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ORIGINAL ARTICLE

Lowering the cost of large-scale energy storage: High temperature adiabatic compressed air energy storage

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Electricity storage;
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Abstract Compressed air energy storage is an energy storage technology with strong potential to play a significant role in balancing energy on transmission networks, owing to its use of mature technologies and low cost per unit of storage capacity. Adiabatic compressed air energy storage (A-CAES) systems typically compress air from ambient temperature in the charge phase and expand the air back to ambient temperature in the discharge phase. This papers explores the use of an innovative operating scheme for an A-CAES system aimed at lowering the total cost of the system for a given exergy storage capacity. The configuration proposed considers preheating of the air before compression which increases the fraction of the total exergy that is stored in the form of high-grade heat in comparison to existing designs in which the main exergy storage medium is the compressed air itself. Storing a high fraction of the total exergy as heat allows reducing the capacity of costly pressure stores in the system and replacing it with cheaper thermal energy stores. Additionally, a configuration that integrates a system based on the aforementioned concept with solar thermal power or low-medium grade waste heat is introduced and thoroughly discussed.

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Nomenclature

c	specific heat capacity (unit: J/(kg · K))
$\dot{m}$	mass flow rate of air (unit: kg/s)
n	number of stages of compression/expansion in the system
P	pressure (unit: Pa)
R	specific gas constant for air (unit: J/(kg · K))
s	specific entropy (unit: J/(kg · K))
T	temperature (unit: K)
u	specific internal energy (unit: J/kg)
W	work done by the compressors (unit: W)
X	fraction of the total exergy that is stored as high grade heat

Greek letters

γ	ratio of specific heat capacities
σ	compression ratio per stage
ψ	exergy content per unit mass (unit: J/kg)

Subscripts

0	ambient conditions
1–9	reference to a certain state within the system
H.G.TES	reference to the high grade thermal energy store
high	maximum level of variable within the system
L.G.TES	reference to the low grade thermal energy store
med	intermediate level of variable within the system
p	isobaric
v	isochoric

1. Introduction

At present there is a growing impetus worldwide towards replacing traditional fossil-fuelled power generation with clean energy sources in view of the serious environmental threats posed by the emission of greenhouse gases. However, as the electric network is decarbonized, the challenge of matching supply to demand intensifies because renewables and nuclear are much less flexible than fossil fuels due to their intermittent and not entirely predictable nature and high thermal inertia, respectively [1,2].

Therefore, having effective energy storage methods by means of which the disparity between energy availability and consumption can be managed is imperative to achieve a much more widespread utilization of inflexible renewable generation [3]. Compressed air energy storage (CAES) has been extensively studied and is regarded as a competitive and very promising utility-scale solution for providing stability and other ancillary services to the electric grid [4].

The operation of a CAES system can be divided into two phases: a charge (storage) phase which occurs during off-peak periods and a discharge (generation) phase which occurs during periods of high-demand. When operating in the charge phase a CAES system utilizes electrical energy from the grid to compress air, which is stored at a high pressure and near ambient temperature in a reservoir that may be an underground cavern or a pressure vessel placed aboveground or underwater. Hence, it may be stated that CAES systems store excess electricity in the form of mechanical potential of the pressurized air. During the discharge phase, the compressed air is extracted from the reservoir, heated and expanded in a turbogenerator to deliver electricity to the grid.

Currently there are only two operational large-scale CAES plants, one is located in Huntorf, Germany and the other one is found in McIntosh, Alabama. These CAES plants, known as diabatic or conventional CAES, produce pressurized air through a multi-stage compression process. The heat resultant from each compression stage is removed from the air stream and rejected to the atmosphere. Finally, the cool compressed air is stored in a solution mined underground salt cavern. When operating in discharge mode, the compressed air is released from the reservoir and used as the combustion air in gas turbines to produce work. Before being expanded, the air is heated in combustion chambers to increase the work output and prevent any moisture content from freezing in the turbines [5].

The main drawback of these plants is that energy is vented to atmosphere (in the form of heat) in the charging phase, and an additional energy input (combusted natural gas) is used to regenerate the electric energy that was stored, markedly affecting their roundtrip efficiency.

An improved configuration known as adiabatic CAES (A-CAES) has been investigated by many researchers [6–11]. These systems operate very similarly to the existing plants, the main difference being the integration of heat storage. During the charge phase, the heat of compression is removed from the compressed air stream and stored in dedicated thermal energy stores (TES) instead of being vented to atmosphere. Subsequently, during the discharge phase this heat is restored to the air to increase its temperature before expansion, eliminating the need to burn gas and thus giving A-CAES systems a higher efficiency than diabatic CAES systems and the benefit of being a storage technology with zero combustion emissions. It has been reported that A-CAES systems have the potential of reaching round-trip efficiencies of up to 70% [12,13].

The pressure vessel of a CAES system has in many cases a higher cost than heat storage materials per unit of exergy storage capacity. A study carried out by Black & Veatch in 2012 revealed that for a 260 MW system with 15 h of storage the cost of the cavern (pressure store) represented 40% of the total capital cost of the A-CAES system [14]. It is therefore logical to try to maximize the amount of exergy stored by an A-CAES system in the form of heat.

Accordingly, an innovative configuration and operating scheme for a CAES system that can potentially achieve a lower cost per unit of exergy storage capacity by storing a larger fraction of exergy in the form of high-grade heat as compared with existing designs (in which the main exergy store is the compressed air itself) is presented and discussed herein.

2. Fundamentals of CAES

The operation of A-CAES systems is based on a reversible isentropic compression/expansion process. The work that an ideal adiabatic compressor exerts on the air to increase its pressure (decrease its specific volume) causes a temperature rise in it, given by Eq. (1), where γ is the ratio between isobaric (Cp) and isochoric (Cv) specific heat capacities of the air. This equation is valid for the reverse process as well; during an adiabatic expansion the temperature of the air decreases as it is expanded to produce work.

$$T_2 = T_1 \cdot \left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}} \tag{1}$$

Figure 1 is a diagram of pressure-temperature for the isentropic compression/expansion of air.

In an ideal process, the change in the exergy content (ψ) of the air between the initial and final states is equal to the work (W) done by the compressor, which can be calculated through Eq. (2). If the air is at ambient conditions at the initial state it has no enthalpy or entropy. The work of the compressor represents the amount of electricity (exergy) from the grid that the A-CAES system is capable of storing per unit mass of air.

$$W = \Delta\dot{\psi}_{2-1} = u_2 - u_1 - T_0(s_2 - s_1) \tag{2}$$

$$W = C_p(\Delta T) - T_0\left(C_p \ln\left(\frac{T_2}{T_1}\right) - R\ln\left(\frac{P_2}{P_1}\right)\right) \tag{3}$$

Work is stored, as aforementioned, in two forms: as mechanical potential (due to the pressure increment) and as heat (due to the temperature increment). The pressure-related share of the total exergy of air can be calculated through Eq. (3) assuming a constant temperature ($T = T_0$); while the temperature-related share can be obtained assuming a constant pressure ($P = P_0$). Figure 2 shows the distribution of the exergy stored in the air with respect to the pressure at which it is compressed. It may be observed that the temperature-related fraction of the total exergy becomes dominant as pressure increases.

Compressing air to elevated pressures is desirable from a system point of view for two reasons. On one hand the exergy storage capacity of the CAES plant is maximized as the specific exergy of the air increases for increasing pressures (shown by Figure 2); on the other hand, as the final pressure increases the specific volume of air decreases, resulting in a higher volumetric exergy density, which reduces the volume of the reservoir required to store the compressed air. However, off-the-shelf compressors are not capable of handling the high temperatures arising from compressing air to elevated pressures; therefore compression is limited to rather low final pressures which, as discussed, impacts negatively the storage capacity of the plant.

To overcome said problem, the compression and expansion processes can be divided into multiple stages, as shown in Figure 3. After each compression stage the air is cooled down isobarically to a temperature sufficiently low (T_{med}) so that the temperature at the outlet of the next compressor (T_{high}) remains within an acceptable range. It is important to mention that, in an exergy storage system of this kind, the thermal stores are considered to be packed rock beds for several reasons. The system needs a thermal gradient within the heat stores to cool down the stream of air from T_{high} to T_{med} without destroying too much exergy in the process; additionally, packed rock beds are simple, have a reasonably good storage capacity per unit mass and volume, low-cost and are a well-studied

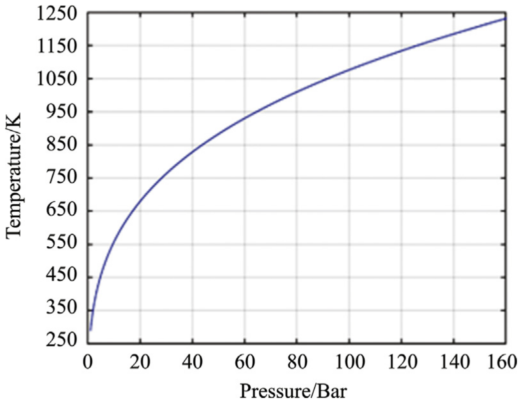

Figure 1 Pressure–temperature diagram for the isentropic compression/expansion of air (assuming a $\gamma = 1.41$).

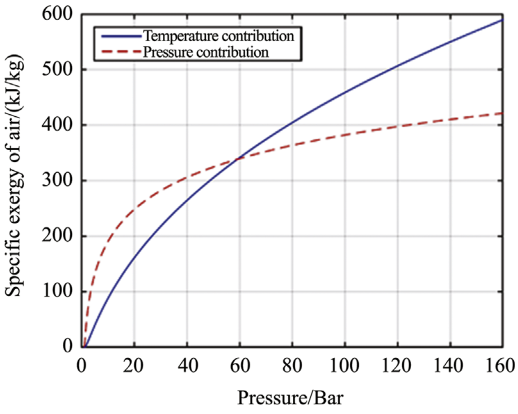

Figure 2 Pressure and temperature contributions to the exergy content of air.

technology [15–17].

The outlet temperatures of the n different compressors will be the same, provided the inlet temperatures and individual compression ratios are the same, according to Eqs. (4) and (5). This equally applies to the reverse expansion process.

$$\sigma = \left(\frac{P_{high}}{P_0}\right)^{\frac{1}{n}} \tag{4}$$

$$T_{high} = T_{med} \cdot \sigma^{\left(\frac{\gamma-1}{\gamma}\right)} \tag{5}$$

Figure 4 shows the effect of splitting the compression into multiple stages and cooling down (isobarically) to ambient temperature after each stage. As it can be seen very high temperatures are reached if air is compressed in a single stage. The introduction of additional stages reduces dramatically the temperature of the air, which allows reaching a higher overall compression ratio thus increasing the exergy storage capacity of the system per unit mass of air.

Maintaining a constant compression ratio across all compression stages (σ) allows storing the heat of compression using a single thermal energy store (as shown in Figure 3); although this is convenient is not strictly necessary. Several independent thermal stores could be used for each of the n compression stages. The expansion process needs to be a mirror image of the compression process in order to extract the same amount of exergy that was stored; however, configurations where the number of expansion stages does not match the number of compression stages can be realized if they are found to be technically favourable.

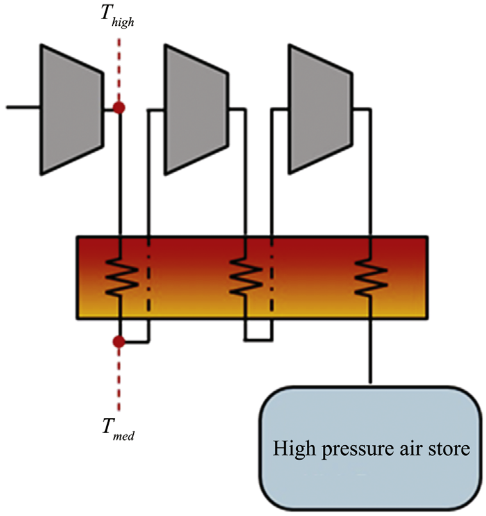

Figure 3 A-CAES system with multiple compression and expansion stages.

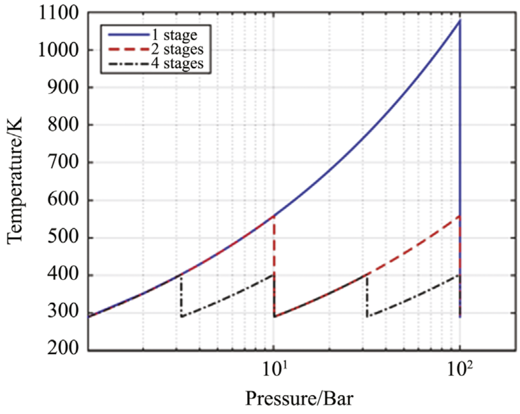

Figure 4 Effect of dividing compression/expansion into multiple stages on the temperature of the air.

3. High temperature adiabatic CAES

A possibility to further increase the exergy storage capacity per unit mass of air of an A-CAES plant is to preheat the air before compression, as shown in Figure 5. Increasing the temperature of the air prior to compression causes an increase of its specific volume, which in turn increases the work requirement (exergy stored) for the compressors. A system operating under this regime is called a high temperature adiabatic CAES (HTA-CAES).

During the charge phase, ambient air is preheated (between points 1 and 2) in a low grade thermal energy store (L.G.TES) before being compressed. The heat of compression is stored after each compression stage in the high grade thermal energy store (H.G.TES) (between points 3–4, 5–6 and 7–8). It should be noted that the H.G.TES is the major exergy store in the system. The remaining heat content of the air stream is stored afterwards in the L.G.TES (between points 8 and 9), so as to have high pressure air at near ambient temperature (point 9), which is finally stored in the high pressure store (HPS). Figure 6 shows graphically the temperatures and pressures of the air stream at different points of interest in the system.

It may be observed that the L.G.TES effectively acts as a recuperator, having a very small net change in its energy

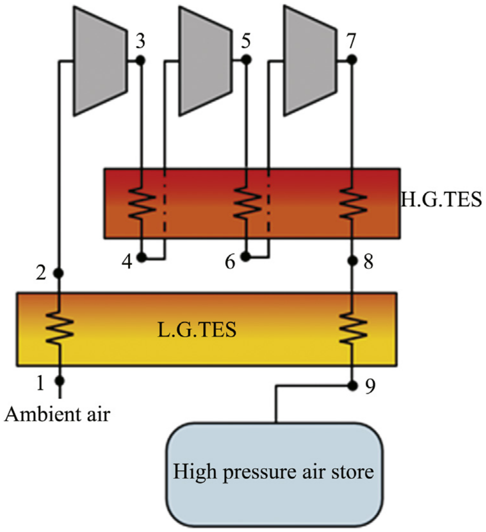

Figure 5 Schematic of an A-CAES system with preheating of air.

content in either phase (charge/discharge) in comparison to the other two stores in the system. Notwithstanding, it is a very important component for the system as the cost reduction intended relies on preheating the air before compression to cause the pressurised stream to emerge at a high temperature from the outlet of the compressors and thus being able to store more exergy in the form of high grade heat (using inexpensive heat storage materials) rather than as mechanical potential in the high pressure air store (which requires a costly pressure containment).

During the discharge phase, the reverse process takes place. The air leaves the HPS, picking up heat from both thermal stores before being expanded in a turbine to generate work. After expansion, the air delivers its remaining heat content to the L.G.TES to be finally vented to the atmosphere at ambient temperature and pressure.

Figure 7 shows a comparison between a 3-stage compression process with and without preheating of air. Dividing the compression process into multiple stages packs, as aforementioned, all the heat of compression into a smaller temperature range; which allows preheating the air before compression without exceeding the operating temperature limit of the compressors. As more compression stages are employed the temperature band over which the heat of compression is stored becomes narrower thus higher preheating temperatures are possible.

In addition to increasing the specific exergy storage capacity of the CAES system, preheating air before compression increases the fraction of the total exergy that is stored in the form of heat. The foregoing results attractive from an economic standpoint as in many cases the pressure vessel of a CAES system has a higher cost per unit of exergy storage capacity than applicable heat storage materials. Consequently, maximizing the amount of exergy stored in the form of heat is desirable; however there is a limitation to the number of stages employed.

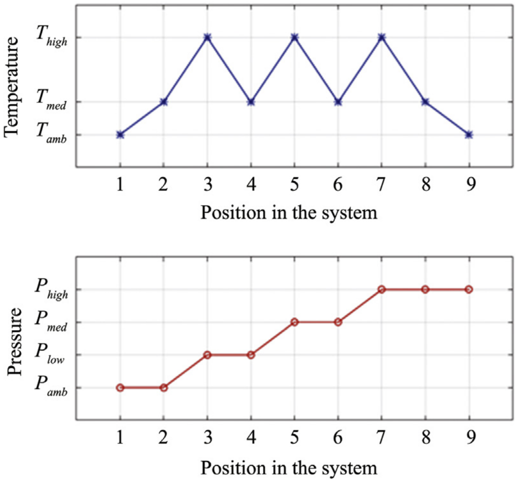

Figure 6 Temperatures and Pressures of the air stream at different positions in the system.

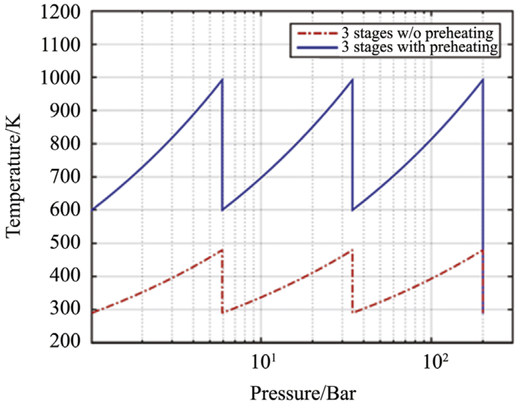

Figure 7 Comparison between a 3-stage compression process starting from: ambient air and preheated air at 600 K.

As the compression process is divided into more stages (which adds complexity to the system) the range over which the heat is stored narrows and is shifted to a higher temperature. This causes the heat storage to be marginally used (if based on sensible heat) because only the high temperature segment of its heat capacity is being exploited; therefore a larger amount of material would be required to store the same amount of heat.

An exergy analysis has been carried out, considering the HTA-CAES system with 3 compression/expansion stages shown in Figure 5, to understand the effect that different outlet temperatures of the L.G.TES and different compression ratios have on the fraction of the total exergy that is stored as heat in the H.G.TES (X). This fraction is defined by Eq. (6) as:

$$X = \frac{\dot{\psi}_{H.G.TES}}{\dot{\psi}_{Total}} \tag{6}$$

During the charging phase, the exergy that is withdrawn from the electric grid by means of the compressors and stored in the system can be expressed as the sum of the exergy increments of the airstream in each one of the compression stages, as shown by Eq. (7):

$$\dot{\psi}_{Total} = \Delta\dot{\psi}_{3-2} + \Delta\dot{\psi}_{5-4} + \Delta\dot{\psi}_{7-6} \tag{7}$$

As aforementioned, the ratio (σ) between the outlet and inlet pressures of the compressors remains constant across all the stages. The arrangement of the components in the system, together with the constant compression ratio, allows having the same inlet and outlet temperatures in all the different stages of compression. Owing to the above, it is possible rewrite Eq. (7) in a simplified form, as shown by Eq. (8):

$$\dot{\psi}_{Total} = n\dot{m}\left[C_p\left(T_{high} - T_{med}\right) - T_0\left(C_p \ln\left(\frac{T_{high}}{T_{med}}\right) - R\ln(\sigma)\right)\right] \tag{8}$$

It can be seen from Figure 5 that the exergy stored by the H.G.TES during the charging phase is the sum of the exergy that the air stream delivers to it upon cooling after each compression stage.

$$\dot{\psi}_{H.G.TES} = \Delta\dot{\psi}_{4-3} + \Delta\dot{\psi}_{6-5} + \Delta\dot{\psi}_{8-7} \tag{9}$$

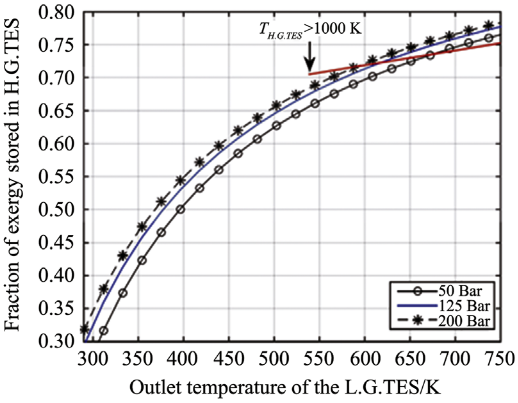

Figure 8 Effect of preheating temperature and compression ratio on the fraction of exergy stored as heat in a system comprising 2 stages of compression.

The air-stream is cooled isobarically in the H.G.TES. Furthermore, the change in temperature that it experiences during each one of its passes through the store is the same (going from T_{high} to T_{med}); therefore, Eq. (9) can be expressed in a simplified form as shown in Eq. (10):

$$\dot{\psi}_{H.G.TES} = n\dot{m}C_p\left[\left(T_{high}-T_{med}\right)-T_0\ln\left(\frac{T_{high}}{T_{med}}\right)\right] \qquad (10)$$

Figure 8 shows the behaviour of the ratio X for different preheating temperatures and compression ratios in a system with 3 compression stages. Air is considered as an ideal gas with a constant specific heat capacity. The higher the preheating temperature is the higher the output temperature of the compressor will be; which means that higher-grade heat is rejected to the H.G.TES.

Increasing the temperature of the H.G.TES translates into a higher fraction of the exergy available being stored as heat. The fraction of exergy that can be stored thermally is limited by the maximum temperature that compressors can handle as well as by the availability (at affordable cost) of storage materials that can tolerate high temperatures; an elevated preheating temperature with a high compression ratio will result in an unacceptably high outlet temperature. The points at which the compressors outlet temperature exceeds 1000 K are indicated in the plot.

Figure 9 shows the relationship between the compression ratio and the L.G.TES outlet temperature. A multi-stage CAES system with a fixed upper temperature of 1000 K for the H.G.TES (discharge temperature of compressors) has been considered as temperatures above this level would be too high for existing or bespoke machinery. For any given final pressure, the temperature of the L.G.TES can be higher as more compression stages are used, which means that the heat of compression is being stored in the H.G.TES in a narrower temperature band.

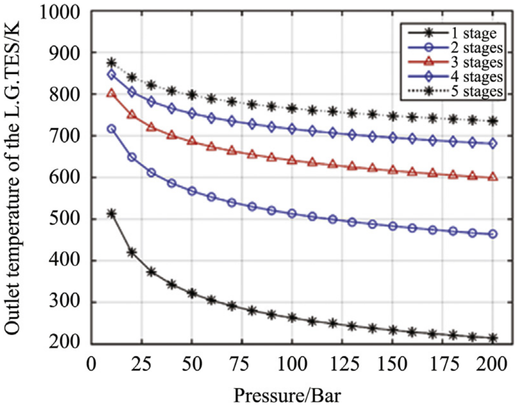

Figure 9 Maximum allowed preheating temperature for a given final pressure.

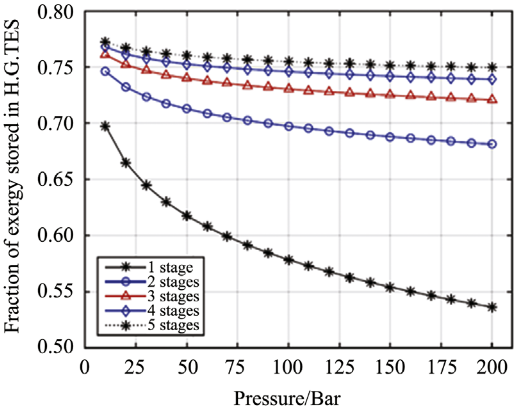

Figure 10 Fraction of exergy stored in the H.G.TES with respect to final compression pressure for different number of stages of compression.

The fraction of the total exergy that is stored as heat in the H.G.TES (X) is shown by Figure 10. It can be seen that for any given number of stages, the ratio X decreases as the compression ratio increases; this is because as the pressure increases the preheating temperature has to decrease to avoid exceeding the upper temperature limit of 1000 K defined for the compressors (and H.G.TES).

However, an important fact to highlight is that, for any desired final pressure, the fraction of exergy stored as heat increases as more compression stages are used, because this allows the L.G.TES to have a higher outlet temperature (i.e. preheating to a higher temperature) which in turn allows storing the heat in the H.G.TES at a higher average temperature, thus increasing its exergy content.

4. Concept of a CAES system incorporating solar thermal capture

The HTA-CAES system discussed in the previous section can be further improved by incorporating solar thermal capture or any other form of low and/or medium grade heat; hence it can act as both, an energy storage plant and a net generator.

The solar-augmented CAES concept considers multiple stages of compression for the charging phase (to increase the fraction of exergy stored as high-grade heat) and a single expansion stage, as shown in Figure 11. It is important to emphasize that the system is being presented as a novel concept based on the concepts discussed in the previous sections and no in-depth exergy efficiency calculations or quantitative cost evaluation that validate the system practical feasibility in the current energy global panorama have been carried out heretofore.

During the charging phase ambient air is drawn into the system and preheated by a group of low and medium grade thermal stores before compression. The preheated air is compressed in a multi-stage process in which the compression ratio is constant across all stages. Following each compression stage, the heat of compression is stored in a H.G.TES bringing the temperature of the air stream down to a suitable level for the next compressor. After the compression process, the high temperature pressurized compressed air flows back through the different thermal stores delivering its heat content to be finally stored at high pressure and near ambient temperature in a high pressure air store (HPS), which could be embodied, as aforementioned, as a cavern underground, a vessel underwater, or a pressure vessel above ground, being the latter the most expensive solution. Therefore, a large fraction of the exergy input by the compressors is stored as heat in the H.G.TES (similarly to the HTA-CAES system described in Section 3) while the remaining is stored as mechanical potential in the pressure store. It should be mentioned that the low and medium temperature thermal stores can receive heat from the solar thermal collectors (or any other external source) at any moment it is available by means of a heat transfer fluid.

In order to generate as much work as possible from the adiabatic expansion of the air it is necessary to expand down to a low temperature; hence a small number of expansion stages should be used. However, having less expansion stages than compression stages makes it necessary to increase the heat capacity of the fluid that passes through the expander so that the heat of compression and added solar heat can be entirely harnessed; therefore an air-steam mixture is used for the discharge phase.

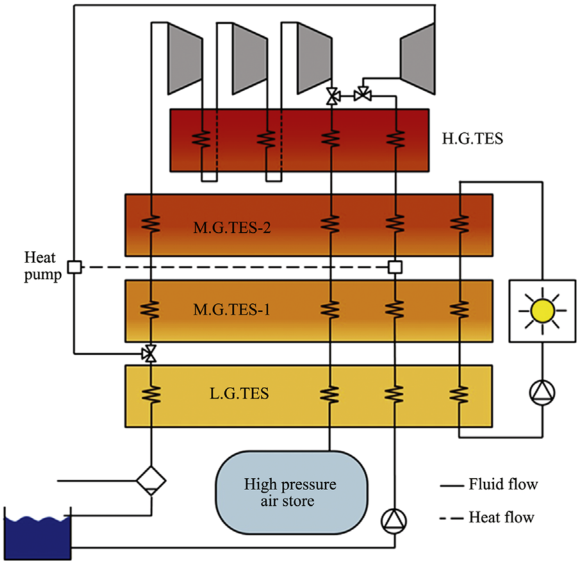

Figure 11 Concept of a CAES system integrated with solar thermal collection or low-medium grade waste heat.

The compressed air is released from the reservoir and circulated through all the tiers of thermal storage to bring it to a high temperature before expansion; simultaneously, water is pumped towards the expander raising its temperature and boiling in a heat pump between the lower-medium (M.G.TES-1) and upper-medium (M.G.TES-2) temperature heat stores. The compressed air and steam mix at the same temperature and pressure after both having passed through the high-grade thermal store.

The air-steam mixture produces work in a turbine, in which it is expanded down to ambient pressure and a temperature just above the boiling point of water to avoid condensation. After the expansion, the steam gives up its latent heat in a heat pump, this heat is used to evaporate the incoming water just before it enters the M.G.TES-2 heat store. Finally, the air-water mixture delivers its remaining heat content to the lowest temperature store and the mixture is separated so that the water can be used again.

It is estimated that the proposed system will attain a roundtrip efficiency of ~65%–70%, comparable to A-CAES projects found in the Ref. [18] being that a great share of the machinery and equipment is the same, and the difference resides in the configuration and operating scheme. Having said the above, the main objective of the proposed system is not achieving a higher efficiency than existing CAES plants and concepts but to achieve a better cost-effectiveness. This is attained in two ways:

(1) The heat of compression is deliberately caused to emerge from the pressurised air at high temperatures, which allows storing a larger portion of the total exergy as high grade heat in a thermal store rather than as mechanical potential in the form of compressed air in a pressure vessel. Even in locations where it is possible to exploit underground or underwater storage of pressurized air, the HP air store will be by far the most expensive component of a CAES system [14]. Consequently, there is a considerable advantage in implementing a system whose configuration allows attaining a required total exergy storage capacity with a smaller high pressure air store.

(2) The cost-benefit of the system is increased by augmenting the functionality of the machinery. The proposed CAES system can act as a net-generator due to the addition of solar thermal capture (or low-medium grade waste heat) without utilizing additional power-conversion machinery, in addition to its main function as an energy storage plant.

Detailed modeling work is required and will be undertaken (as future work) to thoroughly assess the system's performance, round-trip efficiency and cost-effectiveness in order to quantify the potential reduction in cost with respect to existing designs and thereby validate its feasibility.

5. Concluding remarks

A configuration for a compressed air energy storage system has been discussed, which thanks to its operating scheme is capable of storing a larger fraction of the exergy as high-grade heat rather than as mechanical potential of compressed air in comparison to existing designs of A-CAES plants. In other words, the high-grade thermal store is regarded as the main exergy storage in the proposed system and pressurized air is exploited mainly as a means of transferring exergy into and out of that store. The foregoing allows achieving considerable reductions in the cost per unit of exergy storage capacity of a CAES system by reducing the required size of the pressure store which, regardless of its embodiment, is the most expensive component.

An exergy analysis has been carried out whereby it has been shown that the fraction of exergy stored as heat increases as more compression stages are used in the system because it allows the outlet temperature of the low-grade thermal store to be higher, which in turn causes the heat of compression to be stored at a high temperature in a narrower band, increasing thus its exergy content.

The proposed CAES system can has the potential to achieve a better cost per unit of exergy stored because in many cases the cost of exergy storage in the form of heat can be far lower than the cost of exergy storage in the form of compressed air. A possible improvement to the CAES system has been presented in which it could benefit from the integration of solar thermal power or low-medium grade waste heat.

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