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Techno-Economic Analysis of CAES Systems Integrated into Gas-Steam Combined Plants

Coriolano Salvini[a] *

[a]*Dipartimento di Ingegneria-Università degli Studi ROMA TRE, Via della Vasca Navale 79,00147Rome, Italy*

Abstract

In the present paper, an energy storage concept based on the integration of a Compressed Air Energy Storage system into a Gas Steam Combined Cycle plants is investigated. The integration of CAES results in a noticeable power augmentation in respect to normal GSCC plant operations. Being such a power increase obtained without using additional fuel, the storage system can be compared to PHS, BES and A-CAES. Two CAES integrated into medium size GSCC plants arranged with Aero Derivative and Heavy Duty Gas Turbines have been investigated. A techno economic analysis aimed at assessing plant performance and investment costs has been performed. Despite the relatively high investment costs and the storage efficiency lesser than those featuring alternative storage approaches, the proposed system may be considered of interest due to the long life duration and the established technologies available for the key plant components.

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Keywords: Compressed Air Energy Storage; Gas Steam Combined Cycle; Renewable Energy Sources; Electric Energy Storage.

1. Introduction

In the last decade, the production of electricity from Renewable Energy Sources (RES) has rapidly increased worldwide. Such a growth has led to a relevant reduction of CO_2 emissions and to a noticeable improvement of the overall energy system sustainability. Conversely, due to the intermittency and the uncertainty of RES availability,

* Corresponding author. Tel.: +39 06 55173249; fax: +39 06 5793732.
E-mail address: coriolano.salvini@uniroma3.it

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serious problems arose in ensuring a safe and reliable electric grid management. Electric Energy Storage (EES) can bring a relevant contribution in solving the above issues. Depending on charge/discharge time duration, various EES systems are presently available for different applications: power quality improvement (seconds/minutes), bridging power (up to one hour) and energy management applications (hours) [1]. Energy storage systems for renewable integration typically fall into the last category: EESs featured by suitably long charge/discharge duration periods and by an adequate storage capacity could mitigate the effect of intermittency of RES. EESs can generate additional electricity when RES availability is insufficient to meet the forecast production level or store electricity in case of an excess of availability. The most suited technologies are Pumped Hydro Storage (PHS), Battery Energy Storage (BES) and Compressed Air Energy Storage (CAES) [1].

The CAES basic concept is fair simple. Electricity is absorbed from the grid during off-peak periods to drive a compression train which charges with air a natural or artificial reservoir. During peak demand periods, the stored compressed air is expanded in an air turbine to produce electricity. Starting from the basic concept, a variety of solutions have been developed along the time. Such solutions can be grouped in three classes: Diabatic CAES (D-CAES), Adiabatic CAES (A-CAES) and Isothermal CAES (I-CAES).

In D-CAES, an external heat source (usually a fuel) is used to heat the stored air before the expansion. CAES existing plants (Huntdorf and McIntosh plants) operate according to this principle. During the discharge phase, the stored air taken from the reservoir enters a combustion chamber fed with Natural Gas. The combustion gas is expanded in a high pressure turbine, reheated through a supplementary combustion process, expanded in a low pressure turbine and finally discharged at atmospheric pressure. To improve the system overall efficiency, a multistage intercooled/aftercooled compression train is adopted [2].

In a generally de-carbonization oriented context, the use of fossil fuels to support an EES is considered by many as unsuitable. In order to achieve an emission-free, pure storage technology, the adiabatic CAES concept (A-CAES) has been introduced. In such a concept, the heat absorbed by the intercoolers during the compression phase is stored in a Thermal Energy Storage (TES) system and released during the discharge phase to heat the pressurized air [3, 4]. Finally, the recently proposed Isothermal CAES (I-CAES) approach eliminates the necessity of TES [5]. Quasi-isothermal compression and expansion processes are performed by exchanging heat with the surrounding environment through heat transfer surfaces or by using a liquid medium in direct contact with the air.

In their noticeable work, Budt et al [6] analyze the reasons because despite the almost generally recognized CAES potentialities and merits, such a technology has not become competitive to PHS and BES. They individuate economic as well as technical reasons such as the general decrease of peak/off peak electricity price spread, the improved flexibility of fossil fueled plants in respect to the past, the lower storage efficiency in comparison with PHS and BES. Other relevant issues are related to the lack of off-the-shelf machinery suitable for high efficiency A-CAES and I-CAES plants and the difficulty in finding adapt sites for underground storage. The Authors consider that as a mid-term storage technology (from some hours to some days), CAES can fill the gap between short-term BES and long-term conversion storage technology such as Power-to-Gas. Moreover, they believe that CAES might be efficiently and profitably used for off-grid and self-consumption applications as well as for the provision of ancillary services on the lower grid levels. They conclude that newly built CAES system will be at small or medium scale.

The CAES concept here proposed copes with the above guidelines. Although many Countries are pursuing as a final goal a “decarbonized” electrical system, in the next decades the traditional fossil fuel fed power plants still will play a relevant role in fulfilling the electric demand. Taking the above into consideration, an interesting option is represented by the possibility of using such traditional plants to improve the grid storage capacities.

The proposed concept integrates a CAES system (i. e. a compression train, a storage system and an air expander) into a Gas Steam Combined Cycle (GSCC) plant. The plant reference layout is given in Figure 1. In a GSCC plant, the GT exhaust gas is used to generate steam which expands in a Steam Turbine (ST) producing additional power. During the CAES discharge phase, a fraction of the GT exhaust mass flow rate is fed to an Air Heater (AH) to heat the stored compressed air prior its expansion in an Air Expander AE. If the CAES power production per kilogram per second of exhaust gas is higher than that achieved if the gas is used to produce steam, such a power augmentation is attained without any additional use of fuel. Therefore, the storage system can be considered “fuel free” as BES, PHS or A-CAES. According to possible next future applications of CAES plants, small and medium sizes are addressed. To avoid any geological restriction related to the availability of natural reservoirs, artificial

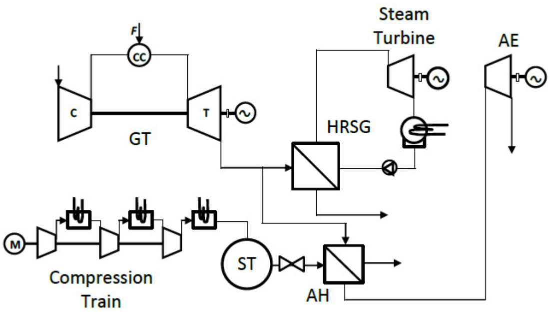

Fig. 1. Reference plant scheme.

Table 1. Data of small-medium size Gas Steam Combined Plants (from [8]).

	Name	Year	P_{EL} [MW] [1]	η [%] [2]	T_{OT} [°C] [3]	m_{GAS} [kg/s] [4]	P_{TG} [MW] [5]	P_{ST} [MW] [6]	$W_{SP,ST}$ [kJ/kg$_{GAS}$] [7]
	LM 1800 e	2010	27.09	47.56	471.7	67.6	19.5	8.1	119.8
A	LM6000PF+	2016	69.55	55.53	500.6	135.6	52.1	18.7	137.9
D	FT4000 SP	2014	83.90	50.77	425.0	177.3	68.1	17.4	98.13
	LMS100PA+	2015	133.9	51.04	413.3	235.0	113.4	22.4	95.3
	MPCP1 (H-25)	2014	59.1	52.90	556.1	110.7	40.6	18.5	167.1
H	SCC800	2010	71.4	55.15	552.0	134.1	49.1	23.1	172.3
D	MCPCP1(H-50)	2015	82.0	54.50	563.9	151.0	55.9	26.1	172.8
	9E04	2014	208.0	53.66	540.0	415.4	141.4	69.6	141.4
	7HA.02	2014	501.0	61.72	630.0	691.2	334.7	172.3	334.1

[1] Plant electric output; [2] plant efficiency; [3] GT exhaust gas temperature; [4] GT exhaust mass flow; [5] GT power; [6] Steam Turbine power; [7] Steam Turbine electricity production per kilogram of exhaust gas.

storage is considered. Two representative cases based on small-medium size GSCC plants have been investigated. For both cases, a techno-economic analysis has been carried out. Results are given and widely discussed.

2. Integration of a CAES system into a GSCC plant

GSCC plants represent currently the most efficient available technology to convert on a large scale the energy content of a fuel into electricity [7]. Main features of small/medium size GSCC plants (up to some 200 MW) recently introduced on the market are reported in Table 1. For sake of comparison, performance data related to a huge size plant are given in the last row of the table.

Relevant operating parameters are mainly depending on the kind of GT employed to arrange the plant, i.e. Aero-Derivative (AD) or Heavy Duty (HD). The two classes of plants show comparable overall efficiency values in the range of 50-55%. Main differences resulting from the diverse design philosophies concern the GT exhaust temperature T_{OT} (Turbine Outlet Temperature): AD-GTs are featured by T_{OT} values sensibly lower than those shown by HD ones. Higher TOTs allow the production of steam at higher temperature and pressure. As a consequence, the HD based plants steam section shows a better performance in comparison to that of the AD based ones. The last column of Table 1 reports the amount of electricity produced per kilogram of exhaust gas. It can be noticed that AD based plants show values in the range 100-140 kJ/kg$_{GAS}$. HD plants are featured by values up to 170 kJ/kg$_{GAS}$.

As stated at the end of Section 1, the integration of a CAES system into a GSCC plant can lead to an increased overall output. A first rough quantification of such an augmentation is performed by assuming typical values representative of AD and HD GSCC based plants chosen according to Table 1 data:

- AD GT based plant: T_{OT} = 450°C, $W_{SP,ST}$ = 120 kJ/kg$_{GAS}$;
- HD GT based plant: T_{OT} = 550°C, $W_{SP,ST}$ = 180 kJ/kg$_{GAS.}$

Table 2. Electricity CAES production by varying the expanding air pressure.

AERO-DERIVATIVE GT BASED PLANT TOT = 450°C; T_{EXP}=400°C; $W_{SP,ST}$=120 kJ/kg$_{GAS}$					HEAVY DUTY GT BASED PLANT TOT = 550°C; T_{EXP}=500°C; $W_{SP,ST}$=180 kJ/kg$_{GAS}$				
p_{EXP} [1] [bar]	m_{AIR} [2] [kg]	$W_{AIR,DS}$ [3] [kJ/kg$_{GAS}$]	$W_{EL,DS}$ [4] [kJ/kg$_{GAS}$]	W_{NET} [5] [kJ/kg$_{GAS}$]	p_{EXP} [1] [bar]	m_{AIR} [2] [kg]	$W_{AIR,DS}$ [3] [kJ/kg$_{GAS}$]	$W_{EL,DS}$ [4] [kJ/kg$_{GAS}$]	W_{NET} [5] [kJ/kg$_{GAS}$]
60	0.99	432.5	419.5	299.5	60	1.00	502.8	487.7	307.7
80	“	450.2	436.7	317.7	80	“	523.3	507.6	327.7
100	“	463.1	449.2	329.2	100	“	538.4	522.2	342.2

[1] Air Expander inlet pressure ; [2] Mass of stored air heated per kilogram of exhaust gas; [3] Work production per kilogram of exhaust gas;
[4] Electricity production per kilogram of exhaust gas; [5] Net electricity production per kilogram of exhaust gas.

CAES production per kilogram of GT exhaust gas is estimated by varying the expanding air pressure p_{EXP} in the range of 60-100 bar. Pressurized air taken from the reservoir is assumed at 30°C. Further assumptions concern the air expander polytropic efficiency (η_{EXP}=0.85), the mechanical-electrical efficiency of the expansion train (η_{M-E}=0.95), the gas discharge temperature (T_{GOUT}=100°C) and, finally, the temperature difference between T_{OT} and T_{EXP}, i. e. the temperature of air exiting the Air Heater (DT_{APPR}=50°C). Results are summarized in Table 2. Of course, both work production $W_{AIR,DS}$ and electricity production $W_{EL,DS}$ increase by increasing p_{EXP}. The HD GT based plant shows higher values due to the higher achievable air temperature T_{EXP} (500°C vs 400°C). Anyway, the increase of electricity production $W_{NET} = W_{EL,DS}\text{-}W_{SP,ST}$ is similar for both plant concepts as a consequence of the higher electricity production from steam $W_{SP,ST}$ featuring the HD GT based plant (i. e. 180 vs 120 kJ/kg$_{GAS}$). Such an electricity surplus ranges from some 300 to 340 kJ/kg$_{GAS}$, depending on the assumed initial pressure. Provided that a relevant electricity surplus exists, the question is now whether such a surplus can be further improved (e. g. by adopting a staged expansion with intermediate reheating) and whether the integration of a CAES system into a GSCC plant can lead to a satisfactory storage efficiency.

3. Thermodynamic analysis

In order to address the above issues, a thermodynamic analysis aimed at optimizing the storage efficiency has been carried out. Analyses are performed referring to one kilogram of exhaust gas. For both plant concepts under investigation (i. e. AD GT based plant and HD GT based one), the same compression and storage system have been considered. Storage pressure p_{ST} has been set at 100 bar. A fixed pressure p_{EXP} =60 bar at the air expander inlet is assumed, i. e. the expander operates at constant pressure ratio. This means that during the discharge phase, the air taken from the reservoir is throttled before entering the air expander. Therefore, the discharge ends when the pressure inside the reservoir reaches the value of 60 bar.

3.1. Charging phase model

During the charging phase, the pressure ratio varies along the time depending on the air mass flow rate entering the reservoir. In case of full charge, the pressure ratio ranges from $\beta_{IN}=p_{IN}/p_{AMB}$ to $\beta_{ST}=p_{ST}/p_{AMB}$, being p_{IN} and p_{ST} the initial and final pressure inside the reservoir and p_{AMB} the ambient pressure.

The work absorbed by the compression system to charge the reservoir has been evaluated according to following assumptions:

1) air is considered a perfect gas;
2) ambient air temperature and pressure are equal to 20°C and 100 kPa respectively;
3) the train is composed by four intercooled compression stages with an after-cooling;
4) operations are supposed to occur at constant compression stage polytropic efficiency η_{PS} = 0.85. Such a value is assumed equal for all the stages;
5) the temperature of air exiting the intercoolers and the aftercooler T_{OUT} is set at 45°C;
6) the pressure drop inside the intercoolers and the aftercooler is assumed equal to 1% of the inlet pressure;

7) at each instant, the overall pressure ratio $\beta(t)$ is equally shared among the compression stages according to:

$$\beta_S(t) = \sqrt[N]{\beta(t)} \tag{1}$$

where $\beta_S(t)$ is the stage pressure ratio at instant t and N the number of stages constituting the compression train;
8) constant air temperature inside the reservoir (T_{ST}= 30°C;
9) mechanical and electrical losses are taken into account by introducing an electric-mechanic efficiency η_{EM}=0.97.

The work required to introduce into the reservoir the mass dm during the time period dt is expressed by:

$$dW_{CH} = \frac{R}{\varepsilon}[T_{AMB} + (N-1)T_{OUT}][\beta(t)^{\varepsilon/(\eta_{PS} N)} - 1]dm \tag{2}$$

being R the air constant and ε the isentropic exponent. According to assumptions 1) and 8), dm can be expressed as a function of the pressure ratio increment $d\beta=dp/p_{AMB}$ occurring during dt. By integrating along the time, the work spent per unit of mass of charged air $w_{EL,CH}$ can be evaluated as:

$$w_{EL,CH} = \frac{R}{\varepsilon(\beta_{ST}-\beta_{IN})}[T_{AMB} + (N-1)T_{OUT}][\frac{N}{N+\varepsilon/\eta_{PS}}(\beta_{ST}^{\varepsilon/(N\eta_{PS})+1} - \beta_{IN}^{\varepsilon/(N\eta_{PS})+1} - (\beta_{ST} - \beta_{IN})]\frac{1}{\eta_{EM}} \tag{3}$$

being β_{IN} and β_{ST} the pressure ratio at the beginning and at the end of the charging phase. According to values assumed for initial and final pressure (p_{IN} = 60 and p_{ST} = 100 bar respectively), the specific electric work required to accomplish the charging phase is equal to 578 kJ/kg_{AIR}.

3.2. Discharge phase model

As previously stated, pressure at the air expander inlet is kept constant during discharge operations. Therefore, the expander is supposed equipped with suitable control devices to adjust the air mass flow rate given that the pressure inside the reservoir decreases as the discharge phase proceeds.

An analysis aimed at maximizing the storage system efficiency has been carried out. A model of the discharge system composed by the Air Heater (AH) and the Air Expander (AE) capable to manage up to three expansion stages with intermediate re-heating has been developed. The model allows the exploration of every possible arrangement in order to determine the optimal number of expansion stages as well as the optimal allocation of the tube bundles inside the AH. The optimization is performed with reference to the mass unit of exhaust gas.

In order to equate the performance of the proposed storage system with those of "pure" fuel free ones (e.g PHS, BES, etc.), the following expression for the storage efficiency has been adopted:

$$\eta_{ST} = \frac{W_{EL,DS} - W_{SP,ST}}{W_{EL,CH}} = \frac{W_{NET}}{W_{EL,CH}} \tag{4}$$

where $W_{EL,DS}$ represents the electricity production achieved by expanding the stored air, $W_{SP,ST}$ the electricity production related to the kilogram of exhaust gas supplied to the HRSG and $W_{EL,CH}$ the electricity absorbed during the charging phase. Actually, η_{ST} expresses the ratio between the electrical surplus W_{NET} discussed in section 2 and the electricity input.

Calculations have been carried out according to the following main assumptions: i) the temperature of gas exiting the AH (T_{GOUT}) is set at 100°C; ii) the minimum temperature difference between gas and air within the AH is set at 50°C; iii) the pressure drop across each tube bundle is assumed equal to 1% of the inlet pressure; iv) all the stages operate with an expansion polytropic efficiency η_{PE} = 0.85; v) an electric-mechanic efficiency η_{EM}=0.97 has been assumed. A recursive quadratic programming technique has been adopted to solve the resulting constrained optimization problem. Routine DNCONF included in Fortran Power Station 4.0 ISML Library has been utilized.

Main results referring to AD and HD GT based plants are summarized in Table 3 and Fig. 2. The optimized plant layouts show relevant differences. The AD GT based plant arrangement consists of three reheated expansion stages.

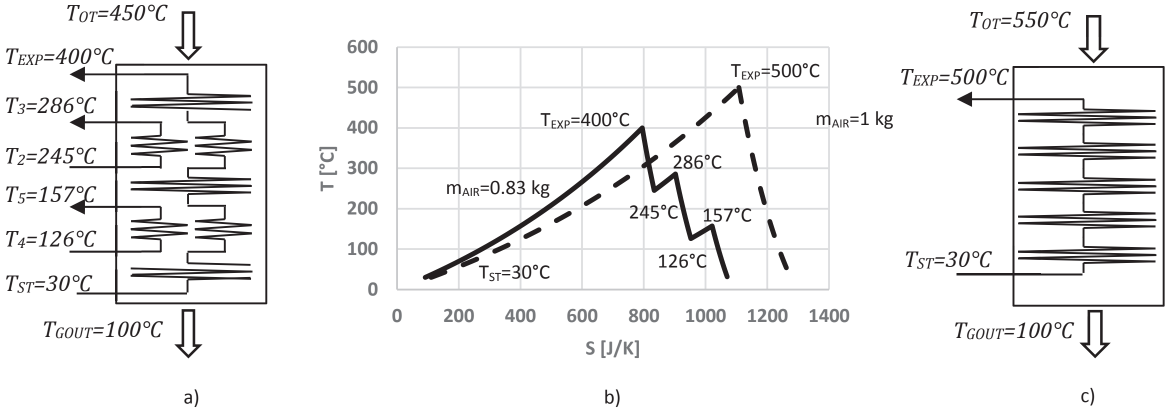

Fig. 2. (a) AD GT based plant AH arrangement; (b) Representation of processes on T-S diagram: full line AD GT based plant, dotted line HD GT based plant;. (c) AD GT based plant AH arrangement

Table 3. AD and HD GT based plants optimization results.

AERO-DERIVATIVE GT BASED PLANT T_{OT} = 450°C; T_{EXP}=400°C; $W_{SP,ST}$=120 kJ/kg$_{GAS}$						HEAVY DUTY GT BASED PLANT T_{OT} = 550°C; T_{EXP}=500°C; $W_{SP,ST}$=180 kJ/kg$_{GAS}$					
N. of stages	m_{AIR} [1] [kg]	$w_{EL,DS}$ [2] [kJ/kg$_{AIR}$]	$W_{EL,DS}$ [3] [kJ/kg$_{GAS}$]	W_{NET} [4] [kJ/kg$_{GAS}$]	η_{ST} [5] [--]	N. of stages	m_{AIR} [1] [kg]	$w_{EL,DS}$ [2] [kJ/kg$_{AIR}$]	$W_{EL,DS}$ [3] [kJ/kg$_{GAS}$]	W_{NET} [4] [kJ/kg$_{GAS}$]	η_{ST} [5] [--]
3	0.83	467.1	375.6	255.6	0.533	1	1.00	502.8	487.7	307.7	0.531
1	0.99	436.6	419.5	299.5	0.518	--	--	--	--	--	--

[1] Mass of stored air heated per kilogram of exhaust gas; [2] Work production per kilogram of air; [3] Electricity production per kilogram of exhaust gas; [4] Net electricity production per kilogram of exhaust gas; [5] Storage efficiency.

Air is heated up to the maximum allowable temperature of 400° C. In respect to a single stage expansion (data are given in the first line of Table 2 and reported for ease of comparison in Table 3), a reduced amount of air is employed, i. e. 0.83 kg versus 0.99 kg. Such a reduction results in a smaller electricity production (375.6 kJ/kg$_{GAS}$ in respect to 419 kJ/kg$_{GAS}$), and thus in a lesser surplus of electricity W_{NET} (255.6 vs 299.5 kJ/kg$_{GAS}$). On the other hand, the three stage arrangement leads to a more efficient use of the unit mass of stored air. In fact, the achieved $w_{EL,DS}$ (i. e. the electricity produced per kilogram of air) is some 7% higher than that produced by adopting a single stage expansion. The adoption of a more complex layout leads to a storage efficiency improvement of some 3%.

HD GT based plant optimized layout is the single stage one. The storage efficiency value is, in practice, equal to that found for the AD GT based plant. The most relevant differences are related to the air mass, the electric production and the surplus production. The effect of such differences on plant size and costs are discussed in the following section.

4. Techno-economic analysis

A techno-economic analysis aimed at estimating the CAES installation costs has been carried out. Taking as a reference Table 1 data, two fictitious GSCC plants based on AD and HD GTs have been taken into consideration. Both plant are featured by an exhaust mass flow rate of 150 kg/s, resulting in an electric power output of some 80 MW. Exhaust gas temperature T_{OT} and electric specific production $W_{SP,ST}$ values are those used to perform the thermodynamic analysis. It is assumed that up to 1/6 of the GT exhaust flow rate (i. e. 25 kg/s) can be withdrawn to fed the AH. For both CAES plants, the rated air mass flow $\dot{m}_{AIR}$ and electric power $P_{EL,DS}$ are obtained by multiplying by the gas mass flow rate m_{AIR} and $W_{EL,DS}$ values given in Table 3. Sizes of machines and apparatuses have been established according to the following assumptions: i) discharge phase duration at maximum rated power: 2 hours; ii) charge phase duration at constant power: 6 hours.

Table 4. AD and HD GT based plants sizing results.

	AD GT Plant	HD GT plant
$P_{EL,DS}$ [1][kW]	9400	12000
P_{NET} [2][kW]	6400	7700
$\dot{m}_{AIR}$ [3][kg/s]	20.75	25.00
$W_{EL,DS}$ [4][kWh]	18800	24000
W_{NET} [5][kWh]	12800	15400
m_{CH} [6][kg]	150000	180000
V_{ST} [7][m^3]	3260	3900
$W_{EL,CH}$ [8][kWh]	24100	28900
$P_{EL,CH}$ [9][kW]	4000	4800

[1] CAES Electric power output; [2] Net electric power output; [3] Compressed air mass flow rate; [4] CAES Electricity production; [5] Net electricity production; [6] Mass of stored air, [7] Storage volume, [8] CAES electricity absorption during charge, [9] CAES power absorption during charge.

Table 5. AD and HD GT based plants economic results.

	AD GT Plant	HD GT plant
Compression train[1] [k€]	3290	3700
Storage system [k€]	11084	13260
Air Heater [k€]	1520	1275
Expansion train[k€]	2600	3335
Overall cost [k€]	18494	21570
Power specific cost [€/kW]	2890	2800
Energy specific cost [€/kWh]	1444	1400

[1] Includes the reversible electric machine

Main sizing results given in Table 4 are employed to estimate the investment cost of main plant components. According to [9], an air storage system constituted by sections of large diameter steel pipe connected by manifolds has been adopted. The system has been sized by assuming a value of the design storage pressure p_{ST} =100 bar. The sizing has been performed according to ANSI standard by using 30" OD, 12 m length ANSI b.125.1 carbon steel pipe sections. The adopted sizing procedure leads to a tube wall thickness of some 40 mm. As a result, 6000 and 7200 ton (metric) of steel are required to build the reservoir in AD and HD case respectively. A compressor train constituted by four centrifugal intercooled stages has been selected for both cases. The air storage as well as the compression train investment costs have been evaluated according to the procedure detailed in [10].

The air heater technology is the same of HRSGs commonly used in GSCC plants. In the present application, pressurized air replaces the water/steam as tube side fluid. Therefore, to determine the AH investment cost the approach proposed by Foster-Pegg in 1989 [11] suitably modified and updated by using available manufacturers' cost data has been applied [12]. The AE is assumed to be derivated from a steam turbine, according to what reported in [2, 6]. Therefore, its investment cost has been estimated by using a correlation developed for steam turbines given in [13].

Economic results are summarized in Table 5. The main cost item is represented by the artificial storage system, which accounts for some 60% of the overall investment costs. Both plants show similar power and energy specific costs of about 2800 €/kW and 1400 €/kWh respectively. Taking into consideration that an effective cost comparison with alternative storage technologies can be performed only if specific cases are addressed and more reliable cost data are available, a qualitative comparison can be attempted on the basis of data reported in [14]. CAES power specific costs are comparable with those acknowledged for Na-S batteries (1000-3000 $/kW) and higher than those characterizing Ni-Cd batteries (800-1500 $/kW). Conversely, CAES energy specific costs are similar to those of Ni-Cd (800-1500 $/kWh) while the Na-S ones result considerably lower (300-500 $/kWh).

However, it has to be pointed out that CAES life duration is estimated two or three times higher than those commonly declared for the BES systems taken into consideration (i. e. 10-15 years [14]). Such a high life duration is expected to bring to a significantly lower Levelized Cost of Electricity (LCOE), as reported in [15].

As discussed in [14], BES technologies (including those presently commercially available) show some drawbacks and need further R&D efforts to improve relevant aspects related to emissions, loss of performance, dismantling and so on. Instead, the key components of the proposed CAES concept (compression train, artificial reservoir, air heater and air turbine) are based on proven and consolidated technologies.

Finally, a relevant issue concerns the relatively low storage efficiency (defined according to eq. 4) shown by both the plant arrangements taken into consideration. It has to be highlighted that the present analysis constitutes a first investigation aimed at exploring the potentialities of the proposed CAES concept. In the Author's opinion, significant storage efficiency improvements can be attained by adopting less conservative assumptions and more complex plant layouts, e.g. by introducing low temperature TES to store heat absorbed during the intercooled compression to preheat the air entering the AH. Moreover, a relevant electric output augmentation can be achieved by reducing the air throttling during the discharge phase by operating the AE in sliding pressure mode. Off course such improvements are expected to bring to higher investment costs and to a more difficult plant management. The matter is the subject of ongoing research works.

5. Conclusions

Two CAES systems integrated into GSCC plants arranged with Aero Derivative and Heavy Duty Gas Turbines have been investigated. In the proposed concept, part of the GT exhaust flow rate is used to heat the compressed stored air before the expansion. As a result, a noticeable power augmentation is achieved in respect to normal GSCC plant operations. Taking into consideration that such a power increase is obtained without using additional fuel, the storage system can be compared to PHS, BES and A-CAES.

A preliminary thermodynamic optimization aimed at maximizing the storage efficiency has been carried out. The different exhaust gas temperatures featuring AD and HD GTs lead to really different optimized plant layouts. The CAES system integrated into the AD GT based plant consists of three reheated expansion stages while a single stage expansion constitutes the optimal solution for the HD GT based one.

CAES systems have been sized by assuming two reference medium size (80 MW) GSCC plants. According to the assumed charging/discharging phase durations and to the maximum usable GT exhaust mass flow rate, the CAES system integrated into the AD GT based GSCC can absorb from the grid up to 4000 kW and release up to 6400 kW. Higher values are found for the HD GT based GSCC plant (4800 and 7700 kW respectively). Both plants show similar power and energy specific costs (i. e. some 2800 €/kW and 1400 €/kWh). Despite the relatively high investment costs, the proposed system may be considered of interest due to the long life duration and the established technologies available for the key plant components.

Both plants show a relatively low storage efficiency of some 0.53. Noticeable improvements can be achieved by adopting less conservative assumptions and more complex plant layouts. Such aspects will be addressed in future works.

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