ENERGY STORAGE FOR INTEGRATION OF RENEWABLE ELECTRICITY
- CASE OF HiTES -

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INTRODUCTION

Energy storage is used to store an overproduction of electricity and to use it again in periods of higher power demand. The pumped hydro storage is one of the oldest systems, especially for mass storage, which has been in use for many years. Previously it was used mostly in systems with higher capacities of base-load plants, like coal and nuclear power plants. Instead of reducing their output and entering into the zone of lower process efficiency, their overproduction was stored, always enabling the optimal operation parameters.

With increased usage of intermittent renewable power generation, like energy from solar and wind farms, there is an additional need for power storage. Roughly, if there are more than 20% of such sources in an electricity network, there is a strong need for energy storage – otherwise curtailment or export under unfavourable conditions has to take place. The examples from Germany, California and Chile are presented here. In contrary to the older pumped hydropower storage systems, there is more need for smaller, distributed storage system, which are more suitable for distributed power generation from renewable energy sources (RES). Some of the main technologies available nowadays are presented, with a little more emphasis on the heat storage. From case to case, one or the other technology may be the most appropriate. The most correct comparison between different energy storage systems is based on the levelised cost of the electricity storage – LCOES. The paper gives a short parametric analysis of the main parameters that influence the levelised cost of energy storage, like the specific investment cost, the round-trip efficiency and the price of the input electricity.
In general, without the wide usage of energy storage, it will not be possible to reach higher penetration of renewable energy sources for power generation, as demanded by many energy policies, and therefore to reach the desired reduction of green-house gases (GHG).

INTERMITTENT GENERATION AND ENERGY STORAGE

Without the intermittent renewable power generation, the energy storage was used only for load control, i.e. for smoothening the electricity consumption, mostly between day and night. Those were well defined periods of time, well planned and without rush load changes. The energy storage was performed with the help of pumped hydropower plants of considerable capacities. In the modern systems with high penetration of renewable energy generation, like from wind and solar, the situation has been drastically changed. Not the consumption, but the generation is now what has to be smoothened. Those changes may be very fast and may last very long, even several days or weeks. It means, the modern power storage devices have to participate in the load control for quite different time periods, but additionally even in the frequency control.

The problems with the intermittent generation does not start immediately after the installation of the first unit. Big power generation systems may absorb easily small disturbances in the system. It depends on many factors, but the experience shows that with about 20% penetration of the intermittent power generation, big problems occur. Then there is a need for higher usage of energy storage systems, together with other measures, like new grids, demand response, etc. However, it is important to understand the difference between the effects of new additional grids and the energy storage systems: With a grid it is possible to transport a local power overproduction to some other area with higher demand at that moment, however a time shift, like with storage systems, is not possible. Moreover, new big grids implicitly lead to a more centralized generation, what was not the idea with the introduction of renewable power generation. Therefore, the best long-term solutions are energy storage systems that support distributed power generation.

The case of Germany was described in Stevanovic [1], showing that 40% of intermittent renewable electricity cannot be used domestically and has to be exported. In 2016 that trend has continued, as seen in Figure 1 (Graichen et al. [2]). Although the yearly increase of intermittent electricity was small (only 4.0 TWh), all of that increase had to be exported! The need for energy storage in Germany is obvious.

![Figure 1: The change in electricity production in Germany [2]](image)

Therefore, the net export from Germany to neighbouring countries is increasing steadily with the increase of renewable power generation. This is presented in Figure 2 (Graichen et al. [2]):
in the years with low renewable generation (2000 – 2002) the production and consumption of electricity were equalised, the imports/exports were required only to balance the system. With higher penetration of the intermittent power generation, the production has to be always higher and the overproduction has to be exported (under unfavourable conditions!). Even with a slight decrease of the domestic consumption, the generation has to increase from year to year. That is another proof for a desperate need for energy storage capacities in the German power system.

Figure 2: Electricity production and consumption in Germany (2000-2016) [2]

Figure 3 gives the total increase of redispatch and curtailment measures in the grid of only one of the four big grid operators in Germany [3]. Due to a very high penetration of wind energy in that grid, about 50% of the value given below is the curtailment of the wind-mills!

Figure 3: Total increase of redispatch and curtailment interventions in the grid of “50hertz” [3]

In some areas of Chile, there is a locally very high penetration of the solar power generation, based on photo-voltaic systems. As the insolation is very high, the price of that electricity is low (< 3 ¢ /kWh). However, every day at around noon, the market price goes into the negative area, as there are not enough consumers when the generation reaches its daily maximum.
Therefore, there are some projects for energy storage facilities and some new generation facilities, but based on CSP (concentrated solar power) with integrated molten salt storage.

California is the US state with the highest penetration of wind and solar power generation. Contrary to Germany, they have started thinking and analysing the potential problems of intermittent generation much earlier. The Duck Chart was created by the California Independent System Operator to show that increasing solar generation paired with conventional base load resources that cannot be turned off (e.g. nuclear and less flexible natural gas) can cause over-generation in the afternoons during certain months beginning in 2018 (Loutan [4]). Each line in Figure 4 represents a different year, from 2012 – 2020. The y-axis shows the net load in MW, meaning load minus wind and solar generation. The chart shows that the shape of the net load curve begins to shift dramatically in 2015 due to increasing solar generation, and there is potential for over-generation during the afternoons beginning in 2018. An especially big problem is a very fast ramping between 17h and 19h (13.5 GW in 2 hours!). To solve those potential problems, several measures were planned, like demand response, import/export, curtailment and energy storage. Being unfavourable measures, import/export and especially curtailment, were minimised. Nowadays California is the area with the most installed energy storage systems and several new projects are planned.

ENERGY STORAGE TECHNOLOGIES

There are many technologies for energy storage. They are all using different principles and therefore they have different advantages and disadvantages. Roughly, there are mechanical, chemical, electrical, and thermal storage technologies.

Mechanical storage is using mechanical energy to store it in the form of potential energy, like in the case of pumped hydro storage, pressurized air storage, or flywheels. The pumped hydro storage is the oldest and still the most used technology. It had the biggest advantages for classical storage application: to store the electricity generated from big power plants (nuclear and coal plants) in the periods of lower consumption, mostly during the night. They are not so
favourable in combination with the renewable power generation, as they are viable for bigger capacities, thus not quite suitable for distributed generation. However, that is still the best technology when efficiency and specific cost are considered.

Chemical storage is transforming electrical energy into chemical energy and then back to electricity when required. Usually such systems are referred to as batteries. There are many types, like lead batteries, sodium sulphur batteries, flow batteries, zinc-air batteries and the most famous nowadays – lithium batteries. They are suitable especially for smaller capacities, have good efficiency, but they are still very expensive. There are expectations that the price will drop considerably in the next years (however, those expectation are many years old). On the other hand, the price of lithium carbonate, an intermediate product in fabrication of the pure lithium, has been more than doubled in 2016, due to the high market demand (Outsider Club [5]). The lifespan is short, between 5 and 10 years, or 12 years in the most optimistic predictions. The capacity drops during the lifetime and at the end of its life it is only at 50-70% of the previous capacity. In order not to get even higher capacity reduction, it is not allowed to have a full discharge and charge. That is in fact a further reduction of the available capacity. Therefore, those batteries are more suitable for the frequency control than for the long-term storage. Discharging time is usually up to max. 4 hours. The first bigger lithium storage batteries have been installed in the last 2 years and the real operation experience is expected in the next years.

The systems with water electrolysis present also a case of chemical energy storage, as the electricity is stored in the form of heat value of hydrogen or methane. They are nowadays very expensive and have a poor round-trip efficiency, when the electricity is generated again. There are also pure electrical storage systems, like big capacitors and superconducting magnetic energy storage. The first one is used in a limited scope for frequency control and regulation.

Thermal energy storage is mostly famous for the molten salt facilities. They are used almost exclusively with the Concentrated Solar Power (CSP) systems, where solar heat is stored and later used for power generation through the steam turbine cycle. The efficiency is about 32-36% and the investment cost is still high. Due to the storage capacity of up to 10 hours (some special cases), they are attractive as that is the only available technology nowadays to store solar power for a longer time period. There is also the development to transform the electricity into heat and store it underground in some rocks or gravels (Siemens [6]). Afterwards, that heat is used in order to generate electricity, again over a steam turbine cycle. In that case, the temperature is limited to 600°C. The HiTES system (Stevanovic et al. [7]) has a considerably higher temperature: up to 1100°C. The leading idea is that the exergy of stored heat is much higher at elevated temperatures. The quality of heat at 600°C is about 65%, while at 1100°C it is already 80% (see Stevanovic et al. [8]). That makes it possible to reach a higher round trip efficiency, even with heat storage systems. In case that a nowadays-available gas turbine is used, the efficiency would be 40%. With some improvements and optimisation, an efficiency of up to 60% may be reached [8]. This system is presented in more details in the next chapter.

**HIGH TEMPERATURE ENERGY STORAGE – HiTES**

High Temperature Energy Storage (or shortly HiTES) is a new technology for energy storage based on three technologies that are state-of-the-art:

- Pebble-Heater technology
- Radial Gas Turbine
- Electric Resistive Heating.
The combination of those three technologies gives rise to a new system that is suitable for medium-term storage, from several minutes up to several days. During periods with electricity overproduction in the system, it is used to heat up the pebbles (heat storage material) in a high temperature pebble-heater by electric resistive heaters. When there is a need for additional electricity, the stored high temperature heat is used to run a gas turbine coupled with a generator.

During the charging phase, only the Pebble-Heater PH-E (see Fig. 5) is in operation. The heat storage material there is electrically heated from 550°C to 1100°C. In that way, the electricity is used only for storing the high temperature heat, which is very important for the round-trip efficiency. During the discharging phase, the whole equipment presented in Figure 5 is in operation. Compressed air is preheated in the low temperature Pebble-Heaters (PH1…PH4) to 550°C and then further to 1100°C in the high temperature storage PH-E. Hot compressed air expands in the gas turbine and released mechanical work is used for compressor drive and electricity generation. After the expansion, the exhaust air heat is stored in the low temperature storage PH1…PH4 and used again for preheating the compressed air. By activating the set of presented valves, always only one Pebble-Heater is in the compressed air loop and the remaining three are in the exhaust air phase. After a certain period (e.g. 20 minutes), another PH is switched to the compressed air loop and the previous PH is switched to the exhaust air loop, and so on.

![Flow diagram and nominal process parameters of HiTES](image)

With the existing gas turbine, the round trip efficiency of 40.4% may be reached. If the available heat is used further, the total efficiency rises to 59.3%. Through additional measures, like evaporative cooling (fogging), increased water injection, increased turbine inlet temperature, optimal pressure ratio, wet compression and intercooling, the round trip efficiency rises from 40.4% to at least 54.5%.
LEVELISED COST OF ELECTRICITY – LCOE

Usually the first criterion for comparison between different energy storage technologies is the round-trip efficiency. It is also clear that the investment cost has to be acceptable in order to achieve the economic viability of the storage system. Some authors use the specific investment costs per one kWh of stored electricity, others prefer the specific investment costs per one kW of the input or output capacity. Comparisons based on such criteria give quite different results. The most correct practice is to use the levelised cost of electricity (LCOE). It is an adaptation of the model used for electricity costs from power plants. The LCOE contains the capital expenditure (CAPEX) and the annual operational expenditure (OPEX), both referring to the energy output Wel. The interest rate \( i \) and the lifespan \( n \) in years are also included [8].

![Figure 6: Influence of specific investment, efficiency and price of input electricity on LCOES](image)

The LCOE has to be extended with the characteristics of energy storage systems. That results in the levelized cost of electricity storage (LCOES). It contains the costs of the input electricity \( \sigma \) and the round trip efficiency \( \eta_{el} \). The complete formula is given below:

\[
LCOES = \frac{CAPEX}{W_{el}} \cdot \frac{i \cdot (1 + i)^n}{(1 + i)^n - 1} + \frac{OPEX}{W_{el}} + \frac{\sigma}{\eta_{el}}
\]

This is the most objective value for comparing the energy storage technologies. For the correct comparison, all technology details have to be known and be analyzed. Sometimes there is a difference between the nominal discharge capacity and the capacity which is achievable in praxis, as the full discharge cycles would mean a drastic reduction in the lifespan. In the case of chemical batteries, the capacity is not the same at the beginning and at the end of their lifespan. In such cases the realistic pair of capacity and lifespan has to be taken into account.

In Figure 6 two energy storage systems are compared:

- One with high round-trip efficiency of 85% and high specific investment cost of 1600 €/kWh; due to further development the cost may be reduced to 800 €/kWh;
- The other system has a round-trip efficiency of 40%, but the specific investment cost of just 250 €/kWh (20 h discharging time); due to further development the round-trip efficiency may be improved to 50% and 60%, retaining the same specific investment cost.
The presented curves show the change of storage cost LCOES (€/MWh) as a function of the input electricity cost, also in (€/MWh). With further development of the solar and wind generation technologies, that price will decrease, a tendency that has already been experienced in the last years (the lowest recorded price from a photo-voltaic system is 25 €/MWh in Chile). Even some negative electricity prices are plotted, as with high penetration of intermittent renewable power generation it happens often that the stock market prices are negative.

CONCLUSION

Without energy storage it is impossible to implement the generation of renewable electricity based on intermittent sources like wind and solar. Although there are many different technologies available nowadays, they are still not widely used, as they are still very expensive and not suitable for distributed power generation. One possibility with a huge potential is the HiTES technology, which is attractive because of its relative low specific investment cost, long discharge time (10, 20, or even 30h) and its potential to improve its efficiency easily towards 60%. The analysis of LCOES, which is the best comparison criteria, shows that those systems are more favourable than the battery storage. The specific investment cost is considerably more important than the round-trip efficiency. With the steadily falling prices of the renewable generation, that effect will become more and more pronounced.

LIST OF REFERENCES