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REVISITING COMPRESSED AIR ENERGY STORAGE

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ABSTRACT

The use of renewable energies as a response to the EU targets defined for 2030 Climate Change and Energy has been increasing. Also non-dispatchable and intermittent renewable energies like wind and solar cannot generally match supply and demand, which can also cause some problems in the grid. So, the increased interest in energy storage has evolved and there is nowadays an urgent need for larger energy storage capacity.

Compressed Air Energy Storage (CAES) is a proven technology for storing large quantities of electrical energy in the form of high-pressure air for later use when electricity is needed. It exists since the 1970's and is one of the few energy storage technologies suitable for long duration (tens of hours) and utility scale (hundreds to thousands of MW) applications. It is also one of the most cost-effective solutions for large to small scale storage applications.

Compressed Air Energy Storage can be integrated and bring advantages to different levels of the electric system, from the Generation level, to the Transmission and Distribution levels, so in this paper a revisit of CAES is done in order to better understand what and how it can be used for our modern needs of energy storage.

Keywords: Renewable Energy, Energy Storage, Compressed Air Energy Storage (CAES).

1. INTRODUCTION

The vision of a low-carbon society is rightly associated with the use of renewable energy sources (RES), such as solar and wind power. The European strategy for Climate Change and Energy sets as targets for 2030 a 40% reduction of greenhouse gas emissions compared to 1990, an increase of 27% of renewable energy, and an improvement of 27% in energy efficiency [1].

Energy policies are promoting distributed energy resources such as energy efficiency, distributed generation (DG), energy storage devices (ES), demand-side management (DSM) and renewable energy resources (RES) [2].

With the increased use of RES and due to their intermittent factor and non-dispatchability there is an urgent need for additional energy storage, in order not to waste the energy that can be generated at low demand periods. So, intermittent generation like wind can cause problems in grids, in balances between supply and demand and in adequacy of power.

Solutions to decrease the problems caused by the variable output of intermittent resources are to add energy storage to the system, to create more flexibility on the supply side to mitigate supply intermittency and load variation, and to increase flexibility in electricity consumption [2].

Energy storage is a process which increases the flexibility of the way we generate, deliver and consume electricity. It provides the ability to balance power supply and power demand, making power networks more resilient, efficient and cleaner than before [3]. It is used to level the load in different time frames. Typically, the energy is stored during low demand periods and released during peak demand hours, to reduce the gap between the tip and the void (daily, weekly and seasonal level).

Energy storage technologies can be divided into several groups (Fig 1):
1. Chemical: Hydrogen; Synthetic Natural Gas and other chemical compounds (ammonia, methanol…).
2. Electrochemical: Lead-acid batteries; Nickel-Cadmium batteries; Sodium-sulphur batteries; Lithium-ion batteries and Vanadium redox-flow batteries.
3. Electrical: Supercapacitors and Superconducting magnetic energy storage.
4. Mechanical: Pumped Hydro Energy Storage; Compressed Air Energy Storage and Flywheel energy storage.
5. Thermal: Hot-water storage; Molten-salt energy storage and Phase change material storage.

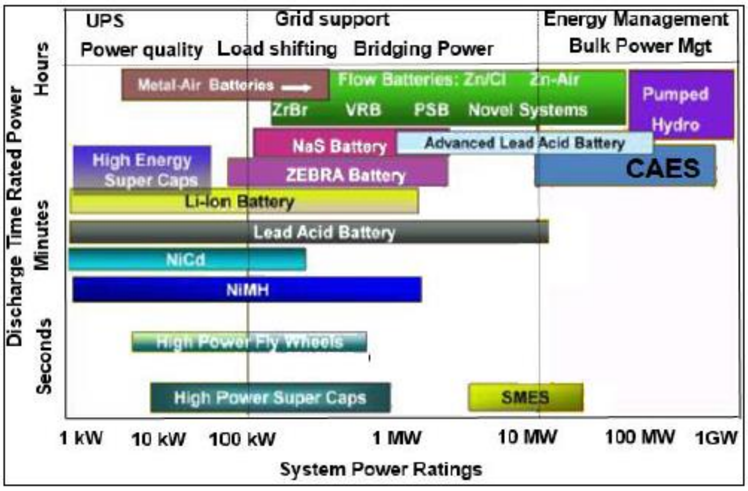

Fig 1- Energy storage technologies comparison. **a)** time to discharge and power; Source: Neumiller, J. L. (2009) [16].

The applicability of different types of storage also depends on the efficiency, lifetime (in operating cycles) and investment costs [2].

One of the larger scale energy storages, are the mechanical types of energy storage, like Pumped Hydro Storage (PHS) and Compressed Air Energy Storage (CAES).

Compressed Air Energy Storage (CAES) is one of the few energy storage technologies suitable for long duration (tens of hours), utility scale (hundreds to thousands of MW) applications [4] and also one of the better storage technologies in terms of cost-effectiveness, reason why it is the chosen technology for this paper.

2. COMPRESSED AIR ENERGY STORAGE (CAES)

Storing energy with compressed air systems emerged in the 1970s as a promising peak shaving option [5] and also because of the oil crisis in the 1970s and searching for alternatives. The interest in the technology has intensified in recent years, because of the increasing interest and need about energy storage.

CAES is nowadays a demonstrated technology (Huntorf CAES Plant and McIntosh CAES Plant are the proof) for storing large quantities of electrical energy in the form of high-pressure air [6]. In a CAES plant, ambient air is compressed and stored under pressure in a geological reservoir or underground cavern or even in surface reservoirs as tanks or pipes; when electricity is required, the pressurized air is heated and expanded in a turbine, driving a generator for power production [3], (Fig. 2).

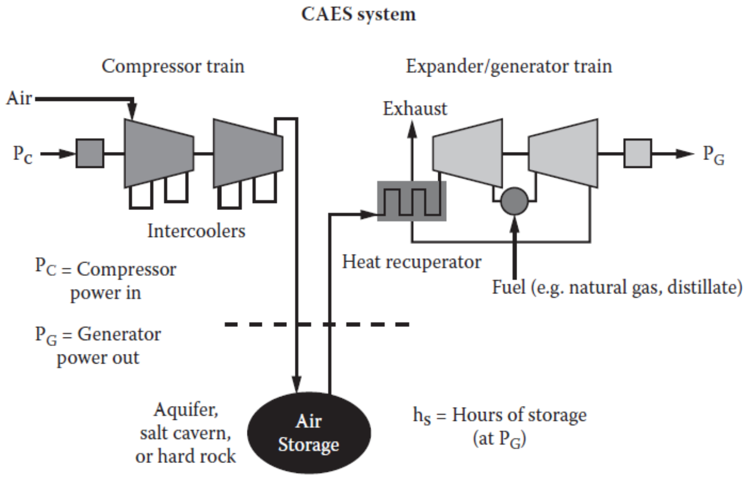

Fig. 2 - Compressed Air Energy Storage System configuration. Adapted from [4, 6]

According to Succar & Williams [4] and Barnes & Levine [6] CAES operation is not very different from a conventional gas operation. These authors describe the process (Fig. 2) as: “During the compression (storage) mode, electricity is used to run a chain of compressors that inject air into an uninsulated storage reservoir, thus storing the air under high pressure and at the temperature of the surrounding formation. The compression chain makes use of intercoolers and an aftercooler to reduce the temperature of the injected air, thereby enhancing compression efficiency, reducing the storage volume requirement, and minimizing thermal stress on the storage volume walls… During expansion (generation) operation, air is withdrawn from storage and fuel (typically natural gas) is combusted in the pressurized air. The combustion products are then expanded (typically in two stages), thus regenerating electricity.”

2.1 CAES Suitable Reservoirs

Carnegie *et al* [7] described a variety of storage means that can be used for CAES, such as salt caverns, hard rock caverns, porous rock formations (like aquifers), abandoned mines, pipes, underwater bladders and above-ground tanks. The same authors also divide CAES into two types according to their capacity of storage and type of reservoirs: a) Bulk CAES, which needs large subterranean geological formations, are the most economical ones and can store from one hundred to thousands of MW for more than 5 hours, usually they store from 300 to 400 MW over the course of 10 to 30 hours. b) Small CAES, which uses above-ground systems, pipes, bladders or other man-made vessels to store the compressed air and usually have capacities on the order of 10 to 20 MW and discharge time less than 5 hours.

Among the geological storage options, salt formations are the most easy to develop and operate. There are two types of these formations, large bedded salt deposits and dome structures and both of them can be used for CAES reservoirs. However, according to Succar & Williams [4] salt beds are usually more challenging to develop if large storage volumes are required, because they tend to be much thinner and often contain a comparatively higher concentration of impurities which present significant challenges with respect to structural stability. On the other hand caverns mined from salt domes can be tall and narrow with minimal roof spans. The only two CAES plants currently operating in the world (Huntorf and McIntosh CAES facilities) use solution-mined cavities in salt domes as storage reservoirs [6].

Caverns in hard rock are also an option for CAES reservoirs, however this is a more expensive alternative due to the cost of mining a new reservoir, unless use is made of abandoned mine cavities [6].

Porous rock formations such as saline aquifers and depleted oil and gas reservoirs are suitable for CAES development too and it appears that this type of geology is the lowest cost option [6]. Depleted oil and gas reservoirs can be used as reservoirs, with more risks associated (like flammability among others, but with three main advantages when compared to saline aquifers: i) containment conditions are proved; ii) the local geology is well known (and therefore require less exploration efforts and investments- of millions of euros of order); iii) the pressure was reduced by hydrocarbons production- injecting air will not cause overpressures and can actually avoid issues such as subsidence.

2.2 CAES Technologies and Efficiency

Although commercial CAES plants have been operating for several decades, the technology is still in a stage of development, which is reflected in the fact that the only two existing plants are based largely on conventional gas turbine and steam turbine technologies [6].

The process of compressing air generates heat, which is usually released into the atmosphere or it could be recovered and also stored. After the compression of air, it is stored in the reservoir and then it is expanded, that is a process that requires heat and where there are always some heat losses. So, according to the ways that a CAES system manages the heat generated in the compression phase and used in the expansion phase, these systems can be classified into three different types.

2.1.1 Diabatic CAES

Diabatic CAES, or Conventional CAES, is the most developed technology and the two existing CAES plants are based on this method. It uses conventional gas turbines where the compression of the combustion air is separated and independent from the actual gas turbine process [3], or according to Carnegie *et al* [7] Diabatic CAES uses heat added during the expansion process to increase the power capacity (Fig. 3). Efficiency of plants based on conventional CAES is around 42% without heat recovery and around 55% with waste heat recovery.

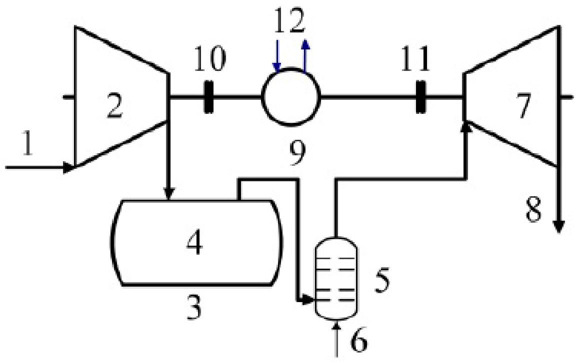

Fig. 3 – Diabatic or Conventional CAES Diagram where: 1- Air, 2- Compressor, 3- Reservoir, 4- Compressed Air, 5- Combustor, 6- Fuel, 7- Turbine, 8- Exhaust, 9- Motor/Generator, 10 and 11- Clutch and 12- Electricity. In: Energy Storage Technologies & Applications, [8].

2.2.2 Adiabatic CAES

The new Advanced Adiabatic CAES Method (AA-CAES) is an evolution of conventional CAES and uses a thermal storage device to capture heat expelled in the compression process and then uses the stored thermal energy to reheat the air during the expansion process [7], (Fig. 4). The heat of compression is recovered and used to reheat the compressed air during turbine operations, so there is no longer any need to burn natural gas to warm up the decompressed air, which diminishes carbon emissions and increases the efficiency of the process to up to 70% [3] alleviating most of the economic uncertainties of CAES [9]. Some Adiabatic CAES projects have been researched and proposed, but until now none has reach design stage. However, there is one project in Germany called ADELE – Adiabatic Compressed Air Energy Storage for Electricity Supply, which has been researched and is more developed and *German Electrical utility (RWE Power)* announced plans to construct the new A-CAES plant [10].

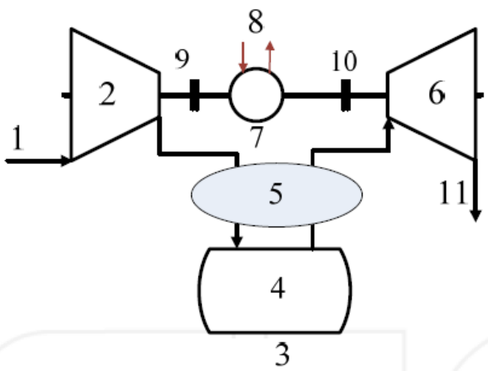

Fig. 4 – Advanced Adiabatic Diagram where: 1- Air, 2- Compressor, 3- Storage Reservoir, 4- Compressed Air, 5- Thermal Energy Storage, 6- Turbine, 7-

Motor/Generator, 8- Electricity, , 9 and 10- Clutch and 11- Exhaust In: Energy Storage Technologies & Applications, [8].

2.2.3 Isothermal CAES

Isothermal CAES technology is an emerging technology that compresses and expands air slowly so that the air temperature remains constant, eliminating the need to burn fossil fuels to reheat the air during expansion, decreases GHG emissions and substantially increases efficiency, theoretically near 100%. The potential for round-trip efficiency is expected to be somewhere between 70% and 80%, although currently there are no commercial Isothermal CAES facilities and it is still an immature technology that requires further research [3].

2.2.4 Considerations on the effciency of CAES systems

The simplest type of a Compressed Air Energy Storage (CAES) facility would be an adiabatic process consisting only of a compressor, a storage and a turbine, compressing air into a container when storing and expanding when producing, this could happen if the machines were reversible and it would have a storage efficiency of 100%; however, in practice due to the specific capacity of the storage and the construction materials, the air is cooled during and after compression, making the CAES process diabatic [11]. The cooling involves exergy losses and thus lowers the efficiency of the storage significantly.

CAES plants have two inputs of energy: electricity to compressor and fuel to burner, that occur at different points in time, so it is not so obvious how to define the efficiency of storage [11]. However, efficiency estimates vary significantly depending on the specific CAES technology (as we previously have seen) and geologic features [7] and it can be defined as a function of exergetic efficiency of compression, storage and production, all together [11].

According to Carnegie et al [7] diabatic CAES is not a pure storage technology, because it is also necessary to burn some fuel and the cost of fuel inputs can significantly raise overall costs. Fertig & Apt [12] described the concept of adiabatic CAES as eliminating the use of fossil fuels, although they say adiabatic CAES (case study in ERCOT, Texas, USA) is likely not cost-effective at current natural gas prices and under the USA GHG regulations, but that situation could reverse under higher gas prices and stricter limits on GHG emissions.

2.3 CAES existing plants

There are two main commercial CAES plants in the world, Huntorf in Germany and McIntosh in USA, and neither was built with the purpose of making use of wind power at the beginning. However, there are several other projects of CAES plants being studied and developed for the future due to the increase and fluctuation of electricity production based on renewable sources.

Huntorf CAES plant, in Germany, was built in 1978 in two salt caverns (310,000 m^3 total) [13], it had a power capacity of 290 MW and in the beginning it had the purpose of providing black-start services to nuclear units near the North Sea and to furnish inexpensive peak power, however it has been increasingly used to help balance the rapidly growing wind output from North Germany [4,6,13].The work by Crotogino et al [13] gives an overview of operation experiences in this CAES plant after 20 years.

According to the same authors the availability and starting reliability for this unit are reported as 90% and 99% respectively and its efficiency is about 42%.

McIntosh CAES plant, in Alabama, USA, has been operating since 1991 in a salt dome (560,000 m^3) and it was built as a source of inexpensive peak power to face the oil and gas prices. The starting reliabilities achieved are described as 91.2% and 92.1% average for the generation cycle and the average running reliabilities are between 96.8% and 99.5% for the compression cycle and its efficiency is around 54% [4,6].

There are several other CAES projects being researched and developed in USA like Norton CAES, in Ohio in an idle limestone mine and a storage reservoir for a 800 MW CAES facility [6]; Iowa Stored Energy park developing an aquifer CAES project directly coupled to a wind farm and with a proposed capacity of 268 MW [6]; Texas CAES projects in Matagorda for a facility of 540 MW [7]; New York State Electric & Gas is developing a 150 MW CAES project in salt cavern [14] and another one aboveground with a 9 MW system [7]. There are also projects being researched in China, in Japan and others also in Europe, like Larne CAES project in Northern Ireland, and ADELE project in Germany.

3. ADVANTAGES AND LIMITATIONS OF CAES

Compressed Air Energy Storage can be integrated and bring advantages to different levels of the electric system, from the Generation level, to the Transmission and Distribution levels.

It has several advantages, including a better management of the grid, ensure energy security, balance supply and demand and converge towards a low carbon economy.

These advantages can be translated in several benefits like reliability and security of the grid, power quality, transmission optimization, black-start functions and arbitrage for utility companies.

The primary benefits of a CAES system are ancillary services provided to the grid, where their applications include: peak shaving, spinning reserve, VAR (Value of Reactive Energy/Reactive Power) support and arbitrage [9]. The advantages of CAES are particularly interesting when coupled with an intermittent source such as wind energy.

Because of the heat generation during the process of air compression and the need for heat in the expansion fase, there are losses which are inevitable, as in any energy conversion. Less energy eventually makes it to the grid if it passes through the CAES system than in a similar system without storage [9]. In any event, the requirement for additional heating in the expansion process is the most significant disadvantage [9], mainly because current CAES systems are based in gas burning.

Another limitation is the fact that for installing a CAES Plant with underground reservoirs it is needed some specific geological conditions that are not available everywhere. So, there are restrictions on the availability of places with suitable geological conditions.

4. CONCLUSIONS

Compressed Air Energy Storage is a proven technique of storing large amounts of energy as the potential energy of a compressed gas, usually referring to the air that is pumped into large storage reservoirs that can be above ground tanks or naturally occurring underground formations.

Compared to other storage technologies, CAES is a cost-effective option for load shifting and one of its main purposes is to store wind energy during times of transmission curtailment and generation onto the grid during shortfalls in wind output [6].

In the light of nowadays Climate Change and Energy European and National regulations, CAES technologies are one of the energy storage technology alternatives that allow to store large amounts of energy for periods where other large systems like pumped hydro storage fails because for instance, lack of water.

CAES also have less environmental impact on land (because its underground reservoirs are precisely underground) and also less impact on water compared to Pumped Hydro Storage and less environmental issues compared to batteries.

Until now the two commercial existing CAES plants (Huntorf and McIntosh) have shown economic feasibility and reliability [15].

However, CAES technologies need further developing, especially needs further developing of their new adiabatic and isothermal CAES technologies concepts and also need to increase CAES efficiency and decrease the losses during the process.

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