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Performance assessment of a CAES system integrated into a gas-steam combined plant

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Abstract

In the present paper, the performance of an energy storage concept based on the integration of a Compressed Air Energy Storage (CAES) system into a Gas Steam Combined Cycle (GSCC) plant is investigated. CAES systems featured by different design power output have been coupled with a commercially available small size GSCC plant. Storage efficiencies around 63% have been evaluated for CAES design power output ranging from 5 to 10 MW. Such encouraging values, together with other CAES good features (long life duration and established technologies available for key plant components) confirm the potential of the proposed system to emerge as an economically viable energy storage alternative.

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*Keywords:*Compressed Air Energy Storage (CAES); Energy Storage Systems (EES); Gas-Stean Combined Cycle (GSCC)

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1. Introduction

The share of renewable energy in the electric system has greatly increased worldwide in the last decade. Such a growth is mainly related to the increasingly utilization of wind and solar energy sources, being the hydraulic one almost completely exploited in many Countries. The use of renewable energy sources (RES) significantly contributes to the reduction of CO_2 emission and to the sustainability of the overall energy system. On the other hand, the intermittency and the uncertainty in forecasting RES availability bring serious issues in the management of

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electric grids. The production from RES (especially from wind and sun) is inherently independent from the electric request and, therefore, to fulfil safely the load demand along the time the production from thermo-electric and hydro plants has to be scheduled accordingly. The intermittency and the uncertainty in predicting with a sufficient level of accuracy the RES availability over the time force the electric grid operators to rearrange the unit commitment by putting in operation (or switching off) other generators or by deploying the available spinning reserve. Such actions entail additional costs, which are ultimately passed on to the end consumer.

Electric Energy Storage (EES) can contribute to mitigate the above issues and, consequently, further promote the market penetration of RES. EES systems 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.

Such an application calls for EES featured by suitably long charging-discharging phase durations (hours) and by an adequate storage capacity. The most suited technologies to accomplish such a task are Pumped Hydro Storage (PHS), Battery Energy Storage (BES) and Compressed Air Energy Storage (CAES). A comprehensive review about the state-of-the-art of the above technologies is given in [1].

Many Countries are pursuing as a final goal a “decarbonized” electric system. Nevertheless, the traditional fossil fueled plants still will play in the next decades a key role. Taking the above into consideration, the possibility of using such plants to improve the grid storage capabilities can represent an attractive option.

In the past decade, Nakhamkin introduced the so called second generation diabatic CAES concept [2]. Basically, Second Generation Diabatic CAES plants (D-CAES2) integrate the air compression and storage system with a commercially available Gas Turbine (GT). According to such a concept, a GT power augmentation is achieved by injecting the stored air downstream the GT compressor. Improvements can be attained by pre-heating the stored air by using the GT exhaust and expanding the heated air in a topping turbine prior the injection in the GT combustion chamber. Such systems have the potentialities to bring to relatively low investment costs, good storage efficiency, high availability and reliability levels, good response to quick load change requests [2]. Such a concept has been further investigated by the Author [3]. The performance of a small size CAES plant coupled with a 4600 kW Mercury recuperated GT has been evaluated during the overall operational cycle (charging, storage and discharging phases). A 30% maximum extra power delivery (some 1500 kW) in respect to the nominal design GT output power has been assessed with a satisfactory storage efficiency values around 70%.

A D-CAES2 system drawback, however, is the need of an additional amount of fuel to heat the stored air mass flow rate injected downstream the GT compressor. To overcome such a downside, the Author proposed an alternative concept integrating a CAES system into a Gas Steam Combined Cycle (GSCC) plant [4]. The plant reference layout is given in Fig. 1. In the GSCC plant, the GT exhaust gas is used to generate steam which expands in a Steam Turbine (ST) to produce 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 the air turbine. Since the CAES power production per kilogram per second of exhaust gas is two/three times larger than that achieved if the gas is used to produce steam, a relevant power augmentation is attained in respect to normal GSCC plant operations without any additional use of fuel. Therefore, the storage system can be regarded as a “fuel free” one as BES, PHS or Adiabatic CAES.

CAES integrated into medium/small 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 [4]. Results have shown that, 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 to the proven technologies available for the key plant components

It has to be pointed out that such a preliminary investigation were addressed to a first assessment of the potentialities of the proposed concept. As reported in [4], evaluations had been performed by adopting conservative assumptions and, for sake of simplification, by neglecting some aspects related to GSCC plant operations expected to give a positive contribution to the performance of the whole integrated system. In the present paper, a more accurate and realistic performance assessment is carried out: taking a reference a commercially available GSCC plant, various design options featured by different CAES power output are analyzed and evaluated taking the above aspects into consideration.

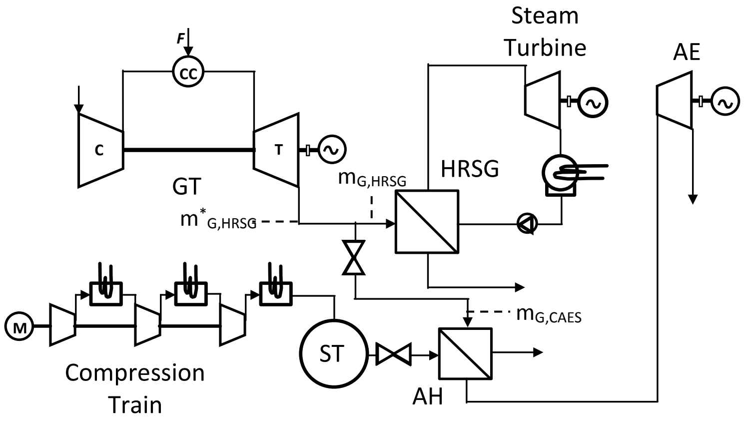

Fig. 1. Reference plant scheme.

2. Technical considerations

In the previously cited Author's paper [4], the integrated system storage efficiency was evaluated according to the following formula:

$$\eta_{ST} = \frac{W_{EL,DS} - W_{EL,L}}{W_{EL,CH}} \tag{1}$$

being $W_{EL,DS}$ the electric production attained by expanding the stored air, $W_{EL,L}$ the loss of electric production from GSCC resulting from the lowering of the gas mass flow rate entering the HRSG and $W_{EL,CH}$ the electricity absorbed from the grid during the charging phase to compress the mass of air fed to the gas expander. The term $W_{EL,L}$can be expresses as:

$$W_{EL,L} = m_{G,CAES} \times w^*_{EL,ST} \tag{2}$$

where $m_{G,CAES}$ represents the mass of gas taken to feed the air heater and, therefore, not contributing to the steam generation in the HRSG and $w^*_{EL,ST}$ the electricity generated per kilogram of gas in the GSCC Steam Section at reference (design) condition.

Nevertheless, the storage efficiency given by Eq. (1) takes no account of two significant aspects characterizing the part load behavior of the GSCC steam section: i) the HRSG performance improvement occurring when the gas mass flow rate is reduced and GT exhaust temperature $T_{ET}$is kept at reference design value; ii) the lowering of the steam condensing pressure.

The first outcome stems from the fact that when the gas mass flow rate reduces, the steam production is reduced too. As a consequence, the ratio between the actual heat transfer surface and gas (or steam) mass flow rate increases. Conversely, the mass flow reduction on both sides leads to a decrease of the overall heat transfer coefficient. If the gas flow rate reduction is not too great, the first effect prevails on the second one and the ratio between steam production and gas mass flow rate shows an increasingly trend. The heat transfer enhancement leads to a reduction of the HRSG exhaust temperature T_{GOUT} and, consequently, to an improved HRSG effectiveness ε_{HRSG}defined as:

$$\varepsilon_{HRSG} = \frac{m_{G,HRSG} \times c_G \times (T_{ET} - T_{GOUT})}{m_{G,HRSG} \times c_G \times (T_{ET} - T_{AMB})} \tag{3}$$

being $m_{G,HRSG}$ the gas mass flow rate entering the HRSG, c_G the gas specific heat, $T_{ET}$and T_{GOUT} the gas inlet and outlet temperatures respectively and, finally, T_{AMB} the ambient temperature.

Such a situation is typically encountered in GSCC plant part load operations when the power output is reduced by closing the compressor Variable Inlet Guide Vanes (VIGVs) and Variable Stator Vanes (VSVs): the GT exhaust flow decreases linearly with the GT power output while the turbine exhaust temperature is kept constant at its design value [5]. The resulting part load HRSG performance is analyzed and widely discussed in [6] and [7].

The second aspect under consideration is related to the condenser heat duty reduction occurring when the GSCC steam section operates at part load. If the coolant mass flow is kept constant at its design value, condensing temperature and pressure decrease with decreasing the steam mass flow rate entering the condenser. Such a pressure reduction can bring to small but not negligible specific work improvements. In fact, due to really high steam specific volume at the last turbine stage exit (around 25 kg/m^3), a condensing pressure drop of 1 kPa leads to a work augmentation of about 25 kJ per kilogram of steam. Taking into account that typical values for steam specific work are within the range of 1100 to 1500 kJ/kg [8], improvements ranging from 1,5 to 2,5% can be achieved.

To take into account benefits arising from the previously discussed aspects, the actual electricity surplus generated during the discharge phase W_{NET} is evaluated as follows:

$$W_{NET} = W_{EL,DS} + W_{EL,ST} - W^*_{EL,ST} \tag{4}$$

being $W_{EL,DS}$ the electric production from the stored air, $W_{EL,ST}$ the electricity actually produced by the GSCC steam section and $W^*_{EL,ST}$ the electric production at reference design condition (i.e. when the CAES plant is not in operation). Eq. (4) can be rewritten as:

$$W_{NET} = W_{EL,DS} + m_{G,HRSG} \times w_{EL,ST} - m^*_{G,HRSG} \times w^*_{EL,ST} \tag{5}$$

where $m_{G,HRSG}$ is the mass of gas fed to the HRSG and $w_{EL,ST}$ the steam section electric production per kilogram of gas. Superscript"*"designates the reference design condition. Taking into consideration that during CAES operations $m^*_{G,HRSG} = m_{G,HRSG} + m_{G,CAES}$ (Fig. 1), Eq. (5) can be rearranged as follows:

$$W_{NET} = W_{EL,DS} + [\, m_{G,HRSG} \times (w_{EL,ST} - w^*_{EL,ST})] - m_{G,CAES} \times w^*_{EL,ST} \tag{6}$$

The last term represents the loss of electric production $W_{EL,L}$ already defined in Eq. (2)and the positive term in square brackets accounts for the increase in electricity production due to steam section improved part load operations. Thus, a formulation that best expresses the storage efficiency of the integrated system has been introduced:

$$\eta_{ST} = \frac{W_{NET}}{W_{EL,CH}} = \frac{W_{EL,DS} + [\, m_{G,HRSG} \times (w_{EL,ST} - w^*_{EL,ST})] - W_{EL,L}}{W_{EL,CH}} \tag{7}$$

3. Integrated plant performance assessment

In order to assess the integrated plant performance, a commercially available small size GSCC plant has been taken as reference. The plant is based on a SGT-800 Siemens GT coupled with a dual pressure HRSG manufactured by Bertsch [9]. On the basis of available Manufacturer information, an equivalent sizing of the steam section has been performed to evaluate data required to carry out the part load analysis. Main steam section design features are given in Tab. 1 and the temperature /transferred thermal power diagram is shown in Fig. 2(a).

The steam section part load model has been set up according to [10] and [11]. Heat transfer devices (HRSG tube bundles and condenser) have been modeled adopting the ε-NTU approach. The steam turbine has been modeled by scaling suitable efficiency curves on the basis of reference design data and by adopting a modified Stodola ellipse law [12].

At first, the GSCC performance enhancement discussed in the previous section has been evaluated. The steam section part load behavior has been analyzed by reducing the gas mass flow entering the HRSG.

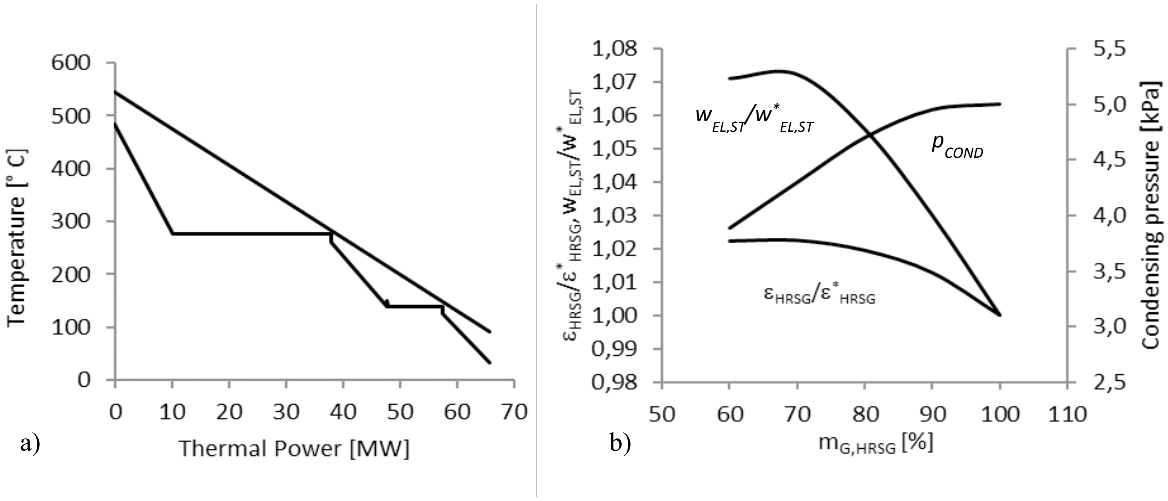

Fig. 2. (a) HRSG Temperature/ Transferred Thermal Power diagram; (b) HRSG effectiveness, electricity production per kilogram of gas and condensing pressure by varying the mass of gas entering the HRSG.

Table 1. GSCC Steam Section main data (design conditions)

Gas mass flow entering the HRSG ($m_{G,HRSG}$)	129 kg/s	Steam condensing pressure (p_{COND})	5 kPa
Gas Temperature at HRSG inlet (T_{ET})	545°C	Steam condensing temperature (T_{COND})	32.9 °C
Gas Temperature at HRSG exit (T_{GOUT})	91 °C	Condensing water mass flow ($m_{W,COND}$)	1075 kg/s
HRSG effectiveness (ε_{HRSG})	0.86	Condensing water temperature ($T_{W,COND}$)	20°C
HP steam pressure (p_{HP})	60 bar	Electric production per kg of gas ($w_{EL,SP}$)	163 kJ/kg
Superheated HP steam temperature ($T_{SH,HP}$)	485°C	Electric production per kg of steam ($w_{EL,ST}$)	980 kJ/kg
HP steam mass flow (m_{HP})	17.0 kg/s	Steam Section power production ($P_{EL,ST}$)	21MW
LP steam pressure (p_{HP})	3.6 bar	Steam section efficiency (η_{ST})	0.315
Superheated LP steam temperature ($T_{SH,LP}$)	150 °C	Overall GSCC electric power ($P_{EL,CC}$)	68 MW
LP steam mass flow (m_{LP})	4.4 kg/s	Overall GSCC efficiency ($\eta_{EL,CC}$)	0.55

As expected, a decrease of the condensing pressure and an increase of the HRSG effectiveness are observed, as reported in Fig.2(b). The effect is an improved electricity production per kilogram of gas: as an example, when the gas fed to the HRSG is reduced to 70%, $w_{EL,ST}$ shows a significant 7% augmentation in respect to the design reference value $w^*_{EL,ST}$.

Fig.3(a) gives the actual steam section power output in comparison with that calculated by assuming $w_{EL,ST} = w^*_{EL,ST}$, i. e. neglecting the steam section off-design operation improvements. The distance between curves at the same abscissa gives a measure of the term in square brackets in Eq. (6).

CAES systems featured by different design values of the gas mass flow $m_{G,CAES}$ entering the Air Heater (AH) have been taken into consideration. In each case, a storage pressure of 100 bar has been assumed. The pressure upstream the Air Expander (AE) is fixed at 60 bar. According to [4], an electric absorption of 578 kJ per kilogram of stored air is required to accomplish the charging phase. Calculation have been performed according to the following assumptions: i) temperature difference between gas and air at AH hot side equal to 50°C (resulting in an AE inlet temperature of 495 °C), ii) AH gas exhaust temperature equal to 100°C, iii) AE polytropic efficiency equal to 0.85, iv) mechanical-electrical efficiency equal to 0.95.

Results achieved by varying $m_{G,CAES}$ from 13 to about 52 kg/s (corresponding to $m_{G,HRSG}$ ranging from 90 to 60%) are shown in Fig. 3(b).The AE electric power output $P_{EL,CAES}$ varies linearly with $m_{G,CAES}$, as a consequence of the above assumptions. The net power production P_{NET} - defined according to Eq. (4) – ranges from 5 to about 18 MW. Storage efficiency - evaluated according to Eq. (7) - decreases by increasing the CAES size, i. e. the reference design power. Higher values (around 63%) are achieved for P_{NET} values ranging from 5 to 10 MW.

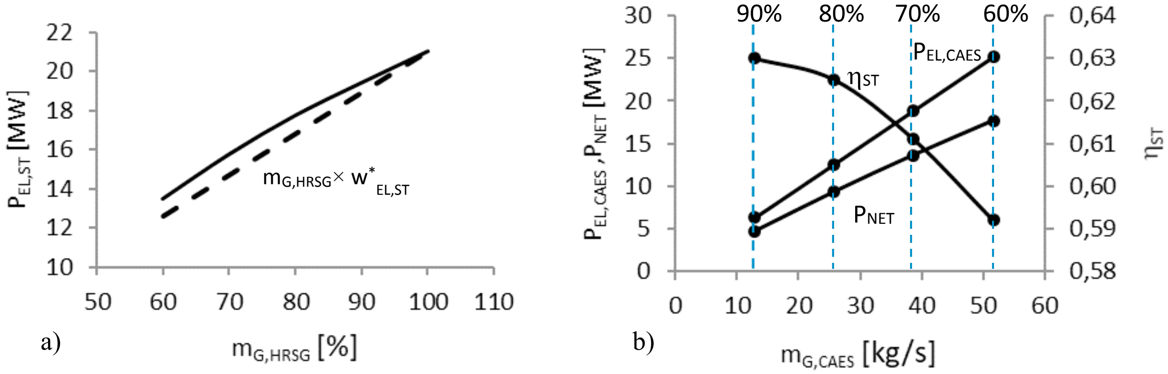

Fig. 3. (a) GSCC Steam Section power output; (b) CAES performance by varying the design gas mass flow rate.

Eq (1) gives a constant storage efficiency value of 0.56, irrespective of the size of the system. It has to be pointed out that the use of Eq. (1) leads to a noticeable 10% underestimation in respect to the actual performance of the integrated system. Such a performance reassessment reinforces the conclusions drawn in [4] regarding the potential of the proposed system to emerge as an economically viable storage alternative.

4. Conclusions

On the basis of promising preliminary results presented in [4], the performance of an energy storage system integrating a CAES into a GSCC has been further investigated. CAES performance has been evaluated taking the integrated system behavior into consideration by introducing a more realistic formulation for the storage efficiency.

CAES systems featured by different design power output have been coupled with a commercially available small size GSCC plant. A storage efficiency of about 63% has been evaluated for CAES design power output ranging from 5 to 10 MW. It has to be pointed out that in such favorable design conditions, the performance reassessment has led to storage efficiencies10% higher than those reported in [4]. The achieved results confirm that the proposed system may be regarded as an interesting option for energy storage applications.

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