Compressed Air Energy Storage

Carolina Crespo (53251), Duarte Batista (51095), Lara Ribeiro (49800), Ricardo Louro (51534)

University of Lisbon - Faculty of Sciences

Energy Systems

ABSTRACT

Compressed Air Energy Storage (CAES) presents itself as a storage option for non-dispatchable renewable energy such as wind and solar energy. This work aims to gather fundamental information about CAES, and analyse whether it is a feasible storage option for the characteristics of the work island.

I. INTRODUCTION

The island under study is inhabited by 50 000 people, who try to make it as sustainable as possible using renewable energy, including locally produced biomass, as energy sources for the supply of the local electricity grid. As we know, renewable energies are complicated energy sources, since it is not always possible to produce energy from them, or to control how much we produce — that is, they are not dispatchable.

In the absence of structures that will compensate for this, the inhabitants of this island will not be able to use their electrical appliances whenever they want or need to, instead being at the mercy of luck. Most modern electricity grids avoid this problem with conventional thermal power plants, such as coal, gas, fuel oil etc., which are dispatchable, or by having a significant contribution from nuclear energy, which is not dispatchable but will also not have gaps in production, as it always operates at approximately the same power.

However, in this island we are trying to build a renewable-based energy system. Considering this, in order to be able to provide energy whenever it is needed, we will need energy storage facilities. These facilities allow energy to be stored during times of excess production, that is, when production is higher than demand, in order to be used later, when production is insufficient to satisfy demand. Energy storage is one of the greatest challenges of our times. Large, country-wide electricity grids are having trouble with the planning and installation of energy storage facilities, and these have much greater diversity of energy sources, so it is to be expected that our island presents an even greater challenge — its small size and small diversity of power sources means it is more likely to have periods in which demand exceeds production.

Compressed air energy storage (CAES) is one of many energy storage solutions. It works by using excess electricity to compress air which is then stored in either air tanks or large natural caverns. Later, when the stored energy is needed, the air is allowed to decompress, passing through a turbine and converting the stored energy back to electricity.

This technology is one that has been deemed "promising" for many years, yet this promise has thus far failed to materialise. The only two existing CAES plants in the world are already quite old and as we shall see ahead they are not pure CAES plants. But with many researchers working on this, perhaps we are close to a breakthrough which will see CAES plants become common in the future.

CAES has two definite advantages when compared to other storage options: it can be used virtually everywhere (in most places there are existing natural caverns which may be used, and in they absence one may use air tanks), which is a great advantage when compared with options such as pumped hydro, whose application is very spatially limited; and its resource — air — is unlimited, in contrast with, for example, batteries, which are currently mostly Li-ion, and worldwide lithium supply is limited in both quantity and variety of sources, creating an issue of dependence on producing countries.

II. WORKING PRINCIPLE

A. Gas power plants

Modern gas power plants produce electricity by burning gas in an air chamber, causing the air to heat and expand and directing the expanding air through a turbine, making it turn. However, air is usually compressed in advance, before the burning of the gas, in order to improve the overall efficiency of the process — compression makes it so that the expanding air will have more energy to turn the turbine, and additionally makes it so that combustion is more complete.

Gas turbines are therefore made out of three major components: a compressor, a combustion chamber, and a turbine. These are necessary for a complete Brayton cycle: air is compressed in the compressor, then moved into the combustion chamber where it is mixed with fuel and ignited. The expanding air is driven through the turbine. This turbine is on the same shaft as the compressor, which makes it so that while part of the energy is used to power a generator and produce electricity, another part is used to compress the air.[1]

B. Existing CAES plants

Nowadays there are only two CAES plants in operation — Huntorf (Germany) and McIntosh (USA). The first to go into operation was Huntorf in 1978 and has a power rating of 290 MW, while the second one, with a power rating of 110 MW, only started to operate 13 years later.[2] More information on both plants is available on table I.

Both Huntorf and McIntosh should not be considered pure CAES plants. They are essentially more efficient gas power plants. What they do is use off-peak electricity in order to compress air and store it in large reservoirs. This compressed air is later used directly in the burning of gas. This avoids the use of energy from gas burning in compression, which means that more of the energy from the combustion is used for generating electricity. This is significant considering that, in conventional gas plants, about 2/3 of fuel is consumed for the compression stage. Bypassing this translates to a 40% decrease in fuel consumption.[3]

	Huntorf. Germany	McIntosh. USA
Manufacturer	Browne Boveri	Dresser-Rand
Year of Operation	1978	1991
Power Rating (MW)	290	110
Charge Time / Discharge Time (h)	8/2	40/46
Air Pressure (bars)	46-66	45-74
Storage capacity (m^3)	310 000	560 000
Heat Sources	Natural Gas	Natural Gas
Efficiency (%)	42	54
Investment costs (million $)	116	45.1

Table I: Data on Huntorf and McIntosh CAES plants.[2, 4]

III. TYPES OF CAES

A. Adiabatic

An adiabatic process is one in which there is no heat coming into or out of the system. So adiabatic compression of air would involve retaining all the heat energy within the air. However, compressing the air leads to a temperature increase and it is quite difficult, if not impossible, to store high-temperature compressed air, or keep it from radiating thermal energy to its environment and thus wasting energy and leading to inefficiencies.

This means that the key to adiabatic CAES is to capture the heat from the compressed air and store it separately, and later release it back into the air as it expands. This can be done through the use of heat exchangers. One type heat exchanger using oil is able to reach 70-75% efficiency for the heat capture and re-release.[1]

Figure 1 shows a diagram of the working principle of this type of CAES.

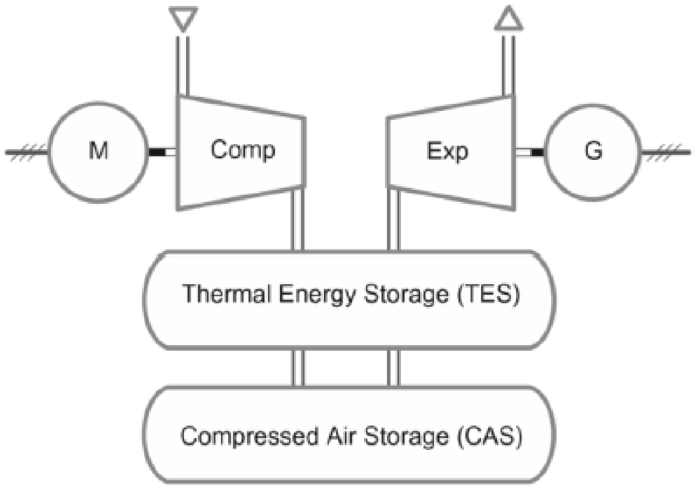

Figure 1: Diagram of the working principle of adiabatic CAES with thermal energy storage[5]

B. Diabatic

In a diabatic CAES system, excess off-peak electricity is used to compress air into large underground caverns, allowing it to release heat into the environment, which will effectively be wasted energy. Later, when the energy is needed, the air is released and heated through fuel combustion, causing it to expand and powering a turbine.[5]

The two existing CAES plants use this method. However, it is theoretically possible (although not yet proved to be economically viable) to build a true diabatic CAES plant, without the need for the burning of gas, and simply using the expansion of the gas to turn a turbine.

C. Isothermal

In isothermal CAES, the air is compressed and expanded extremely slowly, allowing heat to enter and exit the system so that its temperature is always quite close to ambient temperature. This could, in theory, achieve 100% efficiency.[1]

However, we know that true isothermal processes are not possible, and additionally we cannot afford to wait for indefinitely long amounts of time for the gas to compress/expand. With this in mind, current research aims to find relatively quick, near-isothermal compression/expansion methods. One promising technique seems to be spraying small water droplets into the compressors. Water, with its high heat conductivity and high heat capacity helps keep temperature at near-constant values. Research seems to show efficiencies superior to those of adiabatic processes — around 90%. [6, 7]

D. Liquid Air

In this type of CAES, the air is stored in liquid state and not gaseous state. This greatly increases its energy density (at least tenfold), which means that the storage system, for the same capacity, will be much smaller.

Liquefying air, however, is a very expensive process, and liquefied air must additionally be kept in special cryogenic containers. The key to making this process economically viable would essentially be finding a more cost-effective way to liquefy air.[1]

IV. STORAGE OPTIONS - NATURE OF THE RESERVOIRS

CAES requires large volume air reservoirs for an effective and efficient operation of the system. These reservoirs are usually made of salt, hard rock and porous rock layers, which lead to inherent problems such as the presence of animals and salt water, while at the end of each discharge there will be left over air in the system, reducing the overall efficiency of the process.

Isochoric and isobaric storage are the most commonly used storage systems, as well as ideal for underground or above ground storage systems. Above ground storage tends to produce higher energy density, although it has a high capital cost. Because of this, above ground storage tends to be an option mainly for small-scale CAES.[1] Another challenge related to this storage option is the availability of land as well as maintenance costs due to the necessity of maintaining constant pressure throughout the process. Regarding underground storage, airtight cavities could be used when capable of sustaining the required pressures. This type of storage has the benefits of not requiring a vast land and having a low initial capital cost when compared to above ground storage options.

Storage vessels are currently considered to be the main factor making the cost of CAES systems rise beyond profitability. If an appropriate reservoir is available, it is possible for CAES to be a cost-effective option. Otherwise, the costs may simply become too high.[1] However, it is worth noting that appropriate reservoirs certainly exist, and the lack of new CAES plant projects seems to show that there may be other factors at play here.

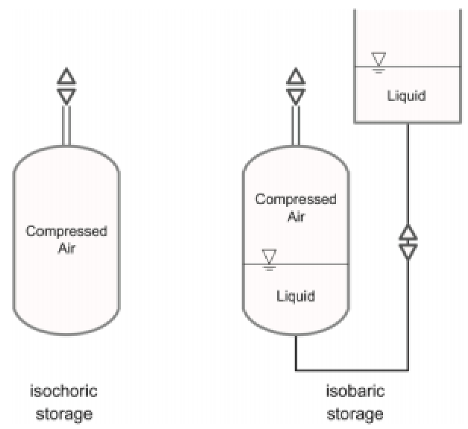

Figure 2: Types of air storage systems

A. Isochoric

Isochoric storage maintains the air at constant volume while the pressure of the air varies. Both natural caverns and steel pressure vessels are examples of isochoric storage. The main limitation of this type of storage has to do with the variation of pressure during compression and expansion which leads to the expander working in pressure conditions which are not the designed pressure ratio, therefore reducing the efficiency of the system.

B. Isobaric

Isobaric storage systems operate at constant pressure, during charge and discharge the volume changes, determining the state of charge. One example of constant pressure storage is underwater storage, where the storage vessel is an expandable container located in the bottom of a lake or sea, or even within an aquifer. When compressed air is pumped into the vessel, the hydrostatic pressure of water controls the pressure of the gas, as more gas is pumped in, the vessel will expand in order to contain it[1]. This type of storage is not often the best choice for the research community due to its complexity.

V. DIMENSIONING A CAES PLANT

The design of a CAES plant should take into account the energy needs of the island population under study, i.e. the discrepancies between production and consumption, as well as its cost-effectiveness when compared to other storage options. Based on the work on electricity demand it is possible to observe the hours in the winter, spring, and summer seasons when there is greater demand and those of lower demand.

For the purposes of this work, we may assume that we would be able to find, somewhere on our island, an appropriate natural reservoir. However, in the absence of recent CAES plant projects worldwide, and considering this is a technology which is largely still in development, it would be difficult, if not impossible, to try to determine costs, whether it be per kWh stored or per kW provided. Nonetheless, considering the point in development at which we are, we can safely assume it would be more expensive than other energy storage options.

One possibility to still use CAES on our island in a cost-effective manner would be to follow the model of the two existing CAES plants, that is, use CAES as support for the air compression phase of the Brayton cycle in a gas power plant. Since we are trying to build a fully renewable energy system, we could in theory substitute the natural gas with locally produced biogas (from waste), and otherwise follow this model, which is the only one which has already actually been proved and executed. Specifically, we could follow the McIntosh model, which has greater efficiency.

A. Biogas values

Through the work carried out by our colleagues on the production of energy through the waste produced on the island, we were able to know the amount of electrical energy that is possible to produce daily — 1.15 kWh per inhabitant. Knowing that the island is inhabited by 50 000 people, this results in a 57 500 kWh daily production.

The use of CAES would act in improving the efficiency of the Brayton cycle and thus somewhat increasing this aforementioned daily production. Studies would be needed to determine whether this increased production would cover the increased costs.

VI. IMPACTS

Beyond the local environmental impacts related to the construction of the plant, the existing CAES plants present GHG emissions because of the use of natural gas for combustion. But since we would in this case replace natural gas with biogas, this issue can be disregarded.

Underground storage seems to be a good option to implement on our island, as we have limited territorial space. On the other hand, this method has some problems, such as the risk of the reservoir "roof" falling, rat holes, damage caused by small animals, and deposition of brine in the reservoir with consequent turbine contamination. These problems can be avoided, but this would imply an increase in maintenance costs.

VII. CONCLUSIONS

The use of CAES is not yet as widespread as it once seemed it would become. The only two existing CAES plants are a few decades old and are not exclusively CAES, instead using CAES simply as a tool to boost the efficiency of gas power plants.

It seems the technology for pure CAES systems is not as mature as one would hope. This means it needs more R&D before it can realistically be applied in a cost-effective manner, meaning it would be better to invest in energy storage options other than CAES for our island. However, further studies could be done in order to determine the cost-effectiveness of adding CAES to the gas power plant which will be installed to burn biogas from waste.

[1] P. A. Breeze, "Chapter 3 - Compressed Air Energy Storage," in *Power system energy storage technologies* (Academic Press, an imprint of Elsevier, 2018) p. 23–31.

[2] J. Wang, K. Lu, L. Ma, J. Wang, M. Dooner, S. Miao, J. Li, and D. Wang, Energies **10**, 991 (2017).

[3] F.-B. Wu, "Chapter 1 - Development of energy storage technology," in *Grid-Scale Energy Storage Systems and Applications* (Academic Press, 2020) pp. 4, 5.

[4] I. Gyuk, EPRI-DOE Handbook of Energy Storage for Transmission & Distribution Applications (2003).

[5] A. Olabi, T. Wilberforce, M. Ramadan, M. A. Abdelkareem, and A. H. Alami, Journal of Energy Storage **34**, 102000 (2021).

[6] X. Zhang, Y. Xu, X. Zhou, Y. Zhang, W. Li, Z. Zuo, H. Guo, Y. Huang, and H. Chen, Energy Procedia **142**, 3388–3393 (2017).

[7] C. Qin and E. Loth, Applied Thermal Engineering **95**, 24–34 (2016).