COMPRESSED AIR ENERGY STORAGE

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Summary

The state of the art of the Compressed Air Energy Storage Technology (CAES) is presented, while focusing over the aspects of this technology which could be useful for the general professional public as well as specialists. The objective of the review is to provide a general overview as well as an updated reference material, which may serve engineers and other professionals who may be required to be involved in the development of a CAES project and alternatively to provide the reader with the latest development of this technology and in particular with novel CAES alternatives.

As such, the review begins by specifying the conditions when energy storage becomes relevant to a particular system and provides a comparison between the different available energy storage technologies. This is followed by a presentation of the Compressed Air Energy Storage Technology and its World-wide status. Thermodynamic and techno-economical aspects of CAES are presented with a view of providing tools for understanding the advantages as well as disadvantages of this technology.

The separation between the above-ground plant and underground reservoir, and their joint contribution to the system are highlighted in separate chapters. Finally, novel CAES alternatives are being presented and their practical future implementation is being considered.

1. Introduction

The largest share of the energy generated by a gas turbine is consumed by its compressor. This fact combined with the fluctuations in the demand for power and its consequent time of use pricing formed the motivation for the development of the Compressed Air Energy Storage (CAES) technology.

The CAES technology consists of converting excess base load energy into stored pneumatic energy by means of a compressor for a later release through a gas turbine (turbo-expander) as premium peaking power. As the operation of the compressor is decoupled from the operation of the turbo-expander the whole amount of power produced by the turbo-expander is available at the generator terminals (except for minor electro-mechanical losses).

Although storage is a major component in CAES, this technology is not a pure storage system as fuel is added to the compressed air in a combustor prior to its expansion through the turbo-expander. An adiabatic alternative can be considered (without fuel consumption), however its viability should be assessed as the outcome of a techno-economical analysis and is therefore a design option.

Therefore CAES, although an energy storage technology, it consists of a hybrid system which includes both storage and generation from fuel consumption, unless the adiabatic alternative is considered.

The CAES system consists of two major parts. The first is the machinery which includes typical elements of an industrial gas turbine, with possibilities of intercooling the air during the compression process, or aftercooling, reheating and recuperating as design options.

The second part of the system is the underground compressed air reservoir, which can be either of a constant pressure type, e.g. an aquifer or a depleted gas reservoir, or of a constant volume type (variable pressure), e.g. a salt dome cavern. Other types of reservoirs like excavated caverns in hard rock with or without a water compensating system to maintain an almost constant pressure, or abandoned mines have been considered.

The reservoir technology, utilised over the last fifty years for seasonal natural gas storage, can be applied almost without variation to store compressed air for the CAES system.

The significant difference between peak and off-peak prices has created the motivation to develop energy storage technologies. Electric utilities often apply energy storage methods to meet daily, weekly and seasonal variations in the power load demand.

Electric energy storage technologies exist for many years. The main proven technologies are pumped hydro, battery storage and flywheel energy storage.

Although all the components of a Compressed Air Energy Storage system represent proven technologies, their combination reached only very recently (with the commissioning of the CAES plant in Alabama, U.S.A.) the status of a proven technology, which has many inherent advantages. However, its implementation as a commercial one is in its beginning.

A 290 MW CAES power plant has operated successfully since 1979 in Huntorf, Germany [2,3]. This plant uses a constant volume salt-dome reservoir and turbo-machinery manufactured by Brown Boveri (today “Asea Brown Boveri-ABB”) and Sulzer. The first unit (110 MW) of a 220 MW power plant has been commissioned in 1991 in the USA by Alabama Electric using a salt-dome reservoir at the McIntosh site.

The turbo-machinery equipment is manufactured by Dresser-Rand. A CAES 30MW pilot plant is being constructed in the island of Hokkaido, Japan. A 300MW CAES plant is being planned for construction in Mount Sedom, Israel. The target date for commissioning the plant is 1998. Another CAES is being considered for Taiwan.

The following sections review the characteristics of CAES as compared to other technologies. As well as the distinction of every one of the above-mentioned plants as well as that of the manufacturers’ developments.

2. Comparison of Energy Storage Technologies

Pumped-hydro storage (PH) has been used for several decades to meet electric utilities’ needs. It consists of pumping water from a lower (usually natural) reservoir to be stored in a higher reservoir during demand depression periods for a later release through a hydro-turbine to meet the peak and intermediate load demand. Since it is based on hydroelectric technology, PH is considered a proven technology.

However, it has the same disadvantages as hydroelectric systems, namely large physical dimensions, long construction time (8-12 years), high investment cost (1000-2000$/kW see Table 1 [1]). The performance and characteristics of various storage plants are shown in Table 2 [1].

The ratio of the output to the input energies in a PH system is lower than 1, usually 0.75, hence about 512 g of coal is consumed at a conventional power plant during off-peak periods to produce 1 kWh of power at the peak.

Gas turbine technology, characterized by low capital cost, is used to meet peak load demand. However its operating cost is very high due to the high specific fuel consumption (~ 300 g/kWh) and the use of expensive natural gas or gas oil.

The main reason for its high specific fuel consumption is a result of the necessity to transfer about 67 per cent of the energy obtained on the turbine shaft to drive the compressor, while only 33 per cent remains available at the generator terminal.

Energy Storage Technology	**$/kW +**	**$/kWh* x**	**H =**	**Total Capital, $/KW**
Compressed Air				
-Large (110 MW)	390	1	10	400
-Small (50 MW)	530	2	10	550
Pumped Hydro				
-Conventional (1000MW)	1100	10	10	1200
-Underground (2000MW)	1200	50	10	1700
Battery (target) (10MW)				
-Lead Acid	120	170	2	460
-Advanced	120	100	2	320
Flywheel(target) (100MW)	150	300	2	750
Superconducting	120	250	2	720
Magnetic Storage (target) (1000MW)				

Table 1: Energy Storage Plants: Capital Cost Data (1995 Dollars)

Nevertheless, the short construction time of gas turbines, their dynamic benefits and low investment cost are the main reasons for their utilization as reliable spinning reserves as well as peak supply generation units.

Compressed air energy storage (CAES) is a combination of an effective storage by eliminating the deficiencies of the pumped hydro storage, with an effective generation system created by eliminating most of the deficiencies of the gas turbine.

A schematic diagram of a CAES system is seen at Figure 1. It consists of turbo-machinery above ground, and the reservoir underground.

* This capital cost is for the storage “reservoir”, expressed in $/kW for each hour of storage. For battery plants, this cost does not include expected cell replacement costs. (Source: EPRI)

Energy Storage	**Efficiency(1), (2), (3)**			**Size**	**Construction**
Technology	**Conversion**	**Delivery**	**Effective**	**(MW)**	**Time (years)**
Compressed Air Energy Storage (CAES)	N/A(4)	28	82	50-220	2.5-4.0
Pumped Hydro (PH)	75	26	75	1000-2000	8-12
Battery Energy Storage (BES)	75	26	75	1-1000	1-2
Flywheel Energy Storage (FES)	70	24	70	0.1-1.0	1-2
Superconducting Magnetic Energy Storage (SMES)	91	31	91	0.1-2000	1-8

Table 2: Storage Plants: Performance and Characteristics

Footnotes:

(1) Conversion efficiency; for energy storage technology only, and is not to be used if the storage device uses anything other than electricity as input.

(2) Delivery efficiency; from primary fuel through base load power generator and energy storage technology, including any supplemental fuel used in the storage facility.

(3) Effective efficiency; useful for comparing all types of storage plants; represents the ability of the storage plant to efficiently store electrical energy.

(4) Requires 0.8 kWh (electricity) + 4100 Btu (oil or gas) to produce 1 kWh. **It is a mistake to calculate conversion efficiency!!**

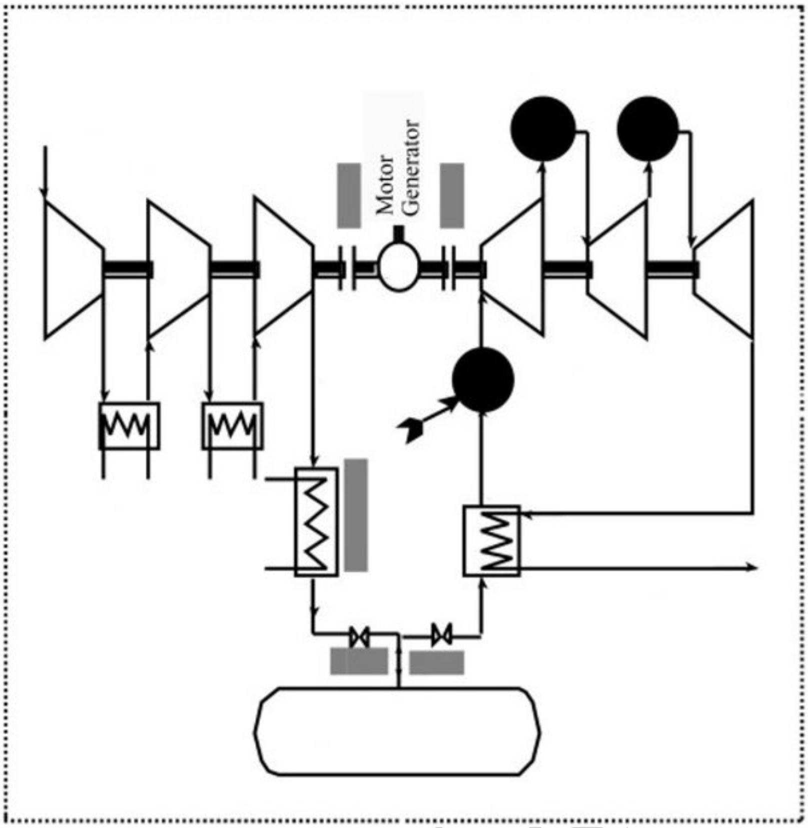

Figure 1: Schematic Description of a Compressed Air Energy Storage System

The turbo-machinery is a combustion gas turbine modified to allow separate operation of the compressor from the turbine through clutches and to permit higher turbine inlet pressures.

During off-peak periods a motor is operated to drive the compressor train using electric power from the grid, which is usually supplied by coal or nuclear baseload plants. For an efficient compression process intercoolers are used at intermediate stages of the compressor train.

The compressed air is stored in the reservoir underground. During peak and intermediate periods the air is released from the reservoir to flow through a recuperator into the combustor where fuel is added to produce high temperature gases. The combustion gases are expanded in the turbine to generate mechanical energy on the turbine shaft. The same machine which in the charging mode was used as a motor, is connected during the discharging process through a clutch to the turbine shaft, and is used as a generator. The exhaust hot gases leaving the turbine pass through the recuperator where part of their thermal energy is transferred to the air released from the reservoir to preheat it before it enters into the combustor.

Two conceptually different types of reservoirs are possible:

- constant volume reservoirs, usually salt caverns (Figure 2a) or abandoned mines,

- constant pressure reservoirs, usually aquifers (Figure 2b) or water compensated hard rock caverns (Figure 2c).

Underground gas storage technologies have been used for 70 years by gas companies to smooth the seasonal variations of the gas demand curve.

The same proven technologies are adopted to store the compressed air in the underground reservoir for the CAES application.

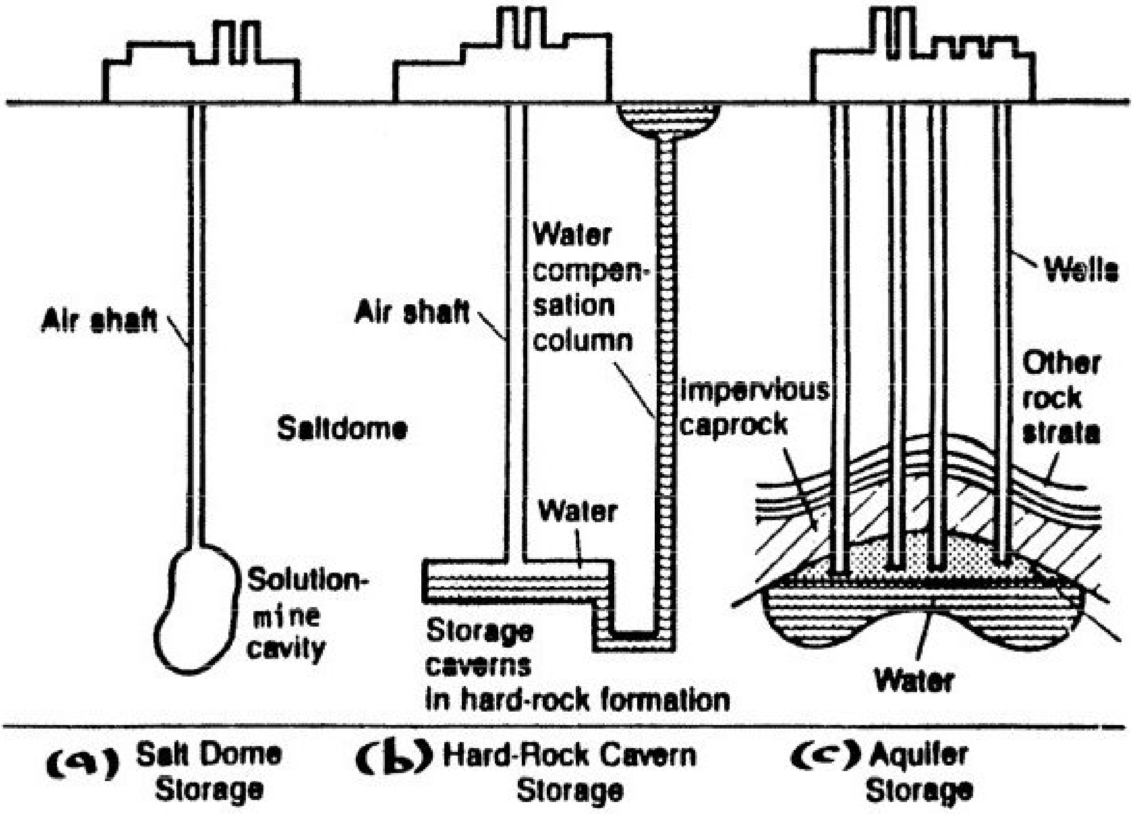

Figure 2: Compressed Air Energy Storage (CAES) - Reservoir Alternatives

3. CAES Technology - World-wide Status

3.1. Huntorf

Plant design was taken in hand in summer 1973 [10] immediately upon the decision to build it on top of a salt dome near Huntorf, a small rural community a few miles north-west of the city of Bremen.

Cavern construction started in November 1974, followed by civil construction in early 1975. Assembly of machinery and electrical equipment began in mid-1976 and was finished in August 1977.

Electric auxiliaries and the extensive control system were tested and commissioned early enough for start-up of machinery in mid-1977. “Teething troubles” arising in various parts of the plant prevented it from being available for commercial use before the end of 1978. It was accepted provisionally in December 1978, and finally in September 1979, after completion of various retrofits and improvements.

The main design parameters are summarized in Table 3.

The main operational capabilities are:

- Quick start: normal 11 minutes , in emergencies 6 minutes from cold stand-still to full load;
- Steep Load Ramp: 30% of MCR with cold expander, virtually unlimited with hot expander;
- Full compliance with specified operating modes;
- Starting reliability 5026 / 5145 = 97.6%, and
- Availability to work = 86.3% in 13 Years.

Nowadays, this plant is not operating and serves only as an emergency power supplier.

Generating Mode	
Output (MCR)	290 MW
Air Consumption (MCR)	920 lb/sec
NG Fuel Consumption (MCR)	17.6 lb/sec
Charging Mode	
Compressor Input	appr. 60 MW
Air Discharged to Store	appr. 230 lb/sec
Charging Time Ratio	920 / 230 = 4
Operating Cycles Per Day	
Normal/Maximum	1/2
Operating Time Per Cycle	
Generating Mode (MCR)	2 h
Charging Mode	8 h
Gross Generation Per Cycle	580 MWh
No. of Cycles Per Annum	300
Total Generation Per Annum	174 GWh/a
Storage System	
Caverns, No. Of	2
Total Volume	10,600,000 cu.ft.
Pressure Limit: “Full”	appr. 1,000 psi
“Empty”	appr. 700 psi
Air Charge Between Limits	6,625,000 lbs.

Table 3: Main Design Parameters

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Biographical Sketch

Peter Vadasz obtained his Bachelor of Science degree in Mechanical Engineering, in 1979 graduating at the Technion-Israel Institute of Technology in Haifa. While holding senior industrial positions as Project Manager and Head of Energy Storage Section in Israel Electric Corp. he continued his post graduate studies and was awarded the Master of Science degree in Mechanical Engineering in 1983 and the Doctor of Science degree in 1988, both from the Technion-Israel Institute of Technology.

In 1991 he joined the Faculty of Engineering at University of Durban-Westville and in 1992 was appointed Professor and Head of the Department of Mechanical Engineering.

A member of the editorial Advisory Board of the International Journal of Applied Thermodynamics and SAIMechE R&D Journal, a Fellow of the American Society of Mechanical Engineers (ASME), a Fellow of The South African Institution of Mechanical Engineering, he was also a Fellow Member of the Southern African Institute of Energy.

In August 2000 he received the National Research Foundation (NRF) “A” rating evaluation, a privilege bestowed only with scientists that are established *“world leaders, for the quality and impact of their recent research outputs”*. This is the first ever and the only NRF (previously FRD) “A” rated scientist at University of Durban-Westville. There are currently 45 “A” rated scientists in South Africa.

In February 2001 the Royal Society of London published a paper by Straughan, B. (*Proc. Royal Society A*, **Vol.457**, pp.87-93, 2001) that names a new dimensionless group, the Vadasz Number (*Va*). The scientific significance and impact of this dimensionless group in oscillatory convection in porous media was first introduced by Prof. Vadasz in his paper: Vadasz, P., J. Fluid Mechanics 376, pp.351-375,1998, and subsequently in: Vadasz, P., *Transport in Porous Media* **41**(2), pp.211-239,2000.

He is the recipient of the 1997 University of Durban-Westville Fellowship Award for *"for distinguished academic work of such quality as to recommend special recognition locally and internationally"* and the ASME Board of Governors Award *"for valued services in advancing the engineering profession as ASME South Africa Correspondent September 1994 - September 1995"*.

Peter Vadasz's professional topics of interest are: Energy Conversion and Storage, Transport Phenomena in Porous Media, Heat and Mass Transfer and Applied Fluid Dynamics, Investigation of Non-Linear Effects, Stability, Bifurcation and Routes to Chaos, Engineering Economics Cost Analysis and Optimization and Computer Aided Engineering-Numerical Models.