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Energy Storage Techniques for Grid Integration of Intermittent Renewable Sources

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Abstract:

Renewable Energy sources are fast becoming a necessity for meeting the energy demands of the world. The various forms of renewable energy being harnessed in the current scenario are primarily intermittent in nature. Their availability and load conditions have a vast difference. Due to the intermittent nature of these sources, harnessing and utilization of such sources as a bulk source of power is seen as a major hindrance. To utilize these intermittent sources, it is desirable to store energy harnessed from the alternative sources and utilize them according to the needs of the grid. Energy storage techniques are capable of showing a path to overcome this problem, however, bulk storage of energy is still a major source of study.

The present paper tries to introduce the basics of various storage techniques present and gives a critical observation of their advantages, technical glitches and impacts in the future.

I. Introduction:

The world's energy demand is growing and the resources are running low. Pollution and climate change contribute further escalate the problem. This makes us to find alternatives for energy requirements 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 the demand is increasing at a high pace, but the sun isn't always shining nor is the wind always blowing. For technical reasons, the power fed into the grid must be maintained at optimum levels as per the demand failing which the blackouts and damage to the grid occur. It may also be observed that it may lead to 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, the problem of storing energy at the level of hundreds to thou-sands of wind turbines and photovoltaic cells is manifold.

The way we handle the fluctuating energy demand today works fine – for now. 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 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.

II. Load Management

In order to maintain grid stability, a frequency of 50 or 60 hertz, it is necessary to produce the almost exact amount of electricity that is demanded by customers. Higher deviations (± 2.5 Hz) will result in causing damage to the generators. The curve progression varies over the day; but, behaviour 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. The concept of a load management 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 start up 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.

Types of Storage Technologies

Flywheels

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.

The flywheel technology essentially is having a low maintenance and a long lifespan, almost nil carbon emissions, fast response and is built with non toxic components. However, the high acquisition costs, low storage capacity & High self-discharge (3 –20 percent per hour) are a hindrance for their usage.

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. 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.

Superconducting Magnetic Energy Storage (SMES)

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 with-out almost any energy loss (practically 90 – 95 percent efficiency).

However, since relevant superconducting materials are only known to work below 20ºK (e.g. niobium-titanium -264º C [9º K], niobium-tin -255ºC [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 (110º 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.

The SMES techniques are fast and capable of partial and deep discharges. They do not posses no environmental hazard. They however posses high energy losses (~12 percent per day) and are very expensive in production and maintenance. Due to the cooling process requirement they have a reduced efficiency

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.

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 (an-ode). 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.

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.

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 an-odes 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 pro-cess. 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.

Lithium-Ion Batteries

Lithium is the lightest metal with the highest potential due to its very reactive behaviour, 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

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

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 refuelling 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 in-crease 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.

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.

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.

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. The first plants of this type were built in Switzerland and Italy in the 1890s, making the concept over a hundred years old.

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.

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 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.

The technology is mature, capable of storing huge amounts of energy and the overall efficiency is also high (around 70 - 80 %). It is fast and an inexpensive way to store energy. However, there are few potential sites and have huge environmental impact

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 under-ground 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.

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.

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 decom-pressed. 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, the stored air in the caverns can be used, meaning that, technically, these CAES plants both store and produce electricity.

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 ap-proximately 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. 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 vapour while combustion engines will emit water vapour and small amounts of nitrogen oxides.

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 pro-cess, 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 efficien-cy coming to only about 30 – 40 percent overall.

This process is a clean and sustainable way of storing energy and can store huge amounts of energy for long duration even upto months. However, it is very low in efficiency and is unlikely to pass 50%. It also requires a good natural gas grid

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.

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.

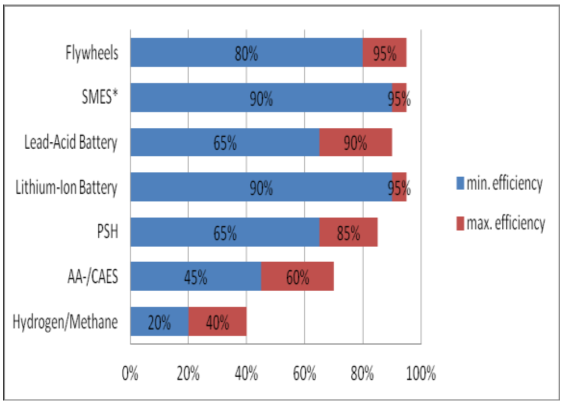
III. Thermal Storage

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.

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.

Gemsolar 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. 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.

Direct Comparison Efficiency



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 favour 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	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

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

The above table 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 ouput
Flywheels	20 Years	1,000 - 5,000 Euros
SMES	1 Million Cycles	30K - 200K Euros
Lead Acid	1000 - 2000 cycles	25 - 250 Euros
Lithium Ion	500 - 3000 cycles or 5 yrs	800 - 1500 Euros
PSH	-	100 - 500 Euros
CAES	-	40 - 100 Euros
Hydrogen / Methane	-	Unknown

Comparison of 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 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.

Conclusions

The problem of harnessing renewable energy sources on a large scale and grid integration of such energy produced depends largely on the load management. The problem of intermittency is bound to stay and storage of energy on large scale is seen as a viable option for overcoming this.

The fluctuating production of the renewable energy sources make storage facilities inevitable, which are available but need time to be put to commercial operation. With the absence of storage technology, the expansion of renewable sources shall slow down

The bulk storage of energy is likely to be a great challenge in the next couple of years. Pumped Hydro plants are currently the most economical solution for energy storage but are limited in capacity. Adiabatic CAES plants have good chances to become an alternative to the pumped hydro plants, but the commercial viability of the technology for the operators is likely to take time. Batteries which are a major source of energy storage at present are useful only in decentralized systems and are too expensive for commercial operation. The idea of hydrogen or methane as a means of energy storage is less preferred owing to its low efficiency but shall become an important technique due to its high potential.

The various storage techniques currently available have their own advantages and lacunae. The challenge to integrate them and have a commercial operation of such storage techniques for integrated renewable systems is going to depend on the individual conditions and emerge as a technology for the future.

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