space. The first layer acts as the anode and is made of a lithium compound; the second one is the cathode and is usually made of graphite. Between anode and cathode is the third layer – the separator that, as suggested by the name, separates them while allowing lithium-ions to pass through. The separator can be made of various compounds allowing different characteristics and with that, different benefits and flaws. In addition, the three layers are submerged in an organic solvent – the electrolyte, allowing the ions to move between the anode and the cathode.

In the charging process, the lithium ions pass through the microporous separator into spaces between the graphite (though not compounded), receiving an electron from the external power source.

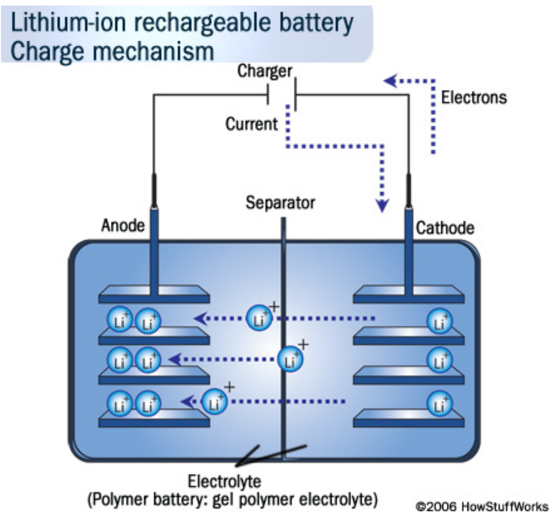

Figure 8: Charge of a lithium-ion battery

Source: http://electronics.howstuffworks.com/everyday-tech/lithium-ion-battery1.htm

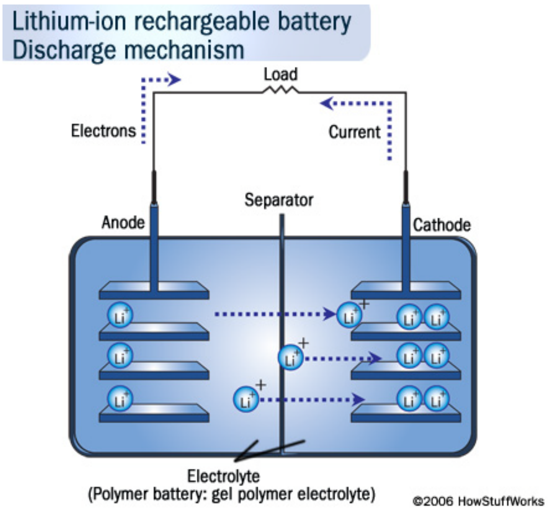

Figure 9: Discharge of a lithium-ion battery

Source: http://electronics.howstuffworks.com/everyday-tech/lithium-ion-battery1.htm

During the discharge process the lithium atoms located between the graphite release its electrons again that migrates over the external circuit to the anode providing a current. The lithium ions move back to the anode as well, parallel to their released electrons.

Because lithium is a very reactive compound and can burst into flames, safety measures have to be included, such as onboard control chips to manage the temperature and prevent a complete discharge.

Pros and Cons

- ➕ Highest energy density in commercial available batteries with huge potential
- ➕ Provides higher voltages per cell (3.7V compared to 2.0V for lead-acid)
- ➕ Low energy loss: only about 5 percent per month
- ➕ Lithium and graphite as resources are available in large amounts
- ➖ Very expensive
- ➖ Complete discharge destroys the cells
- ➖ Deteriorates even if unused (Lifecycle of about 5 years)
- ➖ Lithium is flammable in contact with atmospheric moisture

Future Prospects

Lithium-ion batteries would be suitable for storing large amounts of energy if it weren't for the costs. The rather expensive processing and the safety measures make them too expensive for commercial use besides small electronic devices like smartphones and laptops. Even for small decentralized systems, competitors like lead-acid batteries are more cost-effective right now, although that will change as they become cheaper.

However, lithium-based batteries have an incredibly huge potential. IBM is currently working on a project called *Battery 500*. This project's goal is to develop a battery using lithium and the air of the atmosphere as components (both the two lightest elements suitable for this purpose), capable of storing enough energy to power an electric car for 500 miles (~804 kilometers).[3] Commercial use is targeted somewhere between 2020 and 2030 as there are still a lot of obstacles to overcome.

[3] http://www.ibm.com/smarterplanet/us/en/smart_grid/article/battery500.html

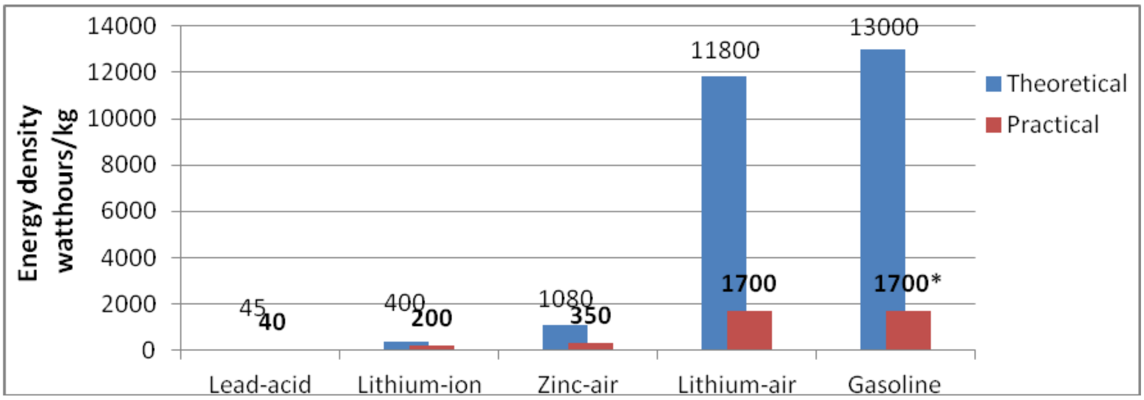

Figure 10: Comparison of energy densities

*in a combustion engine

Data source: several

Besides the ambitious IBM project, several other companies worldwide are working and experimenting on new suitable compounds for lithium-based batteries and it is very possible that this technology will reach a point where it becomes cost-effective for storing grid energy.

Despite the ongoing rumor, lithium is not short in supply and, even though in small amounts (0.1-0.2 parts per million [ppm]), it is available in saltwater and can be extracted through technical methods, making the supply almost infinite.

3.3.3 Other Batteries in Development

Redox-Flow Battery

These batteries technically are similar to conventional batteries, except that the electrolytes (there are different forms, using one or two different fluids) can be exchanged, meaning that if the battery is discharged the fluids are replaced with loaded ones. This concept could, in theory, become very handy for electric cars as you could charge your car simply by refueling just as you do now. However, the energy density is about 35 Watt-hours per kilogram (Wh/kg) in the same region as lead-acid batteries right now and therefore considerately low, although the Fraunhofer Institute in Germany claims to have managed to increase density up to the level of lithium-ion batteries (200 Wh/kg). Other advantages are the long life span of roughly 40 years and the fact that capacity can be increased by simply increasing the tanks and adding more electrolytes.

For the purpose of grid storage, there are commercial available plants; but, the value is limited similar to flywheels, SMES or other battery storage types due to the yet low energy density. Pilot projects are in operation, most recently in California for an agricultural processing facility with a capacity of 3.6 MWh.[4]

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[4] http://www.sustainableplant.com/2012/05/vanadium-flow-battery-to-provide-grid-level-storage-for-gills-onions/

Sodium Battery

The liquid sodium sulfur battery is yet another type of battery in development, but already operational in some countries like Japan. About 250 Megawatts (MW) of sodium battery power have been installed there.[5] Sodium batteries have the advantage of a relatively high density with up to 240 Wh/kg, a long life span of 10 – 15 years and high efficiency (75 – 90 percent); but, they need to be operated at high temperatures (350° C/623° K) to get the sodium liquid, which not only makes it more difficult and expensive to operate but also more dangerous as the liquid sodium reacts easily with the water in the atmosphere. Since the Nippon Tokusyu Tōgyō Kabushiki-gaisha Co. LTD (NGK) and the Tokyo Electric Power Co. LTD (TEPCO) began shipping out sodium batteries in 2002, three incidents resulting in fires have occurred, setting the development back.

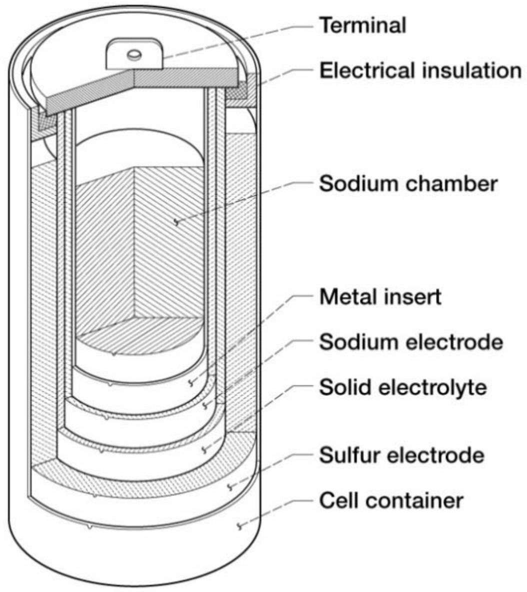

Figure 11: Inside of a sodium battery

Source: http://en.wikipedia.org/wiki/File:NaS_battery.png

Zinc-air Battery

Just like the lithium-air battery, the zinc-air battery uses air as a second component. Zinc-air has been a focus in development for a while because of its safety aspects and potential in density; but, was dropped due to the low efficiency and short life cycles. Two independent companies claim to have solved these problems and plan to begin small-scale field tests this year, but have yet to present reliable data.[6, 7]

Zinc-air, just like lithium-air ,holds potential for grid storage due to its density and the fact that zinc is a commonly found metal, But as long as no data is presented and no field tests have been made it remains as an idea with theoretical potential.

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5 http://www.greentechmedia.com/articles/read/is-sodium-the-future-formula-for-energy-storage/

6 http://phys.org/news/2012-01-eos-zinc-battery-recipe-energy.html

7 http://www.treehugger.com/clean-technology/very-promising-zinc-air-battery-could-hold-300-more-energy-than-lithium-ion.html

3.4 Pumped Storage Hydroelectricity (PSH)

Pumped hydro plants, so far, is considered to be the only possible way to store energy in a huge amount while maintaining a high efficiency and being economical as well and has about 98 percent share of total global storage predominant in today's grid.[8] The first plants of this type were built in Switzerland and Italy in the 1890s, making the concept over a hundred years old.

Concept

When you lift an object of a certain mass you overcome gravity. In order to do so you must supply a force over a height. The force required to lift is defined by the physical law $F = m * a$ (*m* for mass and *a* for acceleration), but in this case *a* is replaced by g for the gravitational acceleration (9.81 meters per square second [m/s^2]). The work, meaning the energy supplied and therefore stored in the object is defined by $W = F * d$ (in this example the term d for distance can be replaced by h for height). This results in $W = m * g * h$, meaning the energy stored equals the mass multiplied by the gravity and the height.

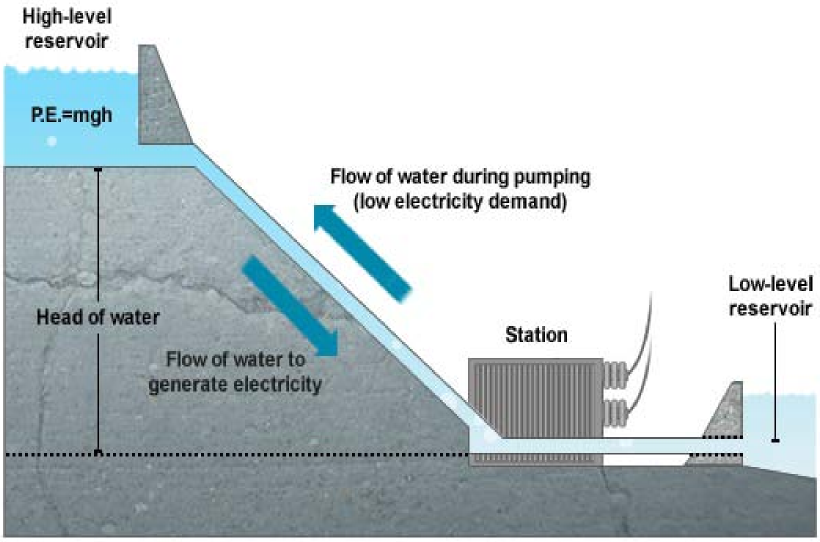

Figure 12: Schematic of a Pumped-Storage Plant

Source:http://www.bbc.co.uk/scotland/learning/bitesize/standard/physics/energy_matters/generation_of_electricity_rev3.shtml

A PSH plant puts this math into practice. Basically, the system contains two water reservoirs at different elevations. In times of low electricity demand and high production, water is pumped from the lower reservoir into the higher, storing the electricity in the water in the form of potential energy. When needed, for example on peak demand, the water can be

8 http://energy.gov/sites/prod/files/oeprod/DocumentsandMedia/FINAL_DOE_Report-Storage_Activities_5-1-11.pdf

released, flowing down the pipes again and back through the turbine which then generates the electricity. The general formula for the power output is $P = Q * h * \eta * g * \rho$, including the factors of volume flow rate passing the turbines (Q), the hydraulic efficiency of the turbine (η) and the density of the water (ρ).

Depending on the height difference, Pelton Wheels, Kaplan or Francis Turbines are used to maximize efficiency, each reaching roughly about 90 percent. These turbines are reversible and, therefore, capable of handling both the pumping and generating process.

Capacities for PSHs are depending on the location and scale of the reservoirs as well as the altitude difference and can reach from a few MWh to several GWh.[9]

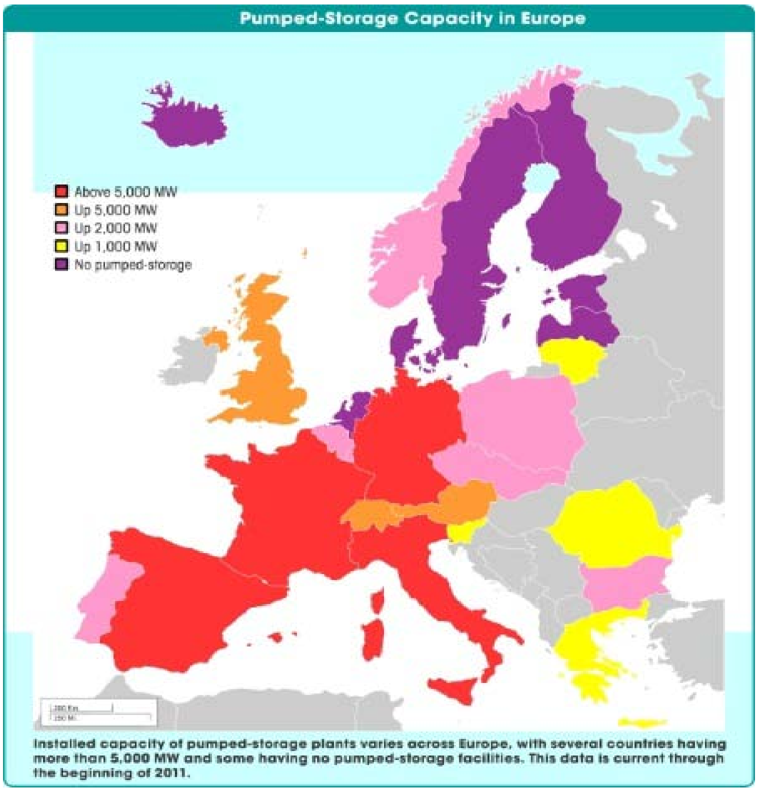

Figure 13: Map of pumped storage capacities in Europe

Source: http://www.renewableenergyworld.com/rea/news/article/2011/08/renaissance-for-pumped-storage-in-europe

Pros and Cons

- ✚ Mature technology, capable of storing huge amounts of energy
- ✚ High overall efficiency (around 70-80 percent)
- ✚ Fast response times
- ✚ Inexpensive way to store energy

[9] Bath County Pumped Storage Station, Virginia, USA is currently the largest PSH worldwide with a storage capacity of 30GWh and a 3GW power output.

- Few potential sites
- Huge environmental impacts
- Requires a significant huge water source

Underground Pumped-Storage Hydroelectricity

German scientists and engineers are working on the feasibility of a PSH using old unused coal or salt mines as the lower reservoirs. This kind of storage would minimize environmental impact as most of the intervention would be underground. Depending on the circumstances, even the upper reservoir could be built in the caverns. However realizing such a project underground is more difficult and expensive than conventional PSHs; but, both mining and PSH technologies are well explored and mature. They just haven't been combined yet. Though in theory a pleasant idea, practical implementation poses a lot of problems as no field tests have been made yet. Also, pumping huge amounts of water up and down with high pressures could hold the risk of fracturing the soil and in the worst case even collapse. More research and at least one field test will need to be conducted before larger projects will be considered. Right now, the focus of the big energy players still lies on the conventional plants as they are cheaper and easier to realize. But, with the diminishing number of potential sites, the idea of underground solutions will eventually become a focus point.

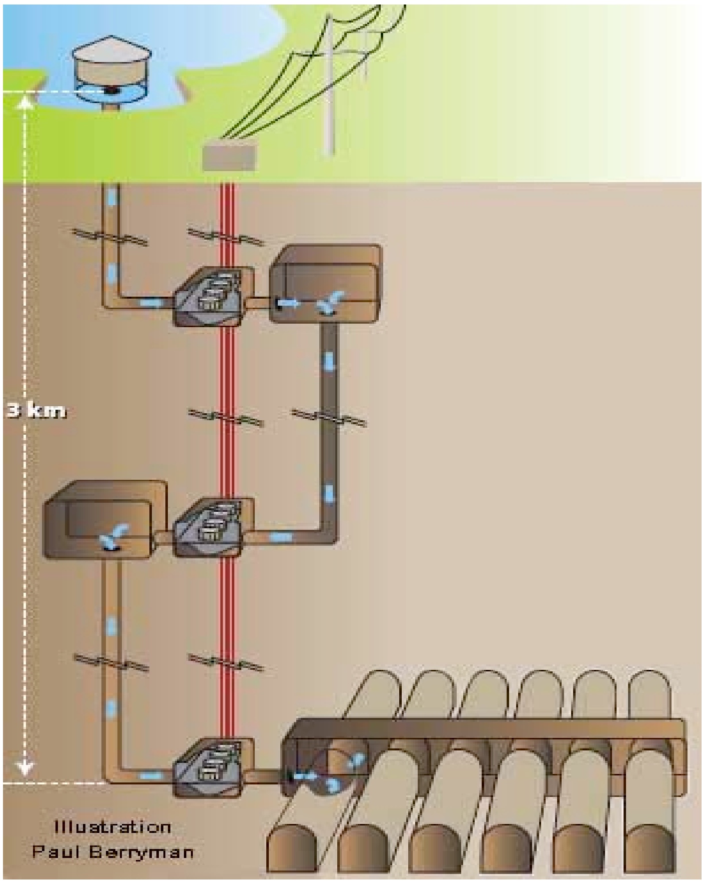

Figure 14: Schematic for an underground PSH

Source:http://greentransportandenergy.blogspot.com/2009/04/underground-pumped-hydro-storage-to.html

German power plant operator Energie Baden-Württemberg AG (EnBW) has expressed plans to upgrade its plant in Forbach with a third reservoir located in an underground cavern, making it a 3-level plant and the first of its kind using an underground cavern.[10]

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10 http://www.enbw.com/content/de/der_konzern/enbw/ausbau_pumpspeicher/projektvorstellung/index.jsp

Future Prospects

PSH were originally built as control power plants to regulate the power supply. Back then the need for control energy was considerately low as the conventional power plants delivered a stable energy output, but with the renewable energies emerging PSH plants are now have a whole new relevance. As previously stated, other technologies still need time, development and breakthroughs to be competitive with pumped hydro plants, which is the reason the big energy companies still must rely on this technology. This wouldn't be a big problem if it wasn't for the requirement of a high altitude difference with steep falls, which limits the potential sites to very few in the mountains in most countries. Exceptions are countries with mountainous landscapes like Norway, which almost completely draws its power from hydro facilities. Although Norway is one of the few countries who can claim to be 100 percent renewable, it came with a price. Hilltops have to be blasted, damns concreted and valleys flooded in order to build hydro facilities, damaging the environment and fauna permanently. Eagles and hawks have left regions in Norway where plants have been built. They are a reliable indicator for environmental issues as they are at the end of the food chain. Thus the refusal of the Norwegian Union for Industry and Energy on European plans to make them the battery for Europe in the future as they still have several potential sites left. In addition to environmental issues, further energy losses at a minimum of 10 percent will have to be accepted for the transmission grids connecting Norway to the rest of Europe. It remains to be seen if and to what degree Norway will make concessions in the future.

The increasing demand for storage will definitely lead power plant operators to use every possible and economical site they're allowed to and upgrade and modernize existing older plants to improve capacity and efficiency. Countries with a mining history will certainly give underground PSH a shot at some point as soon as enough research has been done.

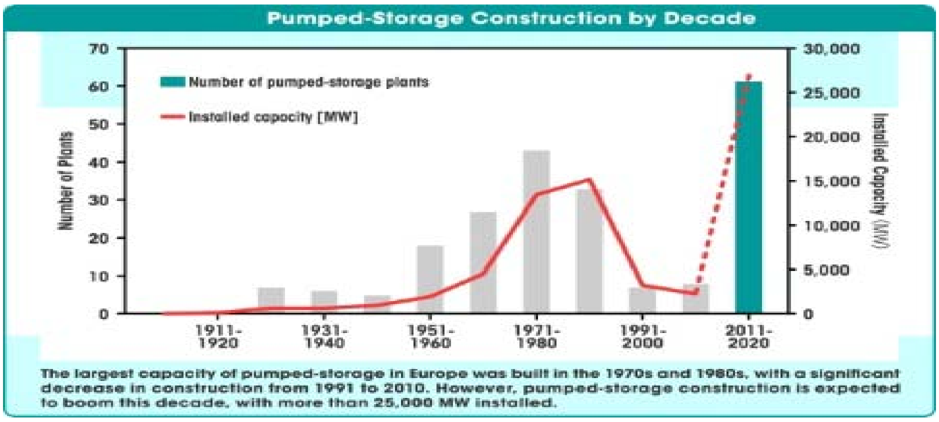

Figure 15: Pumped storage constructions through the years and future expectations

Source: http://www.renewableenergyworld.com/rea/news/article/2011/08/renaissance-for-pumped-storage-in-europe

3.5 Compressed Air Energy Storage (CAES)

CAES plants store energy in form of compressed air. Only two plants of this type exist worldwide, the first one built over 30 years ago in Huntorf, Germany with a power output of 320 MW and a storage capacity of 580 MWh. The second one is located in McIntosh, Alabama, USA and began operation in 1991 with a 110 MW output and 2860 MWh of storage capacity. Both are still in operation.

Concept

The basic idea is to use an electric compressor to compress air to a pressure of about 60 bars and store it in giant underground spaces like old salt caverns, aquifers or pore storage sites and to power a turbine to generate electricity again when demanded. These cavern storages are sealed airtight as proved by the existing two plants and have also been used to store natural gas for years now.

However, the concept has two major problems when it comes to pressuring air. First, compressing the air leads to a very significant amount of heat generation and subsequent power loss if unused. In addition, the air will freeze the power turbine when decompressed. Therefore, both the existing plants in Huntorf and McIntosh use a hybrid concept with gas combustion as gas turbine power stations require compressed air to work efficiently anyway. Instead of using the combustion of the gas to compress the air like in a conventional gas turbine[11], the stored air in the caverns can be used, meaning that, technically, these CAES plants both store and produce electricity.

Advanced Adiabatic Compressed Air Energy Storage (AA-CAES)

Currently in development phase is the first ever AA-CAES plant called ADELE[12] in Germany under the direction of the Rheinisch-Westfälisches Elektrizitätswerk AG (RWE) and in cooperation with General Electric (GE), Züblin AG and the German Aerospace Center (DLR).[13] Construction is planned to begin around 2013 in Staßfurt, Germany with a storage capacity of 1GWh and an output of 200 MW.

The notable difference to existing CAES plants is that the heat produced by the compressing process, which reaches up to 600°C (873 K) was dissipated into the environment. Now it is now transferred by heat exchangers and stored in heat storage sites. During the

[11] http://www.youtube.com/watch?v=grPzZ39ZyUI

[12] ADELE stands for the German acronym for adiabatic compressed air energy storage for electricity supply

[13] http://www.rwe.com/web/cms/de/365478/rwe/innovationen/stromerzeugung/energiespeicherung/druckluftspeicher/projekt-adele/

discharge, the heat-storage releases its energy into the compressed air so that no gas co-combustion to heat the compressed air is needed in order to prevent the turbines from freezing, making it a real energy storage with a theoretical efficiency of approximately 70 percent and vastly carbon dioxide ($CO_{2)}$ neutral.

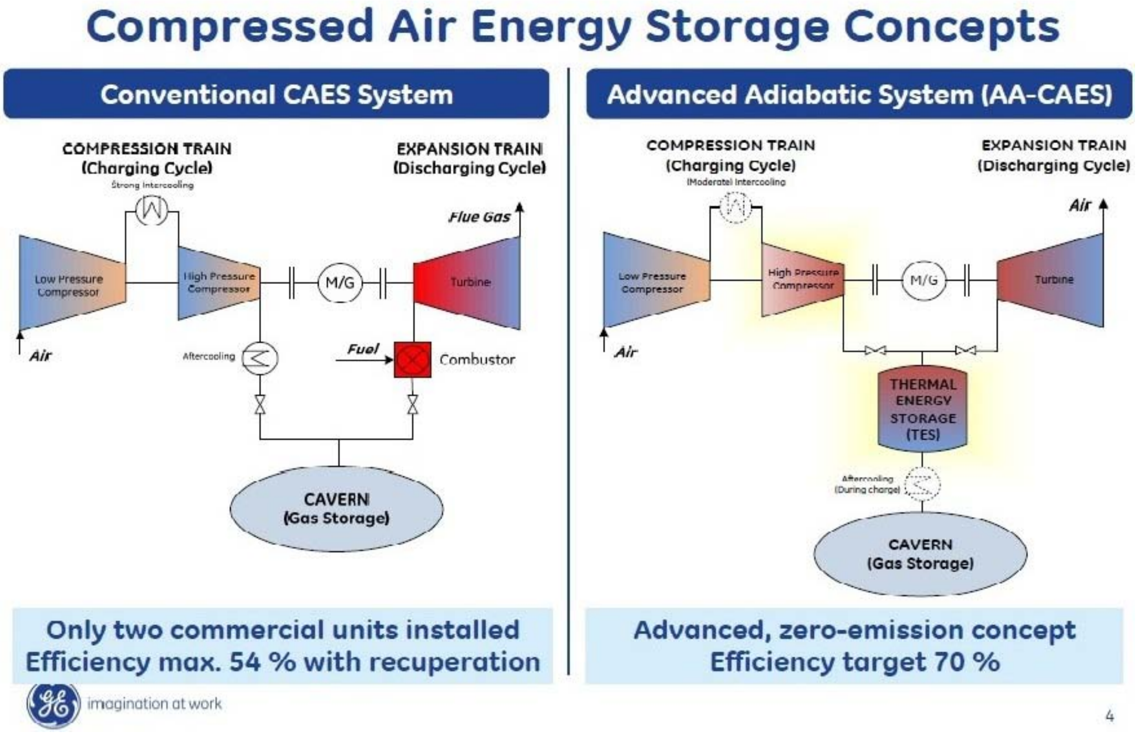

Figure 16: Compressed Air Energy Storage concepts

Source: http://eleves.ec-lille.fr/~seerc10/solution.html

However, construction of a prototype brings new obstacles and other challenges. The engineering of heat storage sites capable of holding the energy over longer periods without significant losses; compressors that can handle both the high pressures as well as the high temperatures and turbines with the ability to maintain on a constant output under changing conditions (changing temperatures, decreasing air pressure) are some of the challenges. But, with the current state of the art very doable.

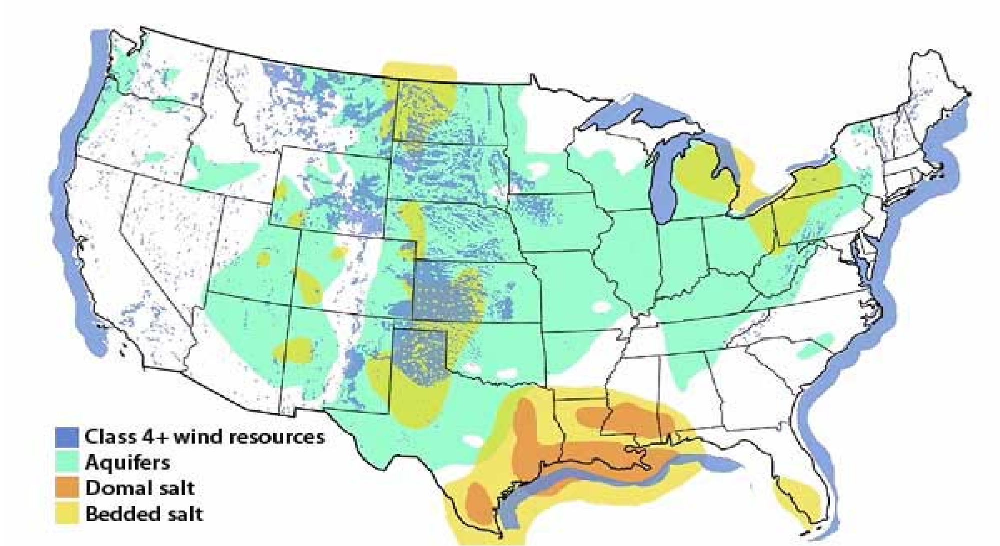

Figure 17: Map of geological formations suitable for CAES plants in the US

Source: http://www.neuralenergy.info/2009/06/caes.html

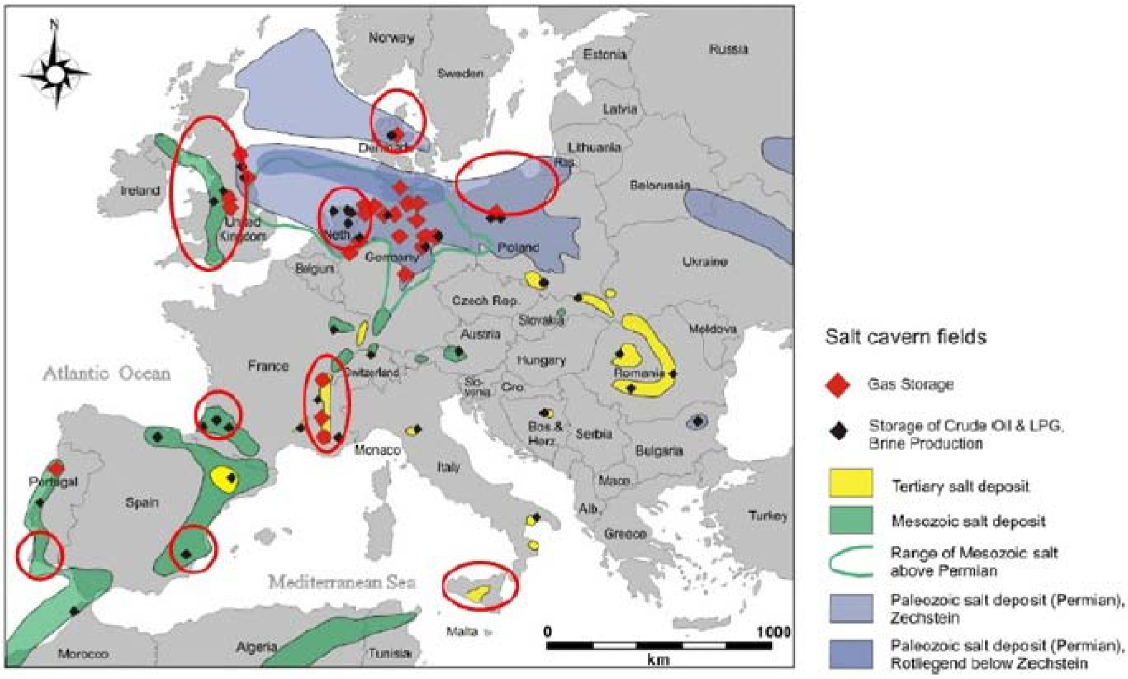

Figure 18: Map of salt cavern fields in Europe

Source: http://web.fhnw.ch/plattformen/ee/CAS%20EE%2009%20ZA%20Druckluftspeicher.pdf

Pros and Cons

- ✚ Capable of storing huge amounts of energy, similar to PSH
- ✚ AA-CAES capable of efficiencies nearly as good as PSH (around 70 percent)
- ✚ Fast response times
- ✚ Inexpensive way to store energy
- ▬ Requires sealed storage caverns

- Economical only up to a day of storage (for AA-CAES)
- Competing against other storage needs (natural gas, hydrogen)
- Not yet fully developed

Future Prospects

The AA-CAES concept ADELE seems to be in the finale stage of development and will set the foundation for the future CAES technology. Once the demonstration plant has been operating successfully and enough experience and data have been acquired, AA-CAES plants will become commercially available. RWE is aiming for a date somewhere around 2018.

While the technology is of global relevance, as underground caverns exist everywhere around the world, Germany delivers the optimal conditions for its use with the country's plans to expand its wind farms in the north, on- and off-shore with areas nearby where most salt caverns are located. This could lead AA-CAES plants to be the most important storage technology next to the PSH in Germany and probably Europe in the foreseeable future because it is an inexpensive way to store energy in huge amounts with good overall efficiency. And, even though underground storage sites are comparatively smaller than water reservoirs for PSHs; in most cases, compressed air provides a higher energy density, bringing it almost to the same capacities most of the time.[14]

For the integrated use of these plants two different applications are possible: A fixed integration within the wind farms to ensure a stable and constant output or a grid integration to provide the opportunity to control energy, just like PSH does now. The fixed solution would result in a safer, more reliable grid but higher energy losses and therefore costs as the output will always be within the 70 percent efficiency range of the AA-CAES plant. The use as a control energy plant will require an expanded electric grid and make load management more difficult; but, will decrease costs and rise overall efficiency. A combination of both scenarios is possible and likely to lead to a compromise.

Salt caverns are already being used for storing natural gas and hydrogen and with the increasing demand for both in the future the need for storing them to compensate peak demands will rise as well. This could become problematic due to the fact that suited underground caverns are limited, priorities will have to be set.

[14] cf. Robert G. Watts, Innovative Energy Strategies For CO_2 Stabilization

3.6 Electrolysis of water and Methanation

Another Idea would be to use the excess electricity of renewable energies to make hydrogen (H_2) through electrolysis of water and, in further steps, methane. Both methane and hydrogen could be stored in existing natural gas grids, although experts recommend a limitation for hydrogen to store only up of 5 percent in order to preserve pipelines and gas turbines. Especially Europe with its splendidly constructed gas grid holds gigantic storage capacities. The German grid alone offers storage capabilities of approximately 220 Terawatt hours (TWh), even with the recommended 5 percent limit for hydrogen it would still result in 1,8 TWh, 25 times more than their current share of pumped hydro plants.[15] The production of hydrogen through electrolysis is a well-known process. Efficiencies depend on the technology and range from 70 – 80 percent, but have potential for improvement. Re-electrification can be achieved through fuel cells with efficiencies around 50 percent or conventional combustion in gas turbines with approximately 55 percent efficiency in modern closed-cycle gas turbine plants (CCGT), leading to an overall efficiency of about 40 – 45 percent. Electrolysis itself bears no emissions but plain air. Electrification in fuel cells results in water vapor while combustion engines will emit water vapor and small amounts of nitrogen oxides.

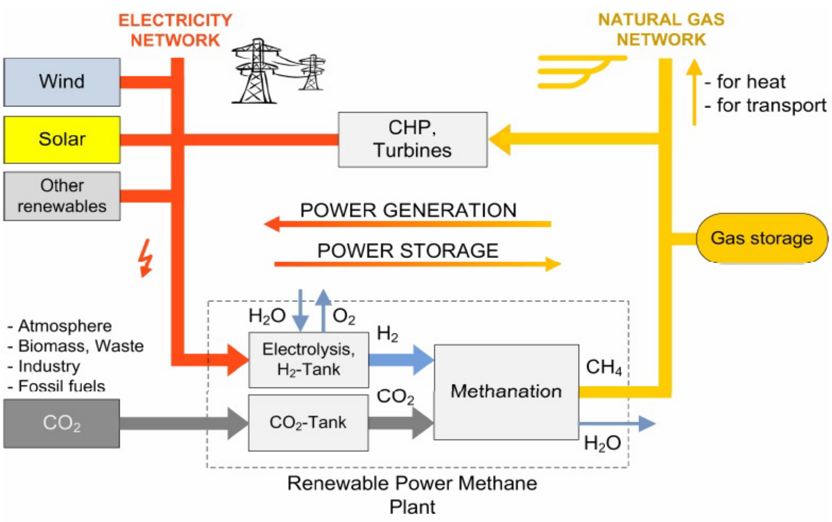

Figure 19: Concept of methanation for storing wind and solar energy

Source: http://www.uni-kassel.de/hrz/db4/extern/dbupress/publik/abstract.php?978-3-89958-798-2

15 http://www.greenpeace-energy.de/fileadmin/docs/sonstiges/Greenpeace_Energy_Gutachten_Windgas_Fraunhofer_Sterner.pdf

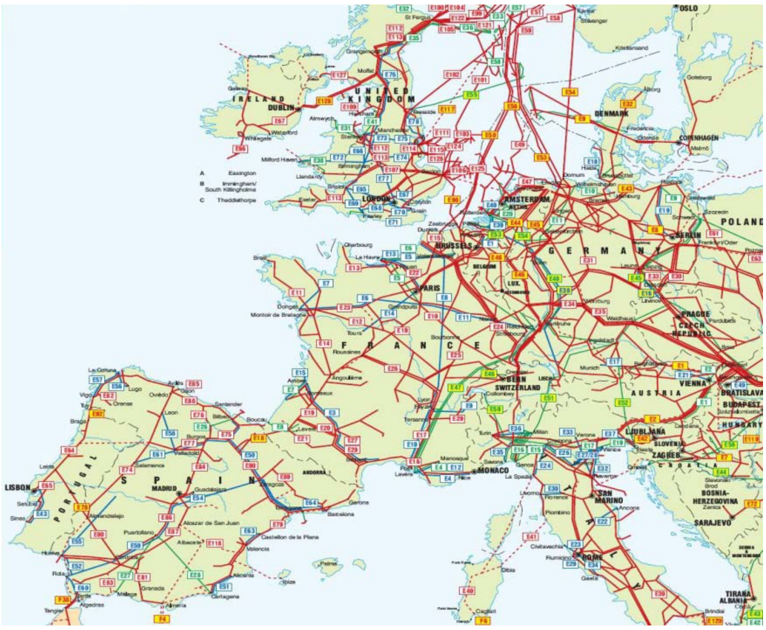

Figure 20: Map of the natural gas grid in Western Europe

Source:
http://www.theodora.com/pipelines/europe_oil_gas_and_products_pipelines.html

Methanation of hydrogen would be the next step once the limit for hydrogen has been reached and could be completely injected into the natural gas grids, making the full 220 TWh available in the example of Germany. Carbon dioxide (CO_2) is needed for the process, combined with H_2 it results in methane (CH_4), the main component of natural gas (99 percent). The bound CO_2 will be emitted again during re-electrification, making the whole process CO_2-neutral. Although methanation is a well-known process, it decreases efficiency coming to only about 30 – 40 percent overall.

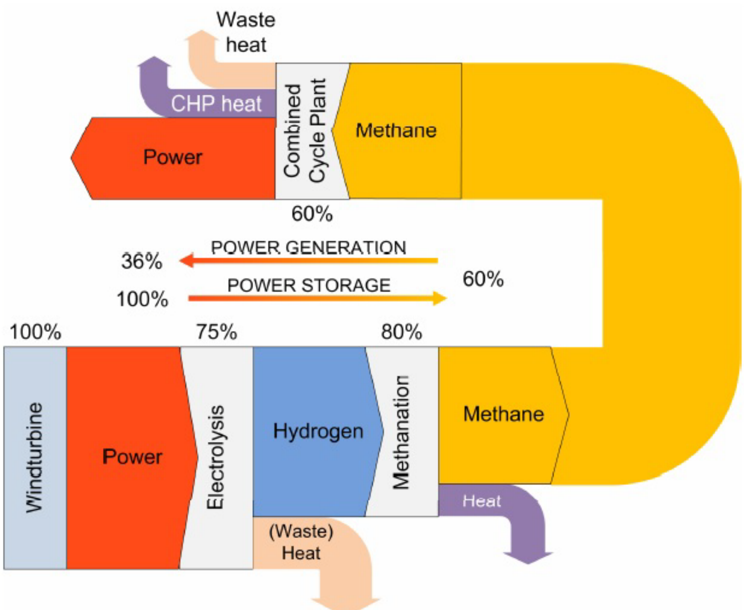

Figure 21: Energy losses during the methanation process

Source: Sterner, http://www.uni-kassel.de/hrz/db4/extern/dbupress/publik/abstract.php?978-3-89958-798-2

Pros and Cons

- ✚ Clean sustainable way of storing energy
- ✚ Capable of storing huge amounts of energy
- ✚ Capable of storing energy for several days, even months
- ▬ Very low efficiency (30 – 40 percent)
- ▬ Potential for efficiency unlikely to pass 50 percent
- ▬ Requires a good constructed natural gas grid

Future Prospects

Looking at the whole chain the low efficiency makes the idea look bad at first. Forty percent overall efficiency means that three of five wind turbine's production of electricity go to waste. Considering the fact that wind turbines are often turned off in order to prevent the grid from overloading, makes the idea not as bad as expected, because, after all, 40 percent is better than nothing. The main obstacles for practical implementation right now are the costs. The electrolysis of water and the methanation process are still more expensive than purchasing conventional natural gas; but, this will only change once more plants have been installed.

On another note, production of hydrogen through wind turbines could be beneficial for electrical cars using hydrogen as fuel. An advanced hydrogen economy would push the electrification of automobile traffic, as hydrogen cars are about to go into mass production.[16]

Greenpeace Energy is successfully operating a system that injects hydrogen produced from excess energy of wind turbines into their gas grid.[17] It is likely that in some countries the technology will be pursued and improved furthermore to carry a part of the required storage needs.

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16 http://www.insideline.com/mercedes-benz/mercedes-benz-fuel-cell-car-ready-for-market-in-2014.html

17 http://www.greenpeace-energy.de/windgas.html

3.7 Thermal Storage

Thermal storage is the concept of storing energy in form of heat. There are different approaches to storing large amounts of heat, one of the most promising is the concept of phase changing materials (PCM). These materials are capable of holding large energy amounts when changing from one phase into another. We know this effect from a simple ice cube. If you heat the cube up it stays at 0° C (273° K) until completely molten. The amount of energy used to melt an ice cube is equivalent to the amount you need to heat water to 80° C (353°K). The same effect, but with a higher energy density, holds the molten salt storage concept, containing a combination of sodium and potassium, which is currently the first choice in several solar projects. However, research is being done to find other thermal storage concepts using materials that are cheaper and easier to handle.[18]

Because heat is the lowest form of energy, it hasn't been really considered for storing energy because the most common way to produce electricity is to power steam turbines; it would be just too inefficient to transform already produced electricity through steam once again into heat just to power a steam turbine again. However, the concept is relevant for balancing solar thermal power plants, as they use the heat of the sun during the day to simultaneously produce electricity and "fill up" the thermal storage tanks, which allows them to generate electricity at night.

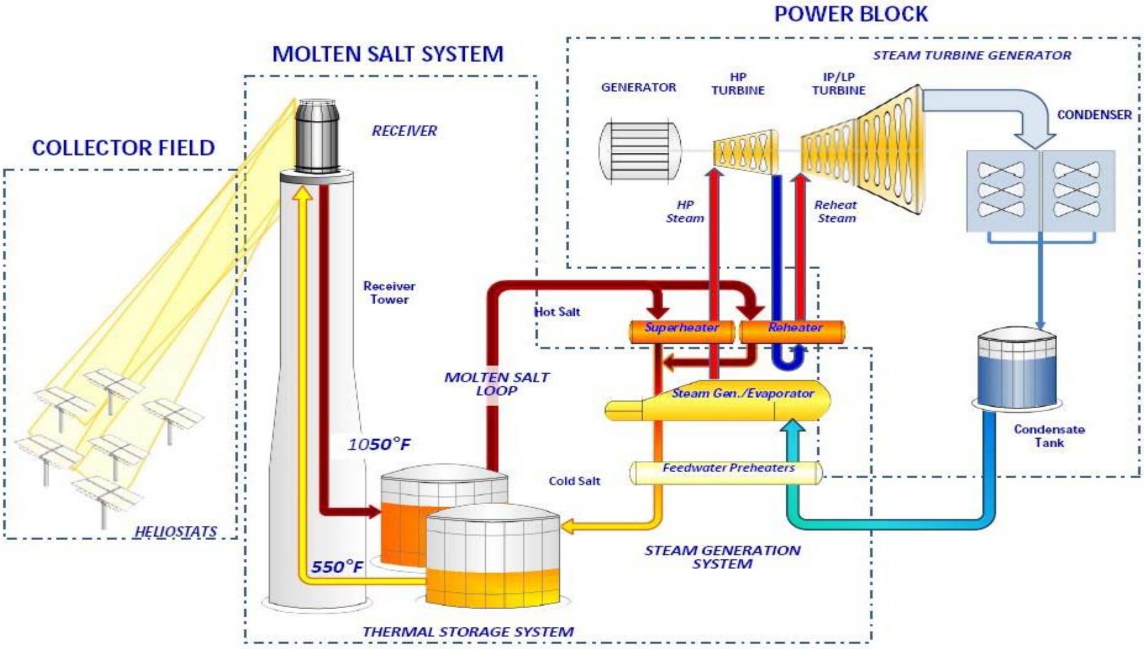

Figure 22: CSP plant with a thermal storage cycle.

Source: http://news.cnet.com/8301-11128_3-10420278-54.html

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[18] http://www.dlr.de/desktopdefault.aspx/tabid-6224/10236_read-26786/

Gemasolar in Seville, Spain is the first commercial-scale plant ever to make use of this concept, capable of producing 19.9 MW for 24 hours a day, enough to power 25,000 homes.[19] Solar thermal power plants using concentrated solar power (CSP) or parabolic troughs are only efficient enough in areas with enough solar irradiation per day though. The technology is of significant importance for the DESERTEC project.[20]

Figure 23: Gemasolar CSP in Seville, Spain with molten salt storages

Source: http://www.renewableenergymagazine.com/articulo-panorama-18711-47-panorama

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19 http://www.torresolenergy.com/TORRESOL/gemasolar-plant/en

20 http://www.desertec.org/concept/

3.8 Hydraulic Hydro Energy Storage (HHS)

This concept, proposed and developed by German scientist Eduard Heindl, is just a theoretical idea, but with enormous potential, if feasible.

Basically, the idea is to cut out a large cylindrical body of rock and lift it hydraulically using hydro pumps to force water underneath it. The body would rise several hundred meters if completely charged and would sink into the ground again during discharge. Environmental impact would be minimal, the storage capacity incredibly huge and costs – depending on the dimension – even lower than PSH, once developed.

Radius [m]	62	125	250	500
Capacity [GWh]	0,5	8,0	125	2000

Table 1: Theoretical energy capacity for different sizes for HHS

Source:http://lageenergiespeicher.de/idee-und-funktion/speicherkapazitaet.html

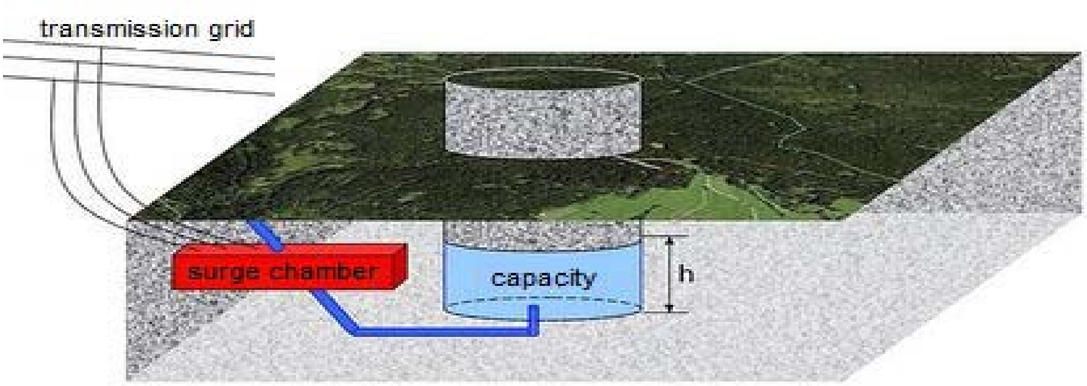

Figure 24: Concept of a hydraulic hydro energy storage

Source: http://www.lageenergiespeicher.de/en/concept-and-design.html

According to Heindl’s own investigations a project like this is technically and economically feasible. Research proposals and feasibility studies have been developed. Future prospects can’t be made yet. It remains to be seen if, how and when a demonstration plant will be built.

4 Direct Comparison

Efficiency

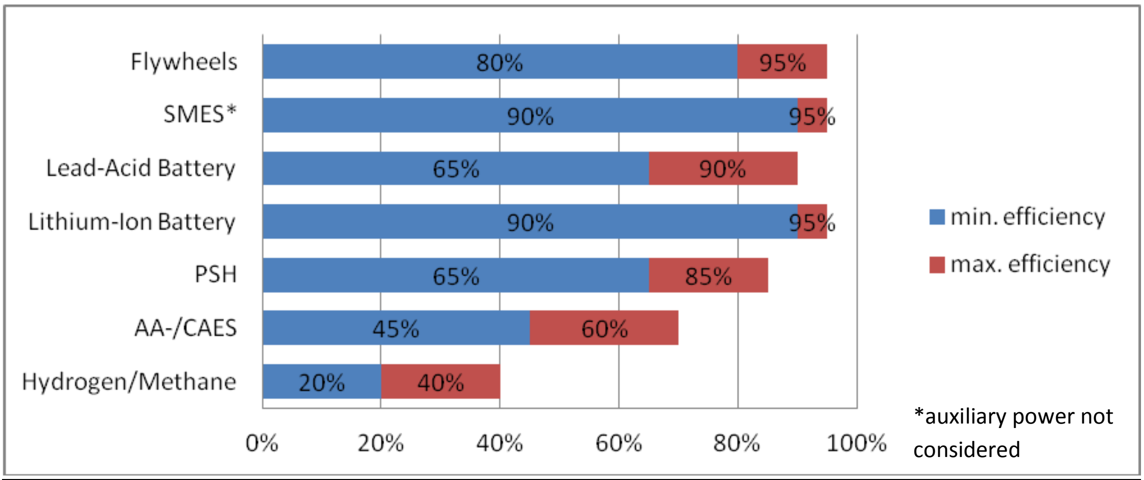

Figure 25: Comparison of the efficiency for different technologies

Data source: http://www.unendlich-viel-energie.de/uploads/media/29_Renews_Spezial_Strom_speichern_apr10.pdf

Several technologies like flywheels or batteries are in favor for having very good efficiencies. The efficiency alone however is not an indicator for suitable technologies in grid systems as they can lack the required storage capacities; are just too expensive; or require large amounts of resources (landscapes for PSH are also considered as resources).

Flywheels	SMES	Lead-Acid	Lithium-Ion	PSH	AA-/CAES	Hydrogen/ Methane
3-20% per hour	10-12% per day	5% per month	5% per year	0-0,5% per day	0-10% per day	0-1% per day

Table 2: Comparison of the energy losses for different technologies

Data source: http://www.unendlich-viel-energie.de/uploads/media/29_Renews_Spezial_Strom_speichern_apr10.pdf

Table 2 shows that most of the technologies listed have minimal self-discharges over longer periods of time, only flywheels and the SMES system holding the short end of the stick. It should be noted though, that in the case of the adiabatic CAES system it is likely that the quota will be approaching more to the 10 percent mark the longer the energy is stored due to heat losses in the storage tanks.

Costs

	Life cycle	**Specific Investment costs / kWh output**
Flywheels	*20 years*	1,000 - 5,000 €
SMES	1,000,000 cycles	30,000 - 200,000 €
Lead-Acid	1,000 - 2,000 cycles	25 - 250 €
Lithium-Ion	500 - 3,000 cycles or 5 years	800 - 1,500 €
PSH	-	100 - 500 €
AA-CAES	-	40 - 100 €
Hydrogen/Methane	-	*unknown*

Table 3: Comparison of the costs for different technologies

Data source: http://www.unendlich-viel-energie.de/uploads/media/29_Renews_Spezial_Strom_speichern_apr10.pdf

Some of the costs as well as the life cycles are estimated, as the technologies are not yet commercial. The costs are projected on those life cycles and thereby tied to requirements to replace them afterwards. Large scale storages like PSH or AA-CAES have no cycle times listed as the locations are planned to be used for several decades and single components like turbines or pumps will be simply replaced or upgraded when defect.

System Power Rating

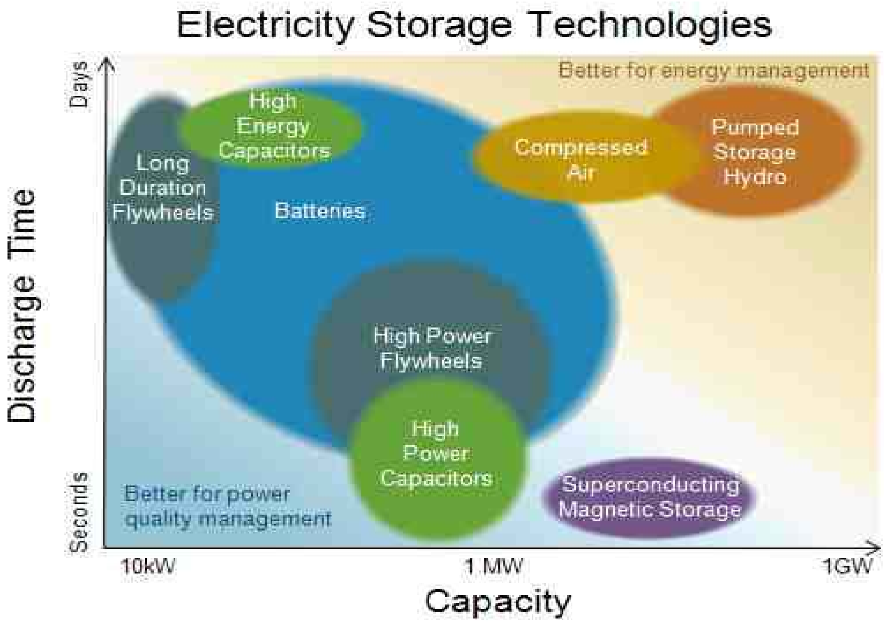

Figure 26: System power rating for different technologies

Source: http://www.realclearenergy.org/charticles/2012/05/21/rating_the_energy_storage_options.html

Figure 26 shows the storage capacities and the discharge times, indicating the PSH as the only commercial available technology to store large amounts of energy providing for several hours to days. AA-CAES seems to become the first technology that could compete with the specifications of the PSH, once commercial.

In addition, the stats for water electrolysis respectively methanation for storing in natural gas grids would be far greater and off the shown scale under ideal conditions.

Environmental Impact

	Environmental Impact	
Flywheels	+ +	Very low, only for production, construction
SMES	+ +	Very low, only for construction
Lead-Acid	-	Lead is known to be very poisonous and contaminating for soil and water
Lithium-Ion	+	Rather low, impact mostly through emissions for the production of the cells
PSH	- -	Significant, huge areas of natural landscapes are required
AA-CAES	+ +	Very low, only for construction
Hydrogen/Methane	+ +	Very low, only for construction. CO_2-neutral during the whole cycle.

Table 4: Comparison of environmental impacts for different technologies

Source: Author's assessment

5 Concluding Remarks

Storing large amounts of energy will remain a great challenge in the next couple of years. Pumped hydro plants are currently the only economical solution for this task but capacities for new plants are limited or even completely utilized. Renewable Energies and their fluctuating production however make additional storage possibilities inevitable. Technologies and concepts are available but they still need more time to become mature and economical.

Without appropriate storage opportunities further expansion of renewable energies is forced to slow down, which already happens at some points. For example on times of overcapacity wind farms are shut down in order to prevent blackouts as the production becomes too unreliable. Adiabatic CAES plants have good changes to become an alternative to the pumped hydro plants after a successful testing phase for the ADELE project in Germany; but, it will take probably another decade before this technology will become commercially available and profitable for operators.

Batteries will only find their use in decentralized systems as the existing technologies are simply too expensive or need a great deal of resources. The idea of storing the energy in hydrogen or methane is not desirable due to the low efficiency but is still likely to play a role in the future because of the great storage potential. As each of the shown technologies have their own benefits and flaws, it is possible that a mixture of all of them will come into action, depending on individual situations until at some point one might advance far enough and emerge over the others.

6 Bibliography

Cover photo credit: http://www.flickr.com/photos/vattenfall/6779452824/

Brain, Marshall. "How Power Grids Work." *HowStuffWorks.com*. Web. 17 Apr. 2012. <http://science.howstuffworks.com/environmental/energy/power.htm>.

Power to Gas. "Strom Speichern." - *Powertogas.info*. Web. 17 Apr. 2012. <http://www.powertogas.info/power-to-gas/strom-speichern.html>.

Umweltbundesamt Für Mensch Und Umwelt. *Energieziel 2050: 100% Strom Aus Erneuerbaren Quellen*. FKZ 363 01 277. July 2010. Web. 18 Apr. 2012.

"Das Kraftwerksmanagement in der Elektrizitätswirtschaft." *Waermepumpe-BHKW.de*. 31 Dec. 2007. Web. 18 Apr. 2012. <http://www.waermepumpe-bhkw.de/infos/elektrizitaetswirtschaft.html>.

"Regelenergie." *50hertz.com*. Web. 18 Apr. 2012. <http://www.50hertz.com/cps/rde/xchg/trm_de/hs.xsl/132.htm?rdeLocaleAttr=de&rdeCOQ=SID-1B8528F7-04A23B5B>.

"Renewable Energy and Electricity." *World-nuclear.org*. Web. 18 Apr. 2012. <http://www.world-nuclear.org/info/inf10.html>.

"Neue Speicher Für Die Energiewende." *Energy-storage-online.com*. Web. 18 Apr. 2012. <http://www.energy-storage-online.de/neue_speicher_fuer_die_energiewende.php?Page=1>.

Bellis, Mary. "How a Battery Works." *About.com*. Web. 19 Apr. 2012. <http://inventors.about.com/od/bstartinventions/ss/How-A-Battery-Works.htm>.

"Lead Acid Batteries." *BatterySpace.com*. Web. 20 Apr. 2012. <http://www.batteryspace.com/leadacidbatteries.aspx>.

"How Lead Acid Batteries Work." *Vonwentzel.net*. Web. 20 Apr. 2012. <http://www.vonwentzel.net/Battery/00.Glossary/>.

Oltman, Stu. "The Super Secret Workings of a Lead Acid Battery Explained." *BatteryStuff*.com. 10 Feb. 2012. Web. 24 Apr. 2012. <http://www.batterystuff.com/kb/articles/battery-articles/secret-workings-of-a-lead-acid-battery.html>.

"Pros and Cons of a Lead Acid Car Battery." *CarsDirect.com*. 28 May 2010. Web. 23 Apr. 2012. <http://www.carsdirect.com/car-maintenance/pros-and-cons-of-a-lead-acid-car-battery>.

"About Flywheel Energy Storage." *Beaconpower.com*. Web. 24 Apr. 2012. <http://www.beaconpower.com/products/about-flywheels.asp>.

Oertel, Dagmar. "Energiespeicher – Stand Und Perspektiven." *Tab-beim-Bundestag.de*. Feb. 2008. Web. 30 Apr. 2012. <http://www.tab-beim-bundestag.de/de/pdf/publikationen/berichte/TAB-Arbeitsbericht-ab123.pdf>.

Gatzen, Christoph. *The Economics of Power Storage*. Vol. 65. München: Oldenbourg Industrieverlag, 2008. Web. 30 Apr. 2012.

Rossa, Harald. "Auf Dem Weg Zur Supraleitung Bei Raumtemperatur." *Suite101.de*. 03 Apr. 2009. Web. 30 Apr. 2012. <http://harald-rossa.suite101.de/auf-dem-weg-zur-supraleitung-bei-raumtemperatur-a54534>.

"Factsheet to Accompany the Report “Pathways for Energy Storage in the UK”."*Lowcarbonfutures.org*. Web. 30 Apr. 2012. <http://www.lowcarbonfutures.org/assets/media/SMES_final.pdf>.

"Lithium-Ionen-Akkus." *Elektronik-kompendium.de*. Web. 09 May 2012. <http://www.elektronik-kompendium.de/sites/bau/0810281.htm>.

Brain, Marshall. "How Lithium-ion Batteries Work." *HowStuffWorks.com*. 14 Nov. 2006. Web. 09 May 2012. <http://electronics.howstuffworks.com/everyday-tech/lithium-ion-battery.htm>.

BASF. "Lithium-Ionen-Batterien -- Wie Funktionieren Sie Eigentlich?" *YouTube*. 17 Oct. 2011. Web. 09 May 2012. <http://www.youtube.com/watch?v=ueoSvlB9y5s>.

Buchmann, Isodor. "Ist Lithium-Ion Die Ideale Batterie?" *Batteryuniversity.com*. Web. 10 May 2012. <http://batteryuniversity.com/partone-5-german.htm>.

IBM. "The Battery 500 Project." *IBM.com*. Web. 10 May 2012. <http://www.ibm.com/smarterplanet/us/en/smart_grid/article/battery500.html>.

"Lithium-Ionen-Batterien - Energiespeicher Der Zukunft." *BASF.com*. 18 Mar. 2009. Web. 11 May 2012. <http://www.basf.com/group/corporate/de/news-and-media-relations/podcasts/chemistry-of-innovations/lithium-ion>.

Schott, Benjamin. "Lithium – Begehrter Rohstoff Der Zukunft." *Zsw-bw.de*. 08 June 2010. Web. 11 May 2012. <http://www.zsw-bw.de/fileadmin/ZSW_files/Infoportal/Informationsmaterial/docs/Risikoanalyse%20Lithium_05_08_2010.pdf>.

AMERICAN VANADIUM CORP. "Vanadium Flow Batteries." *Americanvanadium.com*. Web. 14 May 2012. <http://www.americanvanadium.com/vanadium-flow-batteries.php>.

Fraunhofer ICT. "Redox Flow Battery." *Ict.fraunhofer.de*. Web. 14 May 2012.

"Die Redox-Flow-Zelle Als Energiespeicher." *Minotech.de*. Web. 14 May 2012. <http://www.minotech.de/forschung/alternative-treibstoffe/redox-flow-zelle-als-energiespeicher/>.

"Fraunhofer: Riesen-Batterien Für Ökostrom-Speicherung." *Energie-und-technik.de*. 28 Mar. 2011. Web. 14 May 2012.

"Vanadium Flow Battery to Provide Grid-Level Storage for Gills Onions."*Sustainableplant.com*. 01 May 2012. Web. 14 May 2012. <http://www.sustainableplant.com/2012/05/vanadium-flow-battery-to-provide-grid-level-storage-for-gills-onions/>.

Robertson, John. "Danger of Lerwick Battery Fire Forces SSE to Halt Connection."*Shetlandtimes.co.uk*. 25 Nov. 2011. Web. 15 May 2012. <http://www.shetlandtimes.co.uk/2011/11/25/danger-of-lerwick-battery-fire-forces-sse-to-halt-connection>.

"Factsheet to Accompany the Report “Pathways for Energy Storage in the UK”."*Lowcarbonfutures.org*. Web. 15 May 2012. <http://www.lowcarbonfutures.org/assets/media/NaS%20Battery_final.pdf>.

Anthony, David. "Is Sodium Sulfur (NaS) Battery a Viable Grid Energy Storage Solution?"*Davidanthonyvc.com*. 11 Jan. 2012. Web. 15 May 2012. <http://davidanthonyvc.com/?p=559>.

Owano, Nancy. "Eos Says Zinc Battery Recipe Is Energy Game-changer." *Phys.org*. 04 Jan. 2012. Web. 16 May 2012. <http://phys.org/news/2012-01-eos-zinc-battery-recipe-energy.html>.

Gudmundsson, Agust. "Pumped-Storage Hydroelectricity." *Agust.com*. Web. 16 May 2012. <http://www.agust.com/energy/Pumped_Storage.pdf>

Murphy, Tom. "Pump Up the Storage." *Physics.ucsd.edu*. 15 Nov. 2011. Web. 16 May 2012. <http://physics.ucsd.edu/do-the-math/2011/11/pump-up-the-storage/>.

Deutsche Energie-Agentur GmbH (dena). "Analyse Der Notwendigkeit Des Ausbaus Von Pumpspeicherwerken Und Anderen Stromspeichern Zur Integration Der Erneuerbaren Energien." *Dena.de*. 05 Feb. 2010. Web. 17 May 2012. < http://www.dena.de/fileadmin/user_upload/Projekte/Energiesysteme/Dokumente/Zusammenfassung_Endbericht_PSW_-_Integration_EE_dena.pdf>

"Isentropic Pumped Heat Storage." Energystoragenews.com. 13 Aug. 2009. Web. 17 May 2012. <http://www.energystoragenews.com/Isentropic%20Pumped%20Heat%20Storage.html>.

Khazaleh, Lorenz. "Wasserkraft in Norwegen: Saubere Energie Legitimiert Verschwendung."*Lorenzk.com*. 08 Jan. 2002. Web. 17 May 2012. <http://www.lorenzk.com/deutsch/2002/wasserkraft-in-norwegen-saubere-energie-legitimiert-verschwendung/>.

Hermanny, Christian. "Strom Von Untertage." *WDR.de*. 06 Sept. 2011. Web. 18 May 2012. <http://www.wdr.de/mediathek/html/regional/2011/09/06/westblick-energiewende-in-nrw.xml>.

Schramm, Stefanie. "Speicherplatz Für Ökostrom." *ZEIT.de*. 24 Nov. 2010. Web. 18 May 2012. <http://www.zeit.de/2010/48/Pumpspeicherkraftwerk>.

The British Hydropower Association. "A GUIDE TO UK MINI-HYDRO DEVELOPMENTS." *British-hydro.org*. Jan. 2005. Web. 18 May 2012. <http://www.british-hydro.org/mini-hydro/download.pdf>.

StadtwerkeMuenster. "Funktionsweise Gasturbine." *YouTube*. 11 Oct. 2010. Web. 21 May 2012. <http://www.youtube.com/watch?v=grPzZ39ZyUI>.

Auer, Josef. "Moderne Stromspeicher - Unverzichtbare Bausteine Der Energiewende."*Dbresearch.de*. Deutsche Bank, 31 Jan. 2012. Web. 21 May 2012. <http://www.dbresearch.de/PROD/DBR_INTERNET_DE-PROD/PROD0000000000284196/Moderne+Stromspeicher%3A+Unverzichtbare+Bausteine+der+Energiewende.pdf>.

RWE. "ADELE - Der Adiabate Druckluftspeicher Für Die Elektrizitätsversorgung."*RWE.com*. Web. 22 May 2012. <http://www.rwe.com/web/cms/de/365478/rwe/innovationen/stromerzeugung/energiespeicherung/druckluftspeicher/projekt-adele/>.

Projekt-Cluster. "Mit Druckluft Strom Speichern." *Kraftwerkforschung.info*. 22 July 2010. Web. 22 May 2012. <http://www.kraftwerkforschung.info/mit-druckluft-strom-speichern/>.

Burkhardt, Flurina. "Druckluftspeicher die Lösung Zur Netzintegration erneuerbarer Energien?" Diss. Fachhochschule Nordwestschweiz, 2009. Web. 23 May 2012. <http://web.fhnw.ch/plattformen/ee/CAS%20EE%2009%20ZA%20Druckluftspeicher.pdf>.

Kruck, Christoph, and Ludger Eltrop. "Perspektiven Der Stromerzeugung Aus Solar- Und Windenergienutzung Für Eine Nachhaltige Energieversorgung in Deutschland." Ier.uni-stuttgart.de. 2007. Web. 24 May 2012. <http://www.ier.uni-stuttgart.de/publikationen/pb_pdf/Endbericht_Projekt_FKZ_A204_04.pdf>.

Watts, Robert G. Innovative Energy Strategies for CO2 Stabilization. Cambridge University Press, 2002. Print.

"Torresol Energy - Gemasolar Thermosolar Plant." *Torresolenergy.com*. Web. 30 May 2012. <http://www.torresolenergy.com/TORRESOL/gemasolar-plant/en>.

"DLR-Speicherkonzept Für Solarkraftwerke Mit E.ON-Forschungspreis Ausgezeichnet."*DLR.de*. 27 Sept. 2010. Web. 30 May 2012. <http://www.dlr.de/desktopdefault.aspx/tabid-6224/10236_read-26786/>.

Henig, Marion. "Von Batterien Bis Zum Riesenwärmekissen - Chemische Technik Für Energiespeicher." *Process.vogel.de*. 16 Jan. 2012. Web. 30 May 2012. <http://www.process.vogel.de/achema/management_und_it/articles/341306/index5>.

Fraunhofer IWES. "Energiewirtschaftliche Und ökologische Bewertung Eines Windgas-Angebotes." Green-
peace-energy.de. Feb. 2011. Web. 01 June 2012. <http://www.greenpeace-
energy.de/fileadmin/docs/sonstiges/Greenpeace_Energy_Gutachten_Windgas_Fraunhofer_Sterner.pdf>.
Heindl, Eduard. "Lageenergiespeicher." *Lageenergiespeicher.de*. Web. 06 June 2012.
<http://lageenergiespeicher.de/startseite.html>.

Lienert, Anita. "Mercedes-Benz Fuel-Cell Car Ready for Market in 2014." *Insideline.com*. 21 June 2011.
Web. 07 June 2012. <http://www.insideline.com/mercedes-benz/mercedes-benz-fuel-cell-car-ready-for-
market-in-2014.html>.

"Wirkungsgrade Verschiedener Stromspeicher ." *Unendlich-viel-energie.de*. Web. 08 June 2012.
<http://www.unendlich-viel-energie.de/de/strom/detailansicht/browse/2/article/162/wirkungsgrade-
verschiedener-stromspeicher.html>.

Mahnke, Eva, and Jörg Mühlenhoff. "Strom Speichern." *Unendlich-viel-energie.de*. Agentur Für Erneuerbare
Energien E. V., Apr. 2010. Web. 8 June 2012. <http://www.unendlich-viel-
energie.de/uploads/media/29_Renews_Spezial_Strom_speichern_apr10.pdf>.

Arizona Research Institute for Solar Energy. "Study of Compressed Air Energy Storage with Grid and Pho-
tovoltaic Energy Generation." *U.arizona.edu*. Aug. 2010. Web. 8 June 2012.
<http://www.u.arizona.edu/~sreynold/caes.pdf>.