Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 82 (2015) 782 – 788

Energy Procedia

ATI 2015 - 70th Conference of the ATI Engineering Association

Techno-Economic Analysis of Small Size Second Generation CAES System

Coriolano Salvini*

Department of Engineering – ROMA TRE University, Via della Vasca Navale 79, Rome, 00146, Italy

Abstract

Among the presently available energy storage systems, second generation CAES 2 (Compressed Air Energy Storage) shows attractive economic and operational features together with satisfactory level of performance.CAES2 plants integrate an air compression and storage system with a commercially available Gas Turbine. A small size plants based on a 4600 kW Mercury recuperated Gas Turbine equipped with an artificial compressed air storage system has been investigated. Preliminary evaluations have been carried out to assess the maximum achievable GT power augmentation taking operations safety and plant life duration into consideration. For a fixed amount of stored air (defined according to the requested minimum duration of the discharge phase), investment, maintenance and operating costs have been evaluated by varying the air storage pressure from 2000 to 10000 kPa. The minimum annual equivalent cost is achieved by assuming a design storage pressure of 4000 kPa. From 4000 to 10000 kPa, costs are in practice insensitive to the air storage pressure.

Peer-review under responsibility of the Scientific Committee of ATI 2015

Keywords: Compressed Air Energy Storage; Electricity Storage; System Performance Analysis; Economic Analysis

1. Introduction

The intermittency and unpredictability of renewable energy sources availability poses relevant problems in fulfilling safely and in a cost efficient way the electric demand along the time. The mismatch between power generation and consumption is presently resolved by deploying the spinning reserve available on the grid, or by putting in operation fast start generators if a long duration assistance is required. Moreover, in case of high renewable source availability, the producible power can exceed the

---

* Corresponding author. Tel.: +39-57333249; fax: +39-57333425.
E-mail address: coriolano.salvini@uniroma3.it.

Peer-review under responsibility of the Scientific Committee of ATI 2015
doi:10.1016/j.egypro.2015.11.812

transmission capacity limits. The above issues lead to increase ancillary service costs that can be mitigated by introducing energy storage systems [1].

Among the currently available solutions, *CAES*(Compressed Air Energy Storage) represents an interesting option. *CAES* systems work according to a Brayton cycle in which compression and expansion operations are decoupled and shifted along the time. During off-peak periods, electric power is absorbed from the grid to compress air which is stored in a suitable reservoir. During the peak demand periods, the stored air is heated and expanded to produce electricity.

The so called second generation *CAES* concept seems to have the potentiality to achieve satisfactory economic and operational performance [2]. Basically, Second Generation *CAES* plants (*CAES2*) combine the air compression and storage system with a commercially available Gas Turbine (*GT*). In the simplest plant arrangement, during the discharge phase, the stored air is throttled and injected downstream the *GT* compressor to increase the output power. Plant performance can be improved by heating and expanding the stored compressed air in a topping air turbine before its addition to the *GT*. Large plants technical and economic feasibility requires natural underground air storage systems, such as salt-, porous-, hard-rock caverns. Therefore, the location of the plant is constrained to sites presenting suitable geological features. Conversely, small and medium size plants can be economically arranged by using man-made above ground reservoirs, allowing, in practice, the construction of the plant in the most appropriate place according to the particular grid service requested (e.g. transmission congestion relief, wind shaping, etc.).

The paper deals with a techno-economic analysis of a small size *CAES2*plant based on a 4600 kW Mercury recuperated GT equipped with an artificial air storage system. For a given stored mass of air, chosen according to the desired minimum duration of the discharge phase, a techno-economic analysis has been carried out by varying the design storage pressure. Plant performance, investment and operating costs have been evaluated and compared by assuming a simplified scenario.

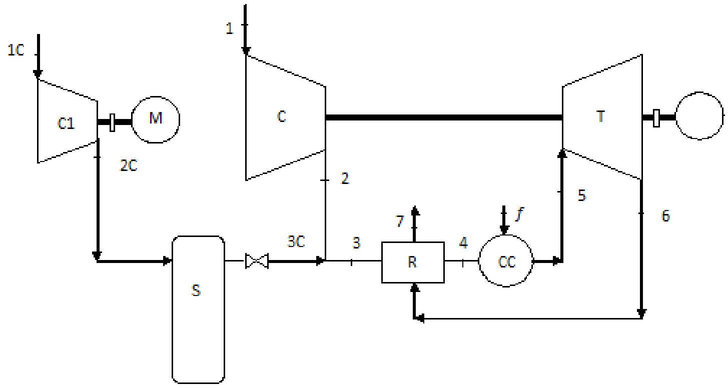

Fig. 1. CAES2 Plant layout

2. Plant Description

The *CAE2S* plant under investigation is schematically depicted in Fig. 1. During the charging phase, the air is compressed in an intercooled and after-cooled reciprocating compressor *C1* by absorbing electric power from the grid and stored in an artificial reservoir *S*. According to the kind of service provided by the plant (i.e. the more appropriate/advantageous power production scheduling), a suitable mass flow rate of stored air is throttled and injected downstream the compressor *C* to augment the *GT* power output. A plant model has been set up and used for plant performance evaluation, as extensively reported by the Author in [3]. In order to introduce the techno-economic analysis, main results are re-called and briefly commented.

2.1. Gas Turbine power augmentation

The plant is based on a 4600 kW recuperative Solar Mercury *GT* featured by a noticeable 38.5% efficiency value at design condition. Preliminary evaluations have been carried out to assess the maximum power augmentation achievable by injecting the stored air. To fully exploit the engine potentialities, it is worth operating the turbine at the firing temperature design value (i. e. 1190°C). In this case, to accommodate the augmented mass flow, the pressure at the gas expander inlet has to rise and, consequently, the compressor pressure ratio too. Such a circumstance can lead to unsafe and unstable operating conditions and, in the worst case to the compressor surge. Therefore, the engine has to be operated with an appropriate value of the surge margin. Results referring to injected air mass flows of 2 and 2.5 kg/s are given in Tab. 1. For sake of comparison, data referring to normal engine operations are reported in the first column. It can be seen that noticeable power improvements can be achieved, namely 26% and 32% when 2.0 and 2.5 kg/s of stored air are fed to the *GT*. Power and *GT* efficiency improvements are related primarily to the increased gas mass flow entering the expander and, secondarily, to the higher specific work achieved by operating at higher pressure ratios. As a consequence of the specific work improvement, the additional work delivered to the grid increases by increasing the injected stored air mass flow, i.e. reducing the discharge period duration.

An appropriate 8% surge margin is left when 2.5 kg/s of air is injected. However, it has to be pointed out that such a result has to be regarded as merely indicative in default of more accurate information about the true compressor operating map. Taking the above into consideration, the injected air mass flow of 2.5 kg/s (corresponding to a power augmentation of 1460 kW) is assumed as the upper boundary for *CAES* plant performance evaluations.

Table 1. Gas Turbine performance by varying the compressed air injection rate (ISO Condition: 15°C, 101.3 kPa, 60% Relative Humidity)

Injected Air Mass Flow [kg/s]	----	2.0	2.5
Pressure ratio [-]	9.90	11.15	11.43
Surge margin [%]	25	11	8
Output Power[a][kW]	4600	5800	6060
Discharge period duration [min]	---	83	67
Power augmentation [%]	---	26.1	31.7
Fuel mass flow[b] [kg/s]	0.249	0.289	0.299
Efficiency[a][%]	38.5	41.8	42.6

[a] evaluated at electric generator terminals
[b] Natural Gas, 48000 kJ/kg LHV

The *CAES* storage system is sized by assuming a minimum discharge period of about one hour. Since the maximum mass flow injectable into the *GT* is 2.5 kg/s, an amount of 10000 kg of air has to be extracted during the discharge phase. According Tab. 1 data, operations at the maximum air flow rate injection entails a compressor delivery pressure of 1150 kPa. Therefore, to allow the complete air withdrawal, the pressure p_{MIN} inside the storage tank at the end of the discharge phase has been set at 1300 kPa.

2.2. The artificial storage system

Various alternatives have been proposed to arrange the man-made storage system: buried pressure vessels, concrete type pipes and steel piping used to transport Natural Gas. According to [4] and [5], an air storage system constituted by sections of large diameter steel pipe connected by manifolds has been adopted. As reported in [5] and [6], such a solution represents the most cost effective alternative for storage pressure up to 150 bar.

The storage system would be constructed *in situ* by welding a number of pipe sections according to the required storage volume. The resulting pipe segments would be closed by welding hemispherical end caps and connected to a series of manifolds and headers.

The system has been sized by assuming values of the design storage pressure p_{MAX} ranging from 2000 to 10000 kPa. The sizing has been performed according to *ANSI* standard by using 30” OD, 12 m length *ANSI b.125.1* carbon steel pipe sections.Main results are given in Tab. 2.

Table 2. Artificial storage system sizing results

Design pressure p_{MAX} [kPa]	2000	4000	6000	8000	10000
Storage Volume [m^3]	1218	322	188	134	104
Pipe Thickness [mm]	7.92	15.88	25.40	31.75	38.10
Pipe Overall Length [m]	2787	770	475	350	280
Material Mass[kg]	410450	224900	202000	200000	192000

2.3. The compression system

The air compression system has been set up by assuming a charging period duration of 5-6 hours. Preliminary evaluations have led to the selection of a four stage intercooled and after-cooled reciprocating compressor operated at constant speed. Since during the charging phase the compressor delivery pressure increases continuously, the various stages operate at variable pressure ratios. To accommodate the air mass flow entering the 1st stage and to maintain the most effective pressure ratio distribution among compression phases, 2nd , 3rd and 4th stage are equipped with suitable variable capacity devices. As a result, a nearly constant air mass flow is delivered to the reservoir.

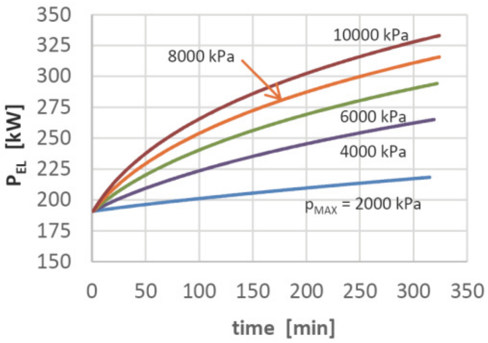

Fig. 2. Electric power absorption during the charging phase for different values of the storage pressure

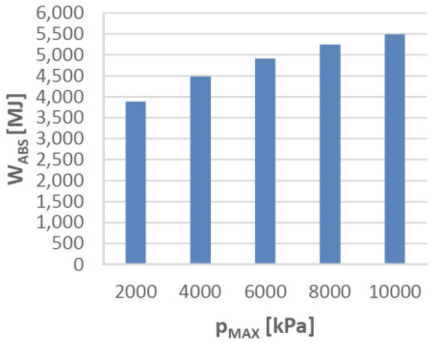

Fig. 3. Electric work absorbed during the charging phase for different values of the storage pressure

Figure 2 shows the trend of the electric power absorbed from the grid during the charging phase by varying the storage pressure p_{MAX}. For each value of the storage pressure, the electric power absorbed from the grid increases along the time because of the pressure raise inside the reservoir. The higher p_{MAX} is, the higher the absorbed power is. Maximum values range from 220 kW at p_{MAX} = 200 kPa to 330 kW at p_{MAX} = 10000 kPa. Maximum absorbed power is assumed as a reference quantity for compressor and driving unit sizing.

Figure 3 gives the electric work absorbed from the grid throughout the charging phase versus the design storage pressure. A remarkable increase of about 40% is observed at p_{MAX} = 10000 kPa in respect to the value achieved at p_{MAX} = 2000 kPa. Since the air is throttled before its injection into the GT, high storage pressures do not bring any benefit in terms of additional electricity production during the discharge phase. Moreover, high values of the storage pressure are expected to cause a relevant operating cost increase.

3. Cost Analysis

The economic analysis has been carried out taking only the items required to equip the *GT* with the compression and storage systems into consideration.*MW-classGT* installations are very popular and cost effective for *CHP* and distribute generation applications. The integration of an electricity storage system can represent a noticeable opportunity for profit improvements related to the possibility of providing well remunerated grid services. In this regard, the following analysis is addressed to explore the advantage to equip a small size *GT* plant (already existing or to be installed *ex novo*)with the energy storage system under consideration.

In the proposed *CAES* plant, revenues are related to: i) the kind of service provided by the plant itself (price arbitrage, spinning reserve, energy imbalance, transmission issues, etc.), which defines the price of the sold kilowatt-hour, ii) on the amount of delivered electricity, which is related on the duration of the discharge phase, as discussed in [3]. In any case, being fixed the amount of stored air (10000 kg), the related additional producible electricity is not dependent from the storage pressure. Conversely, the storage pressure heavily affects both investment and operating costs. Therefore, being the revenues independent from the storage pressure, the compression and storage systems equivalent annual cost has been considered to compare the various alternative under investigation:

$$C_{EQ} = C_{INV} + C_{M} + C_{EL} \tag{1}$$

where C_{EQ} represents the annual equivalent cost, i.e. the cost of owning, maintaining and operating the compression and storage systems, C_{INV} the annual plant depreciation rate, C_{M} the annual maintenance costs and, finally, C_{EL} the annual cost of electricity absorbed by the grid.

The plant equivalent annual cost has been estimated according to the following assumptions:

- 20 years plant life, 90% plant availability, one operating cycle per day;
- 8% discount rate;
- 0.15 €/kWh annual average electricity cost during the charging phase.

The compressor packaged system cost has been evaluated according to [7]. The base compressor cost is given as a function of the gas horsepower, i. e. the power delivered to the compressed air. The base cost includes auxiliary equipment, namely the filtering system and the heat transfer devices for intercooling and after-cooling. An installation factor equal to 1.64 (accounting for foundations, piping, instruments, electric equipment, painting, insulation and labor) has been applied to determine the direct cost. The compressor cost is estimated by multiplying the direct costs by an indirect cost factor of 1.35. Finally, the cost of the compressor packaged system is obtained by adding to the cost of the driving motor, given as a function of the brake horsepower. Costs are given with an accuracy of ±20% in 2001 USD. Costs have been updated by using the Marshall&Swift escalation index for industrial equipment and translated into euro. An annual maintenance expense equal to 5% of the direct cost has been assumed.

The artificial storage system investment cost has been evaluated taking the following items into consideration:

- steel pipe purchase cost, assumed equal to 800€/tonne (metric) on the basis of actual vendors information;
- shipping cost, assumed equal to 30% of the purchase cost;
- welding cost, evaluated according to [7] on the basis of Tab. 2 data. Additional required information concerning welding techniques, number of passes, etc., has been taken from [8]. The storage system base cost has been calculated by adding the welding cost to the steel pipe purchase cost;
- installation costs, including support and base structure, hoisting, testing and labor. Storage system direct cost have been evaluated by applying a factor equal to1.5 to the base cost;

The storage system overall investment cost is given by adding the indirect costs (20% of the direct cost) and the shipping cost. The adopted operating and maintenance cost model includes inspection, anticorrosion, inner cleaning and replacement expenses. Costs have been evaluated by introducing suitable coefficients established on the basis of data reported in [6]. Dismantling costs as well as benefits achievable by selling the waste material are not taken into account. Such an assumption has to be regarded as conservative, because benefits are higher than costs. As an example, in [6], the salvage value is estimated(on the basis of prices provided by the steel recycle manufacturers) as some 25% of the steel pipes purchase cost.

Table 3. Cost analysis results

Design pressure p_{MAX} [kPa]	2000	4000	6000	8000	10000
Compressor packaged system [k€]	590	670	710	730	750
Storage System [k€]	880	430	371	348	357
Overall investment cost [k€]	1470	1100	1081	1078	1107
Annual depreciation rate[€]	149700	112000	110100	109800	112700
Annual maintenance cost [€]	66000	37000	33800	32600	32300
Annual cost of electricity [€]	53400	61700	67600	72100	75500
Equivalent annual cost [€]	269100	210700	211500	214500	220500
Equivalent annual cost w/o electricity [€]	215700	149000	143900	142400	145000

Cost analysis results are summarized in Tab.3. As expected, investment cost for the compressor packaged system and storage system show opposing trends. The assumption of a storage design pressure p_{MAX}=2000 kPa leads to the highest investment cost, mainly due to the really high expense associated to the construction of the air reservoir. Other values of design storage pressure are substantially characterized by the same overall investment cost (some 110 k€).

Maintenance costs increase by decreasing the storage pressure. This is mainly due to the anticorrosion and inner cleaning costs that are directly related to the overall length of the reservoir.

The cost of electricity has been evaluated according to Fig. 3 data: its incidence on the equivalent annual cost ranges from 20% at 2000 kPa to 35% at 10000 kPa.

Although air storage at 2000 kPa is featured by a relatively low electricity cost, the corresponding equivalent annual cost is considerably higher than those featuring the other investigated alternatives. Since storing air at pressures ranging from 4000 to 10000 kPa entails a similar investment cost, the most effective choice is related to the cost of electricity.

As reported in the second-last line of Tab. 3, a minimum equivalent annual cost of 210700 € is achieved by adopting a design storage pressures of 4000 kPa. It has to be pointed out that over 4000 kPa, costs show a reduced increase (5% rise at 10000 kPa in respect to the minimum value). Therefore, the assumption of lower electricity costs shift the best solution towards the higher storage pressures. Figures reported in the last line of Tab. 3 refer to the equivalent annual cost evaluated by assuming a zero-cost for electricity. In such a case, the minimum is achieved for storage pressures ranging from 6000 to 8000 kPa. It has to be pointed out that a free electricity absorption is not an unrealistic case. As an example, if the duty of the storage system is the mitigation of imbalance fees by absorbing the power produced excess of by a renewable based power plant.

4. Conclusions

The techno economic analysis of a small size second generation *CAES* plant based on a commercially available *GT* has been carried out. For a fixed amount of stored air (defined according to the requested minimum duration of the discharge phase), investment, maintenance and operating costs have been evaluated by varying the air storage pressure from 2000 to 10000 kPa. Low pressure values give raise to very high investment and maintenance costs, that are not counterbalanced by the relatively low cost of the purchased electricity. A minimum equivalent annual cost of some 210000 € is achieved by assuming an air storage pressure of 4000 kPa. However, it has to be pointed out that by increasing the storage pressure up to 10000 kPa, the equivalent annual cost increase is very small.

References

[1] .Eyer M, Iannucci J J, Corey J P , *Energy Storage Benefits and Market Analysis Handbook*, SAND2004-6177, 2004.

[2] Nakhamkin M, Chiruvolu M, Patel M, Byrd S, Schainker R, Second Generation of CAES Technology-Performance, Economics, Renewable load Management, Green Energy, *POWER-GEN Int.*, December 8-10, 2009, Las Vegas, NV, USA.

[3] Salvini C, Performance Analysis of Small CAES Systems, *ASME-ATI-UIT Conference on Thermal Energy Systems: Production, Storage, Utilization and Environment*, 17-20 May, 2015, Naples, Italy.

[4] Sayer J, Pemberton D, Jewitt J, Pletka R, Fishbach M, Meyer T, Ward M, Bjorge B, Hargreaves D, Jordan G, Mini-Compressed Air Energy Storage for Transmission and Congestion Relief and Wind Shaping Application, Final Report, *Nyserda Report 08-5*, July 2008.

[5] Pedrick J, Marean J B, Compressed Air Energy Storage Engineering and Economic Study, Final Report, *Nyserda Report 10-09*, December 2009.

[6] Liu J, Zhang X, Xu Y, Chen Z, Chen H, Tan C, Economic Analysis of using Above Ground Gas Storage Device for Compressed Air Storage System, *Journal of Thermal Science*, Vol. 23, No. 6 (2014), p. 535-543.

[7] Douglas L E, *Industrial Chemical Process Design*, McGraw-Hill, 2002, p. 326-334.

[8] Lincoln Electric, Welding Pressure Pipelines & Piping Systems – Procedures and Techniques, http://www.lincolnelectric.com/assets/global/ Products/Consumable_PipelinerConsumables-Pipeliner-PipelinerLH-D90/c2420.pdf

Biography

Coriolano Salvini is currently Associate Professor in System for Energy and Environment in the Department of Engineering at ROMA TRE University. He is involved in research manly focused on energy system design and optimization, optimum management of complex plants, power production planning.