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Analysis of diabatic compressed air energy storage systems with artificial reservoir using the levelized cost of storage method

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Summary

A detailed analysis has been carried out to assess the thermodynamic and economic performance of Diabatic Compressed Air Energy Storage (D-CAES) systems equipped with above-ground artificial storage. D-CAES plant arrangements based on both Steam Turbine (ST) and Gas Turbine (GT) technologies are taken into consideration. The influence of key design quantities (ie, storage pressure, turbine inlet pressure, turbine inlet temperature) on efficiency, capital and operating costs is analysed in detail and widely discussed. Finally, D-CAES design solutions are compared with Battery Energy Storage (BES) systems on the basis of the Levelized Cost of Storage (LCOS) method. Results show that the adoption of D-CAES can lead to better economic performance with respect to mature and emerging BES technologies. D-CAES ST based solutions can achieve a LCOS of 28 €cent/kWh, really close to that evaluated for the better performing BES system. Interesting LCOS values of 20 €cent/kWh have been attained by adopting D-CAES plant solutions based on GT technology.

KEYWORDS

artificial air reservoir, battery energy storage (BES), compressed air energy storage (CAES), levelized cost of storage (LCOS), techno-economic analysis

1 | INTRODUCTION

To reduce CO_2 emissions, many countries in the world have been moving from conventional fossil fuel based electricity generation to renewable based ones. Such a choice is leading to a relevant reduction of the amount of CO_2 emitted per kilowatt hour of produced electricity and to the reduction of other pollutants associated to fossil fuel electric generation (ie, NOx, SOx, particulate). Other positive effects of the increasing penetration of Renewable Energy Sources (RES) in electricity markets are related to the improved sustainability of the overall energy system and, for many countries, to a reduced dependence on hydrocarbons and coal.

Conversely, the ever larger share of RES in the electric generation raises problems related to the safe, reliable and cost-effective managing of electric grids. The inherent intermittency of non-programmable RES (solar and wind energy) and the uncertainty in predicting along the time the RES availability can easily lead to a surplus or a deficit of generated electricity in respect to the actual demand.[1] Moreover, in case of large availability of RES, the generating power can exceed the capacity of the transmission lines, which can bring to significant production curtailments. Therefore, the growing use of RES calls for more flexible electric grids able to meet the needs of improved balancing services, such as load levelling, peak shaving and spinning reserve with adequate ramping and de-ramping rates, as discussed in Reference 2.

Electric Energy Storage (EES) systems can give a relevant contribution to the improvement of the electric grid flexibility and, consequently, it can further promote the RES penetration in the electricity markets. Suitable EES applications are addressed to different installed power and charge/discharge time durations. According to Reference 3, power quality improvement applications typically require installed power up to 1 MW and charge/discharge time from milliseconds to minutes, while bridging power applications are featured by installed power ranging from 0.1 to 10 MW with charge/discharge time in the order of seconds, minutes or, in some cases, hours. Other typical applications for RES promotion and integration – specifically addressed in the present paper – are energy management (1–100 MW or more, hours or days) and transmission upgrade deferral (~1–100 MW, 1–6 hours). As reported in Reference 3, the most suited technologies to accomplish such duties are Pumped Hydro Storage (PHS), Battery Energy Storage (BES) and Compressed Air Energy Storage (CAES).

PHS is presently the most effective technology for large storage requirements. In fact, it is a well consolidated and economically viable storage technology widely used since the end of 19th century. The construction of new facilities, especially in developed countries, is hampered by the difficulty of finding new suitable sites and by the impact on the environment connected to the realization of the artificial water reservoir. A significant increase of PHS is occurring in developing countries such as India and China, alongside the increase of the installed generating capacity required to support the rapid economic growth.

BES systems are common solutions for small and very small size applications. The relatively short lifetime and high costs have to some extent hindered the implementation of BES based medium-large storage systems. However, utility-scale plants for energy management and for transmission upgrade deferral are in operation in many countries. Utility-scale systems capacity typically ranges from few megawatt-hours to some hundreds of megawatt-hours. Predominantly used technologies are Lead-Acid, Sodium-Sulfur and Lithium-ion batteries. In recent years (from 2011 to 2016), the latter had shown an increasing share in storage capacity addition, as reported in Reference 4.

Utility-scale battery storage systems based on consolidated and emerging BES technologies installed before 2015 are listed in Reference 3. Typical ranges for rated power and storage capacity for different BES technologies are given below:

- Lead-Acid batteries, utilities ranging from 1 MW and 1.4 MWh to 36 MW and 24 MWh;
- Sodium-Sulfur batteries, from 1 MW and 7 MWh to 34 MW and 245 MWh;
- Lithium-ion batteries, from 6 MW and 10 MWh to 32 MW and 8 MWh;
- Vanadium Redox Flow batteries, from 0.2 MW and 0.8 MWh to 2 MW and 12 MWh.

A large Lithium-ion based plant (100 MW and 129 MWh) located in Southern Australia became operational in December 2017.[5] The main purpose of such a plant is to prevent blackouts resulting from renewable energy intermittency. Another noticeable application has been promoted by TERNA (the Italian Transmission System Operator) to mitigate the curtailment of wind energy production resulting from the insufficient capacity of transmission lines. The project has led to the installation (accomplished in 2016) of three similar storage facilities based on Sodium-Sulfur batteries located in southern Italy. Each facility is featured by a rated power of 12 MW and a storage capacity of 90 MWh.[6] This application will be taken as a reference case to evaluate the techno-economic performance of the D-CAES system proposed in the present paper.

Essentially, a CAES system operates according to a Brayton thermodynamic cycle where various processes (air compression, combustion or heating and expansion) do not co-occur as in a Gas Turbine, but take place separately in different time periods. During the charging phase, ambient air is compressed by using electric power taken from the grid and stored in a natural or artificial reservoir. During the discharge phase, the stored compressed air is heated and subsequently expanded to produce power exported to the electric grid.

According to the basic operating principle, diverse CAES concepts have been proposed: Diabatic CAES (D-CAES), Adiabatic CAES (A-CAES), Isothermal CAES (I-CAES) and Supercritical Compressed Air Energy Storage (SC-CAES).[7]

Presently, the only concept developed at industrial scale is D-CAES. Other CAES concepts are still at laboratory or at demonstration scale.[8] Both high-temperature and low-temperature A-CAES show technical issues which are hindering their application on an industrial scale. Concerning the high-temperature A-CAES, relevant technical challenges deal with the availability of centrifugal compressors capable of operating at high inter-stage and discharge temperature (ie, 500°C-600°C).[9] Conversely, despite the low temperature A-CAES concept relies on mature technologies, adequate performance levels can be achieved only if both compression and expansion trains are made of a relevant number of intercooled or re-heated stages.[10] Although components do not require any technological development, such complex arrangements need considerable engineering efforts and costs for their implementation, justified only for large facilities. Moreover, the complexity of such systems generally entails relevant problems in terms of plant management.

In existing conventional D-CAES plants (Huntorf and McIntosh plants), a fuel (Natural Gas) is used to heat the stored air during the discharge phase. To improve the overall efficiency of the system, a multistage intercooled/aftercooled compression and a two-stage re-heated expansion are adopted.[11,12] Such plants are featured by relevant installed power and storage capacity: the output rated power of Huntorf facility (located in Germany) is of some 320 MW with a storage volume of some 310 000 m^3. The compressed air is stored in underground mined salt caverns. During operation, the air pressure ranges from 46 bar at the end of the discharge phase to 72 bar when the reservoir is completely charged. McIntosh plant (Alabama, USA) even uses a salt mine for air storage. The operating pressure range (46-75 bar) is in practice the same as that of Huntorf, while the storage volume (538 000 m^3) is about twice. The declared rated output power is of 110 MW.[7,13]

Budt et al.[13] enumerate and discuss in detail the economic and technical aspects for which, in spite of its potential, CAES has not established itself as a diffused storage technology. Some of such aspects are common to all the grid-connected storage technologies: the generalized reduction of peak/off-peak electricity price spread and the improvement of the flexibility of both generation plants and electric grids. In particular, the lower cycle efficiency in respect to competitors (e.g. PHS and BES technologies), the lack of off-the-shelf machinery to arrange high-efficiency plants and, finally, the restrictions imposed by the availability of suitable underground reservoir are indicated as major CAES downsides. Nevertheless, they retain that for the near future, decentralized CAES systems could be successfully and profitably employed for off-grid and self-consumption applications as well as to deliver lower grid levels ancillary services. The above applications require small/medium size facilities conveniently located on the electric grid. In addition, the development of small/medium scale systems entails reduced costs, and a broader market is expected in terms of installed units.

Taking the above into consideration, the main objective of the present paper is the techno-economic assessment of small-/medium-size D-CAES systems having the following characteristics:

- installed power ranging from 5 to 15 MW (small/medium size plants);
- the well-established D-CAES technology will be taken as a reference, to minimize the need of technological developments;
- artificial tank reservoirs will be addressed, in order to overcome any constraint to the plant location related to the availability of suitable underground storage reservoirs.

In the following, the thermodynamic performance of D-CAES plants equipped with artificial air storage will be investigated by varying key design parameters. Subsequently, with reference to an actual case (TERNA storage installation in southern Italy[6]), the influence of design parameters on D-CAES investment and operating costs will be evaluated and widely discussed. Finally, the most economically viable D-CAES design solution will be compared with BES systems on the basis of the Levelized Cost of Storage (LCOS).

For each choice of plant design parameters, D-CAES investment cost is evaluated on the basis of a sizing procedure aimed at defining all design quantities required to estimate the purchase and installation costs of the main plant items. D-CAES equipment cost has been evaluated by taking volumes, thicknesses, heat transfer areas, and so on into consideration by adopting an individual factor method according to Reference 14. Such an approach is expected to lead to more reliable results in comparison to those achievable by simplified methods commonly adopted in the literature (e.g. References 15-18). Indeed, CAES investment costs are merely given in terms of installed power and stored energy. The above aspects represent a novelty of the LCOS analysis discussed in the present work.

Another relevant point addressed in the present paper concerns the great attention paid to the actual feasibility of CAES systems under consideration, which mainly depends on the possibility of using commercially available equipment with no or minor modifications. Such a topic will be discussed in detail in Section 2.1.

2 | D-CAES THERMODYNAMIC PERFORMANCE ANALYSIS

2.1 | Plant description

The D-CAES system under consideration (Figure 1) is made of an inter- and aftercooled four-stage compressor train (CT), a reservoir constituted by an artificial storage tank (AST), an air pre-heater (APH), a combustion chamber (CC) and, finally, a gas expander (GE). The APH is

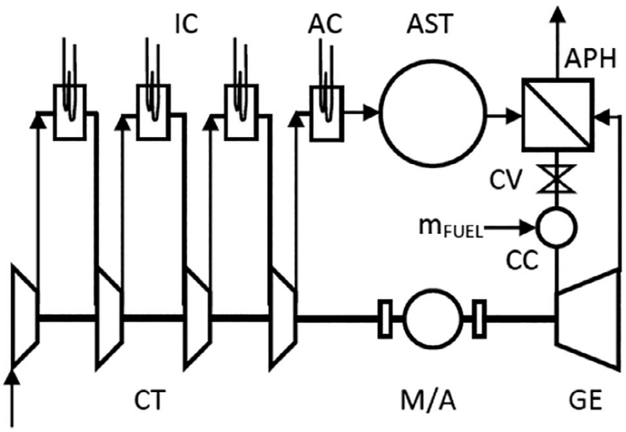

FIGURE 1 Proposed D-CAES plant scheme: CT, compression train; IC, intercoolers; AC, aftercooler; M/A, reversible electric machine; AST, artificial storage tank; APH, air pre-heater; CV, control valve; CC, combustion chamber; GE, gas expander

considered only if the temperature of the GE exhaust gas is high enough to permit a significant pre-heating of the compressed air supplied to the CC.

The compression train and the gas expander are connected by a clutch system to a reversible electric machine working as a motor in charging mode and as a generator during discharge.

During the charging phase, the pressure inside the reservoir varies depending on the mass of air which instant by instant is filling the tank. Consequently, compression takes place at variable pressure ratio.[19]

Therefore, with reference to a complete charge operation, the pressure ratio raises from:

$$\beta_{IN} = \frac{p_{IN}}{p_{AMB}} \tag{1}$$

to:

$$\beta_{ST} = \frac{p_{ST}}{p_{AMB}} \tag{2}$$

being p_{IN} and p_{ST} the initial and the final pressure within the tank, and p_{AMB} the ambient pressure.

During the discharge phase, the Gas Expander (GE) inlet pressure $p_{GE,IN}$ is held constant. This choice implies throttling losses in the control valve (CV, Figure 1), which penalize the plant efficiency. Conversely, constant pressure control facilitates plant operation and management. In fact, both D-CAES existing plants are operated according to this modality.[11,12]

As a consequence, the discharge takes place only if the air pressure within the tank is higher than the GE setpoint inlet pressure. Disregarding the pressure drop across CC and APH (which is in the order of 2%-4% of the GE inlet pressure), the GE pressure setpoint has been assumed equal to the minimum pressure inside the storage tank, that is, $p_{GE,IN} = p_{IN}$.

About plant feasibility, it should be highlighted that all the main items constituting the system can be arranged by using commercially available industrial equipment with no or minor modifications.

In fact, taking the target power range into consideration (5–15 MW), the compression train can be arranged by using industrial intercooled multi-stage centrifugal compressors. A typical four-stage intercooled compressor arrangement has been selected for the present application. Such a choice represents a compromise between the need of reducing the work required to compress the unit mass of air (which reduces by increasing the number of intercooled stages) and the possibility of assembling the compressor train by using typical off-the-shelf industrial equipment.

The man-made storage system is built by welding together large diameter steel pipe sections used for Natural Gas pipelines.[20] As reported in Reference 21, such a solution has been regarded as the most convenient for storage pressure up to 150 bar.

The CC can be derived from Gas Turbine technology[22,23] while the APH can be designed by adopting the same layout and components (tubing, manifolds, casing, etc.) employed in Heat Recovery Steam Generators[22]).

Finally, the GE can be based on Steam Turbine (ST) or Gas Turbine (GT) technology.[13,23] The first one is characterized by elevated inlet pressures (up to 250 bar) and fairly low inlet temperatures (up to 600°C). On the other hand, GT technology is featured by moderate inlet pressures (up to some 20 bar for Heavy Duty GTs and up to 30 bar for Aero-Derivatives ones) and really high inlet temperatures (up 1500°C). An industrial ST and a GT expander have been adopted to assemble the expansion train of the large size Huntorf plant, as reported in Reference 13.

The same approach can be applied to the power range addressed in the present work (ie, 5–15 MW). Major industrial ST manufacturers have developed pre-designed building blocks to assemble turbines suitable to match customer requirements in a wide interval of power ranges and steam inlet conditions.[24-26] Such blocks can be successfully used to assemble efficient and cost-effective GEs with reduced development efforts, as discussed in Reference 27.

According to Reference 28, power recovery turbines commonly used in the process industry show severe limitations in terms of gas inlet temperature (700°C-750°C). Higher inlet temperatures can be managed by resorting to the well-established GT technology. Expanders developed for small size GT units (rated power in the range 5–10 MW) can be easily adapted to operate in D-CAES designed for a power output ranging from 10 to 20 MW. In a study aimed at assessing the techno-economic feasibility of 12 MW D-CAES plant,[28] the use of a modified commercially available GT was proposed by the manufacturer. Modifications essentially consist in the removal of the compressor, maintaining the original combustion chamber, the expander and the heat recovery device located downstream the expander itself. A cost of some 250 $/kW (2005 currency), inclusive of the electric generator, has been estimated for the GT derived gas expander.

Taking the above into consideration, the technical performance assessment of the D-CAES system addressed in the present paper will be carried out by adopting the following criteria:

- if the GE inlet pressure is assumed equal or higher than 40 bar, ST technology is adopted and therefore, the maximum admissible temperature at GE inlet is limited to 550°C;
- if GE inlet pressure is assumed equal to 20 bar (compatible with the current GT technology), the maximum GE inlet temperature is fixed at 850°C. Such a value is consistent with the adoption of less demanding and cost effective uncooled machinery.

2.2 | Plant modelling

In Figure 2, processes accomplished in a D-CAES plant are schematically represented on a T-s (temperature-entropy) diagram. For ease of representation, the inter-cooled/after-cooled compression process actually occurring during the charging phase has been assimilated to an isothermal compression process taking place at ambient temperature, and pressure losses occurring in APH and CC are not considered. Therefore, on the basis of the above assumptions, a complete charge of the reservoir can be represented by a line connecting point A to point B.

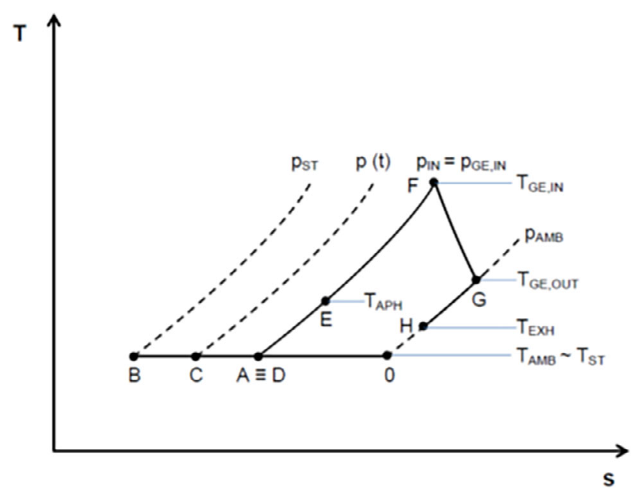

FIGURE 2 Representation on a T-s diagram of processes occurring in the D-CAES plant under consideration [Colour figure can be viewed at wileyonlinelibrary.com]

At the generic instant t of the discharge phase, the pressure inside the reservoir p(t) has a value between p_{ST} and p_{IN} (point C on the diagram). Therefore, according to the adopted GE control mode, the air withdrawn from the reservoir has to be throttled through the control valve to adjust its pressure to the value $p_{GE,IN} = p_{IN}$ (line CD). Subsequently, the air is fed to the APH, where it is preheated to the temperature T_{APH} (line DE). The temperature is further increased up to the value $T_{GE,IN}$ by a combustion process occurring at pressure p_{IN} (line EF) and then, combustion products are admitted to the GE for expansion (line FG). Finally, GE flue gases are cooled in the APH (line GH) to pre-heat the compressed air. The temperature of flue gases exiting the GE $T_{GE,OUT}$ depends on the values assigned to $p_{GE,IN}$ and $T_{GE,IN}$. For low $T_{GE,IN}$ and high $p_{GE,IN}$ values, $T_{GE,OUT}$ may result not high enough to allow an effective heat recovery. In such a case, the throttled air (point D) is directly supplied to the CC. The minimum $T_{GE,OUT}$ value allowing the air preheating is set at 150°C.

2.2.1 | Charging phase modelling

The work required to accomplish the charging phase has been evaluated by adopting a simplified analytical approach according to the following assumptions:

- air behaves as a perfect gas;
- the isentropic exponent k, intended as the ratio between constant pressure and constant volume specific heats, is assumed constant (k = 1.4);
- all compression stages operates at constant polytrophic efficiency η_{PS};
- the temperature T_{OUT} of the air exiting the intercoolers and the aftercooler is kept constant;
- instant by instant, all compression stages operate with the same pressure ratio $\beta_S(t)$. Such a pressure ratio is set up by adopting the following rule:

$$\beta_S(t) = \sqrt[N]{\beta(t)} \tag{3}$$

where $\beta(t)$ represents the overall pressure ratio at time t and N the number of compression stages;

- mechanical and electrical losses are accounted for by introducing an electric-mechanic efficiency η_{EM};
- According to Reference 29, the temperature of the stored air T_{ST} is assumed constant during charging, idling and discharging phases.

By applying the energy conservation equation, the work dW_{CH} necessary to introduce into the reservoir the elemental mass dm during the infinitesimal time interval dt may be expressed as:

$$dW_{CH} = \frac{R}{\varepsilon}[T_{AMB} + (N-1)T_{OUT}] \times \left[\beta(t)^{\varepsilon/(N\eta_{PS})} - 1\right] dm \tag{4}$$

being T_{AMB} the ambient temperature, R the air constant, T_{OUT} the air temperature at the exit of each intercooler, η_{PS} the polytrophic efficiency of each compression stage. The polytrophic exponent ε is evaluated as:

$$\varepsilon = \frac{k-1}{k} \tag{5}$$

being k the ratio between constant pressure and constant volume specific heats.

Recalling that the temperature inside the reservoir T_{ST} is assumed constant, dm can be related to the pressure ratio increase $d\beta = dp/p_{AMB}$ occurring during the time interval dt by applying the state equation of perfect gases:

$$dm = \frac{Vdp}{RT_{ST}} = \frac{Vp_{AMB}}{RT_{ST}} \times \frac{dp}{p_{AMB}} = \frac{p_{AMB}V}{RT_{ST}} \times d\beta \tag{6}$$

where V represents the volume of the reservoir.

The expression of the elemental mass dm given by Equation (6) is then substituted into Equation (4). The resulting differential equation in the one variable β can be easily integrated from β_{IN} to β_{ST}. Therefore, the overall work required to realize the charging phase can be expressed as:

$$W_{EL,CH} = \frac{p_{AMB}V}{\varepsilon T_{ST}}[T_{AMB} + (N-1)T_{OUT}] \times \left[\frac{N}{N + \varepsilon/\eta_{PS}}\left(\beta_{ST}^{\left(\frac{\varepsilon}{N\eta_{PS}}+1\right)} - \beta_{IN}^{\left(\frac{\varepsilon}{N\eta_{PS}}+1\right)}\right) - (\beta_{ST} - \beta_{IN})\right] \tag{7}$$

Using again the state equation of perfect gases, the overall amount of air charged into the reservoir m_{CH} can be expressed as:

$$m_{CH} = m_{ST} - m_{IN} = (p_{ST} - p_{IN})V/(RT_{ST}) \tag{8}$$

The work $w_{EL,CH}$ requested for storing 1 kg of air can be obtained by dividing $W_{EL,CH}$ obtained by Equation (7) by m_{CH} given by Equation (8). Taking into account mechanical and electrical losses, the amount of electricity required for storing the unit of mass of air is given by the following formula:

$$w_{EL,CH} = \frac{R/\varepsilon}{(\beta_{ST} - \beta_{IN})}\frac{1}{\eta_{EM}}[T_{AMB} + (N-1)T_{OUT}] \times \left[\frac{N}{N + \varepsilon/\eta_{PS}}\left(\beta_{ST}^{\left(\frac{\varepsilon}{N\eta_{PS}}+1\right)} - \beta_{IN}^{\left(\frac{\varepsilon}{N\eta_{PS}}+1\right)}\right) - (\beta_{ST} - \beta_{IN})\right] \tag{9}$$

2.2.2 | Discharge phase model

Since the GE operates in a constant pressure mode, stationary operations can be assumed in modelling the discharge phase. Air and combustion products are treated as mixtures of thermally perfect gases, that is, the value of thermodynamic quantities (constant pressure and constant volume specific heats, enthalpy, and so on) are solely dependent on temperature and composition. The above quantities are calculated by adopting the formulae proposed by Rivkin.[30]

The Air Pre-heater (APH) is modelled as a counterflow heat exchanger operating at constant effectiveness ε_{APH}. Therefore, the temperature of air exiting the APH can be evaluated as:

$$T_{APH} = \varepsilon_{APH}(T_{GE,OUT} - T_{ST}) + T_{ST} \tag{10}$$

being $T_{GE,OUT}$ and T_{ST} the temperature of the gas exiting the GE and the storage temperature, respectively.

A complete combustion process is assumed in modeling the Combustion Chamber (CC). Such an assumption greatly simplifies calculations without introducing significant errors. The specific enthalpy of product gases $h_{GE,IN}$ is evaluated by applying the energy conservation equation:

$$h_{GE,IN} = \frac{\alpha}{\alpha+1}\left(\frac{1}{\alpha}H_L\eta_{CC} + h_{APT}\right) \tag{11}$$

being α the air to fuel ratio, H_L the fuel lower heating value, η_{CC} the CC efficiency (accounting for imperfect combustion and insulation losses) and h_{APT} the specific enthalpy of air entering the CC at temperature T_{APH}.

GE is modeled by adopting a polytrophic expansion process. Therefore, the temperature of the gas exiting the GE is calculated as follows:

$$T_{GE,OUT} = T_{GE,IN}\left(\frac{1}{\beta_{IN}^{\varepsilon\eta_{PE}}}\right) \quad (12)$$

representing β_{IN} the ratio between GE inlet and outlet pressures, η_{PE} the polytrophic expansion efficiency and ε the isentropic exponent already introduced in Section 2.2.1.

The knowledge of $T_{GE,OUT}$ enables the calculation of the enthalpy of the gas exiting the GE and, finally, the electricity produced by the GE per kilogram of stored air:

$$w_{EL,DS} = \eta_{ME}\frac{\alpha+1}{\alpha}\left(h_{GE,IN} - h_{GE,OUT}\right) \quad (13)$$

2.3 | Thermodynamic performance assessment

D-CAES systems require both fuel and electricity as energy input. For this reason, as discussed in Reference 31, a consistent and fully satisfactory definition of the storage efficiency is neither simple nor obvious. A possible option is to assume as D-CAES storage efficiency the ratio between the quantity of electricity delivered during the discharge period $W_{EL,DS}$ and the total energy supplied to the system, that is, the sum of the amount of electricity absorbed during the charging phase ($W_{EL,CH}$) and the fuel energy fed to the CC during discharge (Q_{FUEL}):

$$\eta_{ST} = \frac{W_{EL,DS}}{W_{EL,CH} + Q_{FUEL}} \quad (14)$$

Electricity is not equivalent to fuel energy. In fact, electricity is often the end product of a complex chain of energy conversion steps that actually starts with a combustion process. Therefore, from a thermodynamic (and economic!) point of view, electricity and fuel energy have different values and, according to Reference 10, the proposed formulation cannot be regarded as a consistent one.

However, the above considerations are of great concern when D-CAES thermodynamic performance has to be compared with other "pure" electric storage system (such as PHS and BES) not requiring additional energy input. Since the thermodynamic analysis here presented is aimed at comparing the performance of the same D-CAES system by varying key design parameters, the storage efficiency defined according to Equation (14) can be taken as a useful and noteworthy merit index.

Taking into consideration the plant model equations, it can be preliminarily stated that the variables which mainly affect D-CAES thermodynamic performance are p_{ST}, $p_{GE,IN}$ (assumed equal to p_{IN}) and $T_{GE,IN}$. In fact:

- according to Equation (9), for a given value of the storage pressure p_{ST}, the amount of electricity $w_{EL,CH}$ absorbed to store 1 kg of air raises by increasing p_{IN};
- for a fixed value of the difference p_{ST}-p_{IN}, higher values of $w_{EL,CH}$ are expected by increasing the storage pressure, as reported in Reference 23;
- according to Equations (12) and (13), the amount of electricity generated during discharge per kilogram of air increases by increasing both p_{IN} and $T_{GE,IN}$[22,32];
- in any case, the amount of the required fuel energy q_{FUEL} raises by increasing $T_{GE,IN}$;
- finally, according to Equation (8), the volume needed to store 1 kg of charged air (attainable by dividing V by m_{CH}) reduces by increasing the difference p_{ST}-p_{IN}. Such a point does not influence the plant thermodynamic performance, but it is expected to have a relevant impact on D-CAES economic performance, as the plant investment cost is heavily depending on the size of the reservoir.[33,34]

Therefore, an exhaustive investigation has been performed by varying key design quantities p_{ST}, $p_{GE,IN} = p_{IN}$ and $T_{GE,IN}$. Another quantity, really helpful in presenting and discussing the achieved results has been introduced. Such a quantity is the ratio between the electricity delivered during discharge and the electricity absorbed during charging phase:

$$E_R = \frac{W_{EL,DS}}{W_{EL,CH}} = \frac{w_{EL,DS}}{w_{EL,CH}} \quad (15)$$

For PHS and BES, E_R coincides with the round trip efficiency of the storage system and, therefore, its value is necessarily lesser than one and cannot by varied arbitrarily being dependent on the physical and technological features of the system under consideration. Conversely, for a D-CAES system, E_R can be varied by varying the amount of fuel energy provided during the discharge phase. In fact, for a given amount of $w_{EL,CH}$ – which is completely defined by fixing the values of p_{ST} and p_{IN}, according to Equation (9) – the amount of the electricity generated during the discharge phase can be set up by fixing the value of the

TABLE 1 Main assumptions for D-CAES thermodynamic analysis

Quantity	Symbol	Value
Ambient temperature	T_{AMB}	20°C
Ambient pressure	p_{AMB}	100 kPa
Number of compression stage	N	4
Intercoolers/aftercooler outlet temperature	T_{OUT}	35°C
Compression stage polytrophic efficiency	η_{PS}	0.85
Mechanical–electrical efficiency	η_{ME}	0.97
Stored air temperature	T_{ST}	30°C
Natural gas lower heating value	H_L	50 MJ/kg
Combustion chamber efficiency	η_{CC}	0.99
Air pre-heater effectivesses	ε_{PH}	0.80
Air expander polytrophic efficicency	η_{PE}	0.85

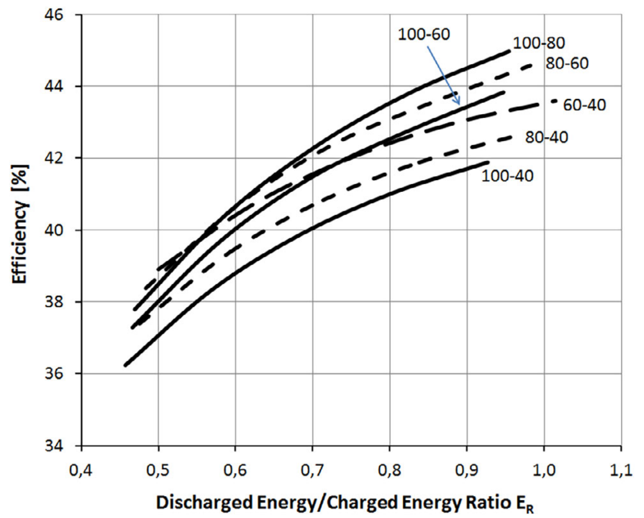

FIGURE 3 ST technology based D-CAES plant efficiency vs discharged energy/charged energy ratio [Colour figure can be viewed at wileyonlinelibrary.com]

temperature $T_{GE,IN}$, which depends on the quantity of fuel fed to the system, as can be seen by recalling Equations (11)–(13). Therefore, E_R can be increased until on the maximum permitted value for $T_{GE,IN}$ is reached.

In the following two sections, the thermodynamic performance of ST technology based and GT technology based D-CAES plant are investigated and discussed. Analyses are carried out according to assumptions reported in Table 1. Thermodynamic analysis results are given with reference to 1 kg of stored compressed air.

2.3.1 | D-CAES plant based on steam turbine technology

Figure 3 shows, for different pairs p_{ST} and $p_{IN} = p_{GE,IN}$, efficiency trends of ST technology based plant by varying the ratio E_R. For each curve reported on Figure 3, the first digit denotes the storage pressure value, the second one the pressure at GE inlet. Values are given in bar.

It has to be premised that the air preheating is not applicable for all the cases taken into consideration. In fact, even for the most favourable cases – characterized by minimum pressure and maximum temperature at GE inlet – the temperature of flue gases exiting the gas expander is always lower than the minimum value required to perform a significant the heat recovery (set at 150°C, as reported in Section 2.2).

It can be observed that, in any case the efficiency increases with E_R. Such an increasing trend may be explained by considering Equation (14). In fact, dividing both numerator and denominator by $w_{EL,DS}$ we get:

$$\eta_{ST} = \frac{1}{\frac{w_{EL,CH}}{w_{EL,DS}} + \frac{q_{FUEL}}{w_{EL,DS}}} = \frac{1}{\frac{1}{E_R} + \frac{q_{FUEL}}{w_{EL,DS}}} \quad (16)$$

Evidently, both terms $w_{EL,DS}$ and q_{FUEL} grow by increasing $T_{GE,IN}$. Actually, the $q_{FUEL}/w_{EL,DS}$ ratio shows an increasing trend by increasing $T_{GE,IN}$. Since $w_{EL,CH}$ does not vary with $T_{GE,IN}$, E_R must raise and, consequently, the ratio $w_{EL,CH}/w_{EL,DS}$ reduces. Such a reduction is greater than the raise of $q_{FUEL}/w_{EL,DS}$ because $w_{EL,CH}$ remains constant while q_{FUEL} increases and, thereby leads to a positive effect on efficiency.

E_R values ranging from 0.9 to 1 can be attained by assuming the maximum allowable temperature at GE inlet (550°C). For a given storage pressure, the best performance is achieved by assuming the highest possible p_{IN} pressure and the maximum E_R ratio. In such conditions, efficiency values higher than 44% can be reached by adopting high storage pressure values (ie, 80–100 bar). The adoption of high storage pressures and a low value of p_{IN} (40 bar) – which is the design choice leading to the lowest storage volume – bring to the worst thermodynamic performance, with maximum efficiency values of around 42%.

2.3.2 | D-CAES plant based on Gas Turbine technology

Results of the thermodynamic analysis of plant-based on GT technology are summarized in Figure 4. It can be noticed that, as observed when dealing with ST based D-CAES systems, the efficiency raises by increasing E_R.

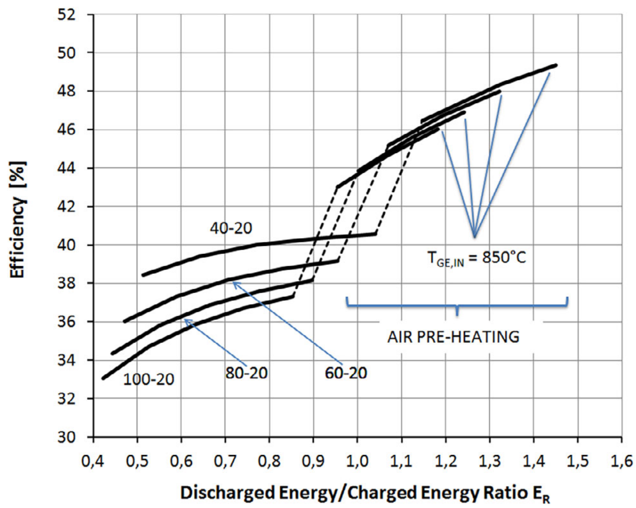

FIGURE 4 GT technology based D-CAES plant efficiency vs discharged energy/charged energy ratio [Colour figure can be viewed at wileyonlinelibrary.com]

Moreover, it can be noticed that the adoption of GE inlet pressure consistent to the GT technology (p_{IN} = 20 bar) entails the achievement of high storage efficiency values when the GE exhaust temperature is high enough to enable a noteworthy pre-heating of the compressed air supplied to the burner. Taking in mind that the APH operates with an effectiveness equal to 0.8, the temperature $T_{GE,OUT}$ of the flue gas leaving the GE is almost close to the temperature T_{APH} of the compressed air fed to the combustion chamber, as can be seen by considering Equation (10).

Consequently, the generated electricity $w_{EL,DS}$ is approximately equal to the energy q_{FUEL} supplied to the CC and, thus, the ratio $q_{FUEL}/w_{EL,DS}$ assumes a value nearly equal to one. Therefore, by deriving Equation (16) with respect to E_R, it can be found that the efficiency increases with a rate proportional to $1/(1 + E_R)^2$.

For E_R values which do not allow the air pre-heating, the thermodynamic performance is noticeably worse than that of ST technology-based systems. Moreover, the efficiency depends markedly on the storage pressure. In fact, ever better results can be observed by lowering p_{ST}.

For E_R sufficiently high to perform the air pre-heating, efficiency values comparable and even higher than those achieved by adopting the ST technology can be attained. Moreover, the efficiency is scarcely affected by the choice of the storage pressure, in contrast to what was found for low E_R values.

For different choices of the storage pressure (from 40 to 100 bar), E_R values ranging from 1.2 to 1.45 are reached by assuming the maximum permitted temperature at GE inlet ($T_{GE,IN}$ = 850°C). The best thermodynamic performance is attained by adopting a storage pressure of 40 bar. In correspondence to the maximum achievable E_R (of about 1.45), the efficiency reaches a maximum value of about 49%.

At the same $T_{GE,IN}$, 100–20 bar plant solutions – characterized by the lowest storage volume requirement, and therefore expected to lead to the minimum investment cost – show efficiency losses of some 3 percentage points in respect to the best efficiency design option (40–20 bar).

3 | D-CAES ECONOMIC PERFORMANCE ASSESSMENT

As declared in Section 1, D-CAES economic performance assessment has been performed by considering a real-world case.[6] In fact, design data featuring the Na-S system built in southern Italy by the national Transmission System Operator (TERNA) have been used to size the D-CAES plant arrangement addressed in the present paper. The BES based storage system under consideration has been sized according to the following specifications:

- charging phase rated power $P_{EL,CH}$ = 12 MW, charging period T_{CH} = 10 hours, absorbed electricity $W_{EL,CH}$ = 120 MWh;
- discharge phase rated power $P_{EL,DS}$ = 12 MW, discharge period T_{DS} = 7.5 hours, generated electricity $W_{EL,DS}$ = 90 MWh.

The system, therefore, operates with an E_R value equal to 0.75 that, as stated in Section 2.3, coincides with the round trip efficiency.

3.1 | The levelized cost of storage (LCOS) method

D-CAES systems economic result has been estimated and compared with other EES technologies by adopting the Levelized Cost of Storage (LCOS) method. LCOS is defined as the ratio between the total costs incurred during the entire plant lifespan T_L and the correspondent amount of generated electricity. The total cost is obtained by adding the investment cost C_{INV} and the operating cost C_A. The latter is evaluated for each year of plant operations and, with reference to the jth year, it is expressed as follows:

$$C_{A,j} = C_{M,j} + C_{INV,j} + c_{EL,j} \times W_{EL,CH,j} + c_{FUEL,j} \times m_{FUEL,j} \tag{17}$$

where $C_{M,j}$ represents the maintenance cost and $C_{INV,j}$ the expenditure incurred in case of replacing of some major plant component at the j-th year. The last two terms account for costs incurred for purchasing electricity and fuel: $c_{EL,j}$ and $c_{FUEL,j}$ are, respectively, electricity and fuel unit costs, and $W_{EL,j}$ and $m_{FUEL,j}$ the amounts of electricity and fuel supplied to the plant during the jth year of operation. In evaluating LCOS, both the annual operating cost and the amount of produced electricity $W_{EL,DS,j}$ are discounted according to the assumed interest rate i:

$$LCOS = \frac{C_{INV} + \sum_{j=1}^{j=T_L} \frac{C_{A,j}}{(1+i)^j}}{\sum_{j=1}^{j=T_L} \frac{W_{EL,DS,j}}{(1+i)^j}} \tag{18}$$

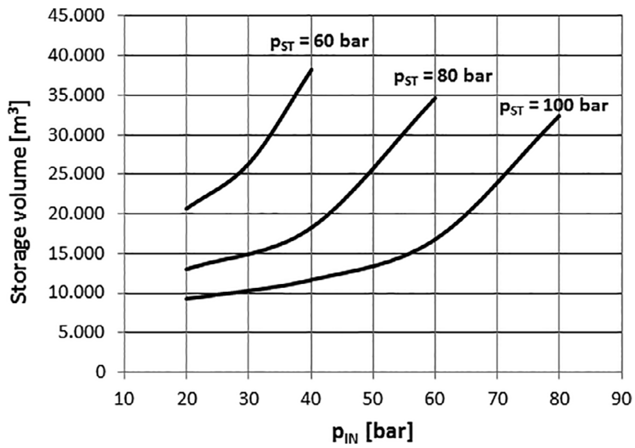

FIGURE 5 Required storage volumes by varying pST and pIN

3.2 | D-CAES investment and O&M costs estimation

The estimation of D-CAES investment cost has been carried out for all cases reported in Figures 3 and 4 by adopting an individual cost factor method.[22,27]

To evaluate the plant capital cost, sizes of main components have been established on the basis of the thermodynamic analysis outcomes.

The compressor train and the storage system have been sized according to design specifications set for the charging phase (ie, 12 MW and 120 MWh).

The mass of stored air m_{CH} is evaluated by dividing the amount of electricity absorbed during the charging phase (ie, 120 MWh) by the amount of electricity required for storing the unit mass given by Equation (9). The volume of the reservoir is then calculated by applying Equation (8).

A D-CAES system can be designed by adopting an arbitrary value for E_R (as discussed in Section 2.3). The assumed E_R value defines the amount of electricity $W_{EL,DS}$ produced during the discharge phase:

$$W_{EL,DS} = E_R m_{CH} w_{EL,CH} = E_R W_{EL,CH} \tag{19}$$

The rated power delivered during discharge is set up by dividing $W_{EL,DS}$ by the discharge period duration T_{DS}. To carry out the techno-economic analysis, T_{DS} has been assumed equal to that of the reference existing plant (ie, 7.5 hours). Therefore, according to Equation (19), for a given amount of $W_{EL,CH}$, the higher E_R is, the higher $W_{EL,DS}$ and $P_{EL,DS}$ are.

Storage volumes evaluated by varying p_{ST} and p_{IN} are given in Figure 5. According to Equation (8), the tank volume increases by reducing the difference p_{ST}-p_{IN}, and by adopting low storage pressures. As an example, taking as a reference a storage pressure equal to 100 bar, the volume grows by 60% by raising p_{IN} from 20 to 60 bar. If the storage pressure is set to 80 bar, a p_{IN} raise of the same extent roughly triples the needed storage volume. Recalling that low storage pressures and reduced p_{ST}–p_{IN} differences lead to improved thermodynamic performance, plant solution characterized by high-efficiency values will require large and, therefore, costly storage apparatuses.

The air reservoir is built by welding 12 m length, 30” OD carbon steel pipe sections. Given the storage pressure, the wall thickness has been calculated by applying an ANSI procedure. The number of pipe sections is then evaluated according to the required storage volume.

Capital expenditure has been evaluated according to the following:

- based on vendor information, the acquisition cost of pipes has been assumed equal to 800€ per metric ton (2018 currency);
- the shipping costs have been estimated as 30% of the pipes acquisition cost;
- the welding cost has been evaluated according to Reference 35;
- costs incurred for installation (inclusive of labour, support and base structures, hoisting operations and testing) have been accounted for by applying a factor equal to 1.5, according to Reference 21.

The reservoir direct cost has been calculated by adding steel pipes, welding and installation cost. The overall investment cost is then obtained by charging the indirect costs (assumed equal to 20% of direct costs[21]) and shipping costs.

Annual operating costs related to inspection, anti-corrosive treatments, cleaning operations and replacement of defected parts, have been evaluated by applying appropriate factors derived from information provided in Reference 21.

Cost of compressor train CT (inclusive of filtration systems, intercoolers and after-cooler) and gas expander (including combustor) are evaluated by adopting the approach proposed in Reference 36. The component base cost is calculated as a function of the rated power. The estimation of the component direct cost (including base structure, piping, control systems, electric equipment, painting, insulation and labour) is performed by applying a factor equal to 1.75 to the base cost. Indirect cost – accounting for engineering and contractor's fee – are evaluated by multiplying by 1.35 the direct cost. Lastly, the ultimate cost of the CT is obtained by adding the contribution of the reversible electric machine, which depends on the brake horsepower. The electric machine is coupled with the CT during the charging phase and with the GE during discharge. Since CT and GE are generally featured by a different rated power, the electric machine is sized to match the highest one. The CT annual maintenance cost is estimated at 5% of the direct cost.

The design of air pre-heater is basically the same of Heat Recovery Steam Generators (HRSG) usually employed in Gas Steam Combined plants. The only difference concerns the kind of fluid evolving on the tubes side. In fact, in APH water or steam is replaced by compressed air. Consequently, the investment cost estimation has been carried out by adopting the methodology developed by Foster-Pegg in 1989 for HRSG cost estimation,[37] subsequently updated by the author.[38] The base cost of such component is given by the sum of three terms, related to the heat transfer surface area, the equipment necessary for the appropriate management of the compressed air (manifolds, valves, couplings and so on) and of the flue gas (enclosure, thermal insulation and chimney). A cumulative factor equal to 1.44 is introduced to take account of direct and indirect costs. Annual maintenance costs are assumed equal to 5% of the direct cost.

GE base cost has been estimated on the basis of the brake horsepower according to Reference 36. The installation cost is accounted for by applying a factor equal to 1.25.

The CE Plant Cost Index has been applied for cost update. All costs are given in 2018 €.

Costs incurred to purchase and install D-CAES main components are shown in Figure 6. Data refer to plant solutions characterized by P_{ST}–P_{IN} pairs reported in abscissa. For each pair, the solution corresponding to the maximum achievable E_R – characterized by the highest efficiency – has been considered.

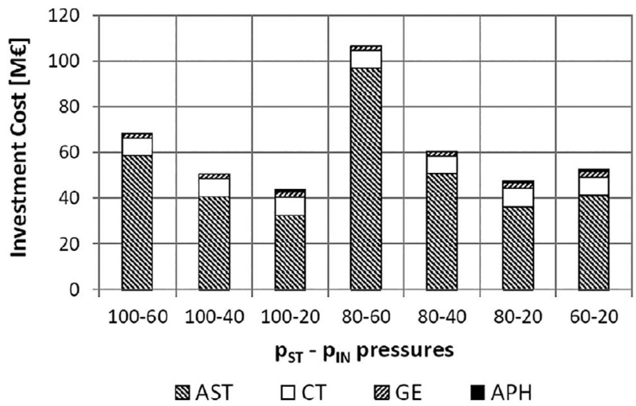

FIGURE 6 D-CAES capital expenditure: CT, compressor train; APH, air pre-heater; AST, air storage tank; GE, gas expander

As expected, the storage tank represents the major expenditure. In addition, being the required storage volume heavily dependent on the difference between P_{ST} and $P_{IN}p_{IN}$, costs raises accordingly. As an example, by considering a storage pressure equal to 80 bar, the overall investment cost the cost doubles by increasing p_{IN} from 20 to 60 bar, rising from about 50 M€ to more than 100 M€. Therefore, plant solutions based on high p_{IN} values entail really high and unbearable investment costs. Moreover, the adoption of ST technology (ie, $p_{IN} \geq 40$ bar) implies relatively low-efficiency values as a consequence of the moderate temperature allowed at GE inlet. Therefore, operating costs also – which are strictly connected to plant efficiency – may result somewhat high.

The adoption of the GT technology ($p_{IN} = 20$ bar, $_{TGE,IN} = 850°C$) leads to significantly lower investment costs, ranging from about 40 to 55 M€. Taking also into consideration that plant solutions based on GT technology are able to reach high-efficiency levels, they appear as the most promising candidates for reaching the best economic result.

3.3 | BES system investment and O&M costs estimation

In the following, the D-CAES economic performance is compared with mature or emerging BES technologies. Lead Acid (Pb-Acid), Sodium-Sulfur (Na-S), Lithium-ion (Li-ion) and Vanadium Redox Flow (VRF) batteries have been taken into consideration. Data to estimate BES technical as well as economic performance have been collected by carrying out an extensive literature survey.[18,39-41] It has to be noticed that different authors

TABLE 2 BES data for cost estimation

	BES type			
	Pb-Acid	**Na-S**	**Li-ion**	**VRF**
Technical data				
Efficiency [%]	80	75	80	80
Deep of discharge DOD [%]	60	80	80	80
Life duration [y]	10	15	10	10
Capital cost data				
C_{POWER} [€/kW]	80	350	510	200
$C_{STORAGE}$ [€/kWh]	240	240	445	600
Maintenance cost data				
C_M [€/kW/year]	24	26	25	32

report really different figures for BES cost data. Therefore, it has been decided to adopt cost indexes leading to the most favourable BES capital expenditure. Such indexes are reported in Table 2, together with technical data required to carry out the LCOS based analysis. As a general trend, cost indexes tend to increase by moving from consolidated (Pb-Acid and Na-S batteries) to emerging technologies (Li-ion and VRF batteries). This especially true for the energy storage index, which mainly depends on the energy storage equipment cost, which includes the costs of the energy storage medium (e.g. the cost of Li-Ion battery cells or flow battery electrolyte), internal wiring and connections, packaging and containers, and battery management system (BMS).

According to a commonly used approach, the investment cost is evaluated by taking into consideration two indexes, C_{POWER} and $C_{STORAGE}$. The first one accounts for the cost of the equipment necessary for power conversion, the cost of devices required for power control and the cost of supporting components and auxiliary systems necessary for proper plant management (Balance of the Plant costs). The second index allows the estimation of the storage equipment and of the installation cost. Therefore, investment expenditure can be calculated according to the following formula:

$$C_{INV} = P_{EL,DS} \times C_{POWER} + W_{EL,DS} \times \frac{100}{DOD} \times C_{POWER} \quad (20)$$

being $P_{EL,DS}$ and $W_{EL,DS}$ the power and the amount of electricity delivered during the discharge phase and DOD the depth of discharge of the battery.

The annual maintenance cost is estimated by multiplying the coefficient C_M (given in Table 2) by the annual amount of delivered electricity.

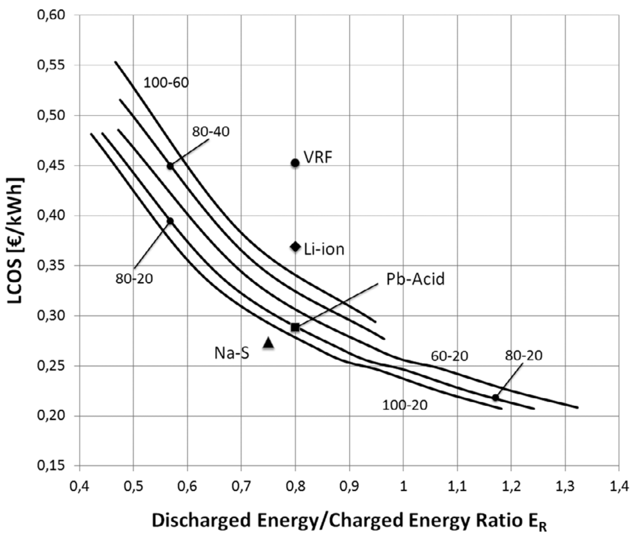

FIGURE 7 D-CAES systems LCOS vs ER and comparison with BES based technologies

3.4 | Comparison among storage technologies

Analyses have been performed according to the following assumptions:

- for both D-CAES and BES systems, a 90% plant availability has been hypothesized;
- one complete operating cycle per day (charging and discharging) at rated design condition is supposed;
- the purchase price of electricity has been set at 10 €cent/kWh;
- the cost of Natural Gas has been set to 25 €cent/Sm^3;
- a 5% interest rate has been assumed.

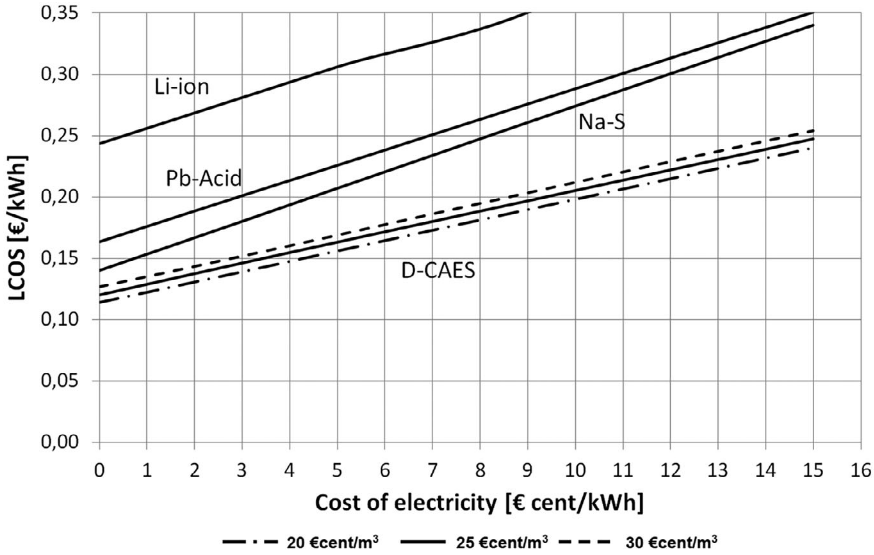

FIGURE 8 Sensitivity analysis by varying fuel and electricity prices

A D-CAES life duration of 30 years has been assumed. Moreover, it is assumed that the GE has to be replaced after 15 years of plant operation.

LCOS estimated by varying E_R is given in Figure 7. As discussed in Sections 2.3 and 3, BES can operate only at fixed E_R, which coincides with the round trip efficiency of the system. Consolidated BES technologies (Pb-Acid and Na-S) can attain LCOS lower than BES technology presently under development (Li-ion and VRF). In fact, LCOS evaluated for Na-S and Pb-Acid batteries are respectively of about 29 and 27 €cent/kWh, Li-ion levelized cost stands at a value of 37 €cent/kWh and, finally, VRF reaches a really high value of 45 €cent/kWh.

Concerning D-CAES systems, LCOS improves by raising E_R. Interestingly, for each value of E_R, the most performing plant solution is always the one that presents the lowest thermodynamic efficiency.

ST based solutions, designed to operate at the maximum allowed E_R with p_{IN} pressures ranging from 40 to 60 bar are able to achieve economic results (LCOS ranging from 28 to 30 €cent/kWh) comparable with Pb-Acid and Na-S batteries.

As predicted, design solutions based on GT technology (characterized by GE inlet pressure equal to 20 bar) lead to better economic results. LCOS figures comparable with those achievable by consolidated BES technology are found for E_R ratios in the range 0.9–1. Moreover, LCOS values around 20 €cent/kWh are reached by assuming the maximum allowable E_R values (E_R = 1,2–1,3), corresponding to LCOS improvements of about 25%-30% in respect to consolidated BES technologies (Pb-Acid and Na-S). Such a result can be regarded as really noteworthy.

Lastly, a sensitivity analysis has been carried out by varying the cost of the fuel and the electricity price. Three values of NG price are taken into consideration: 20, 25 and 30 €cent/Sm^3. The best performing D-CAES arrangement (p_{ST} = 100 bar, p_{IN} = 20 bar and E_R = 1.2) has been compared with the BES systems under consideration. Results are shown in Figure 8. Obviously, the LCOS of D-CAES increases by raising the fuel cost. Anyway, the D-CAES plant shows always the lower LCOS for any electricity price. Another noteworthy feature of the D-CAES system in respect to the BES-based ones (already reported and commented in Reference 18) is the lower sensitivity to the price of electricity, put in evidence by the smaller slope of LCOS lines. In quantitative terms, LCOS of D-CAES increases of some 0.8 €cent/kWh per unit increment of the electricity price, compared to increases of about 1.25 €cent/kWh found for BES based systems.

4 | CONCLUSIONS

A detailed analysis has been carried out to assess the thermodynamic and economic performance of Diabatic CAES systems equipped with above-ground artificial storage. D-CAES plant arrangements based on both ST and GT technologies have been taken into consideration.

The analysis has been performed by varying key design quantities such as the storage pressure p_{ST}, the pressure at GE inlet ($p_{GE,IN} = p_{IN}$) and E_R, intended as the ratio between the electricity generated during discharge and the electricity absorbed along with the charging phase.

Results of the techno-economic analysis are summarized in the following:

- For both ST and GT based D-CAES systems, for a given storage pressure, the thermodynamic performance improves by raising p_{IN} and E_R.

- For E_R values which do not allow the air pre-heating, the thermodynamic performance of ST based systems is better than that of GT based ones. At maximum allowable E_R, ST based solutions show efficiency values in the range 42%-45%.
- For E_R high enough to apply the air pre-heating, GT based systems can attain efficiencies comparable and even higher than those achievable by ST based ones. At maximum allowable E_R, GT based plants can reach efficiencies ranging from 46% to 49%.
- The major investment cost item is constituted by the artificial storage system. Such a cost is heavily dependent on the storage volume which, in turn, mainly depends on the difference p_{ST}–p_{IN}: the higher such a difference is, the lower the cost is.
- According to the above, relatively low investment costs (in the range 40–55 M€) are estimated for GT based plants. Significantly higher investment costs (up to 110 M€) have been evaluated for ST based systems.
- For both ST and GT based D-CAES systems, LCOS improves by raising E_R.
- ST based solutions designed for the maximum allowed E_R (of about 0.95) can achieve LCOS values really close to those evaluated for Pb-Acid and Na-S batteries (29 and 27 €cent/kWh, respectively).
- GT based solutions lead to the best economic result. LCOS values similar to those estimated for mature BES technology can be achieved for E_R ratios ranging from 0.9 to 1. Really interesting LCOS values of about 20 €cent/kWh can be obtained by adopting the maximum allowable values for E_R.
- The LCOS of D-CAES systems shows a lesser sensitivity to the cost of the electricity in comparison to BES based systems.

Future activities will be focused on the investigation of solutions aimed at improving both thermodynamic and economic performance of the proposed CAES system, as well as the storage and re-utilization of the heat absorbed during the compression phase and the adoption of a re-heated expansion process. Moreover, plant performance deterioration over time and plant dismantling costs will be included in future LCOS based analyses.

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