New Utility Scale CAES Technology: Performance and Benefits (Including CO_2 Benefits)

Robert B. Schainker (EPRI, USA) rschaink@epri.com; Michael Nakhamkin (ESPC); Pramod Kulkarni, Tom Key (EPRI)

Abstract

This paper describes design options and comparative results of new compressed air energy storage (CAES) technologies for electric utility applications. Results are based on a CAES technical scoping study for energy storage applications in the California grid. The results show that CAES allows less expensive night-time electric energy to be effectively stored and redelivered to the grid to replace relatively expensive day-time peaking energy. For example, CAES is an effective way to store renewable energy from wind energy that is produced during off-peak periods of the day. This energy arbitrage reduces CO_2 emissions that are normally higher during on-peak hours. The new CAES plant options presented have the ability for fast output response with excellent part-load efficiency and are thus cost-effective for energy regulation and ramping duty. Currently, these services are given relatively high value by the California Independent System Operator (CAISO).

Background

Compressed air energy storage (CAES) plants use off-peak electricity to compress air into an air store reservoir. When electricity is needed, the air is withdrawn, heated by a fuel or from the plant's compressor "waste" heat, and run through expansion turbines to drive an electric generator. If fuel is used to heat the stored air, the CAES plant burns about one-third the premium fuel of a conventional combustion turbine and thus produces about one-third the pollutants (e.g., CO_2, NO_x) per kWh generated. The compressed air can be stored in several types of underground media including porous rock formations, depleted natural gas/oil fields, and caverns in salt or rock formations. When using underground geologic formations to store the air, long hours of energy can be stored cost-effectively, and such plants are much less expensive than pumped hydroelectric plants to build. The compressed air can also be stored in above ground or near surface pressured air pipelines (including those used to transport high pressure natural gas), but due to cost concerns, such above ground air store plants can only store about 2 to 4 hours of energy cost-effectively.

A 290-MW, 4 hour CAES plant has been in operation in Huntorf, Germany since December 1978 and uses two man-made solution mined salt caverns to store the air. In the 1970's through the 1990's, EPRI sponsored numerous technical and economic studies to determine the technical feasibility and economic viability of deploying CAES in the United States. These studies found that approximately three-fourths of the United States has geology potentially suited for siting reliable underground air storage CAES systems.

Alabama Electric Cooperative (AEC) built (with EPRI assistance) the first U.S. based CAES plant, which came on-line in June 1991. This plant uses a first generation design and has a power capacity of 110-MW and its underground air store reservoir is sized to produce this power output for a maximum continuous time duration of about 26 hours. For this plant, the underground air storage reservoir is one man-made solution-mined salt cavern of about 19.6 million cubic feet, operating between the pressures of about 680 psi and 1280 psi, respectively, from full discharge to full charge of the cavern.

There was one major design difference between the German and Alabama CAES plants. The Alabama plant had an exhaust gas heat exchanger in it (i.e., a recuperator, using combustion turbine jargon) , which reduced the plants fuel consumption by 25% to heat the air after it came out of the storage reservoir. The German and Alabama plants are relatively complex, requiring a lot of different types of rotating turbomachinery. They have a cost today in the range of \$700/kW to \$800/kW, which in some cases limits their commercial attractiveness.

In the last 10 years, EPRI developed and evaluated a number of advanced CAES cycles. Some require less fuel than the first generation designs used at the German and Alabama plants. Most take advantage of technology developments in simple cycle and combined cycle gas turbines plants.

In California, as in the rest of the United States, there is a dramatic need to take advantage of renewable generated energy (in particular, wind power) and to more effectively follow the daily increase and decrease of power requirements for both residential and industrial consumers. Advanced CAES plants that cost less could be an extremely cost-effective addition to the California generation mix (as well as the U.S. generation mix) to meet these utility needs.

This paper presents the results of a scoping study funded by the California Energy Commission (Contract #500-01-025, Work Authorization #WA-14) and presents results in two broad areas of work; namely, the identification of potential underground air store regions/sites in California; and presents a new design option for CAES (a so-called second generation CAES plant design option developed by Dr. Michael Nakhamkin of ESPC) that uses a simple cycle combustion turbine module as an integral part of the plant. In 2007 dollars, the second generation design is about 33% less expensive (i.e., in the $460/kw to $530/kw range, which is an overnight construction cost in 2007 dollars) than the existing Alabama and German CAES designs and operates with reduced fuel costs and amount of CO_2 produced per kWh. The new/advanced design is also less expensive to operate and has less rotating equipment, resulting in expected high plant operational reliability/availability. Another feature of one of the new/advanced design options is that air coming from a porous media/aquifer storage media does not go through a combustion process, thus negating any concern for chemical reactions that may occur in this type of geologic air store medium.

CAES Underground Air Store Siting Opportunities in California

The underground geologic formations suitable for CAES in California are numerous, due to the fact that there are many gas and oil fields in California, as well as salt water porous rock and hard rock sites in the State. Over time, many gas and oil fields are now "depleted" and thus could serve as reliable air storage sites for CAES. Maps are available showing the location of these sites. A rather "high level" map (see Figure 1) shows current California sites used to store natural gas. The detailed geologic characteristics of most of these sites are available in State records; and these sites have proven to be stable and have excellent gas pressure "tightness," and are thus attractive for potential use in CAES plants.

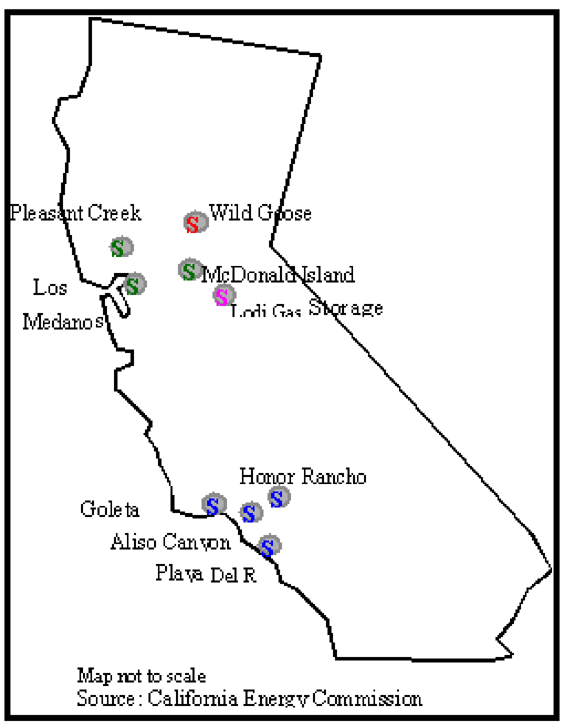

Figure 1: Depleted Gas Field Sites Used to Store Gas in California

CAES Above Ground Air Store Opportunities

Above ground air storage (for example, using high pressure gas pipeline technology) can also be used to store CAES compressed air, and there are a number of people reinventing this possibility, with each having their own specialized designs. Such systems are very attractive from the point of view that they allow CAES plants to be sited virtually anywhere since no underground geologic formation is needed. However, such systems are estimated to be a about a factor of 5 more expensive than salt based air storage caverns and porous aquifer based air storage systems. It should be noted that future R&D on these above ground systems will likely reduce their cost; thus, this R&D topic should be investigated further.

CAES Plant Design Options Suitable for California

The comparative summary is presented below (see Table 1) of performance and cost data for various CAES plant options. Each option relies on a different approach to using the pressurized air in commercially available turbomachinery. It should be emphasized that these data have been generated based on previous experience. To obtain site specific cost estimates, it should be noted that specific trade-off and/or optimization studies need to be performed dictated by economics, hourly electricity prices, local geological formations and localized equipment and installation costs associated with a particular owners conditions. The aim of such trade-off/optimization studies is to lower capital and/or operational costs by choosing the preferred CAES design option, the MW size of the compressor/expander systems and their thermodynamic heat and mass balance parameters.

	CAES – Conven-tional	CAES - Air Injection (AI)	CAES - AI & HP Expander	CAES - AI & HP and LP Expander	CAES - Expander	CAES - Expander & Inlet Chilling	CAES-Adia-batic
Total Power, MW	110	193	202	433	400	427	72
Off-Peak Comp. Power, MW	81	29	30	318	288	300	96
Total Power Fuel Related HR, Btu's/kWh	3967	8394	8182	3819	3696	3809	0
Relative Cavern Volume	1.0	1.08	0.85	1.4	1.35	1.35	1.5
Energy Ratio KWh/in/kWh out	0.80	0.85	0.69	0.73	0.69	0.70	1.3
Approximate Specific Capital Cost, $/kW	727	327	403	506	507	482	1000

Table 1: Summary of Performance and Cost Estimates for Various Second Generation CAES Plant Options. The combustion turbine used to produce the data in columns 3 through 7 above, was a GE Frame 7A. The costs above are only to be viewed on a relative basis and not on an "absolute" cost basis. They are for a 10 hour underground salt based air storage system or for a 2 hour above ground air storage system.

Some of the second generation CAES plant options summarized in Table 1 are shown in schematic form in Figures 2 through Figure 5 below. The CAES – Expander Option is attractive for porous rock air stores since the air from the store does not go through any combustion process; thus, this option is particularly attractive if one is concerned about any chemical reactions taking place in the air store. The adiabatic option is of interest since no fuel is needed when the plant operates, since heat from the compression cycle is stored and used to preheat the air coming from the air store during the generation cycle.

CO_2 Benefits of CAES

In California, the plan is to store wind generated energy produced mostly during off-peak evening hours and then recover that energy for use during daytime on-peak hours. CAES can cost-effectively perform this function; thus enabling renewable wind systems to be "dispatchable". Under this scenario, the only CO_2 produced will occur during the CAES generation cycle; and based on the CAES heat rate estimates shown in Table 1, the actual amount of CO_2 produced per kWh of energy generated is about one third to one half that of a combustion turbine.

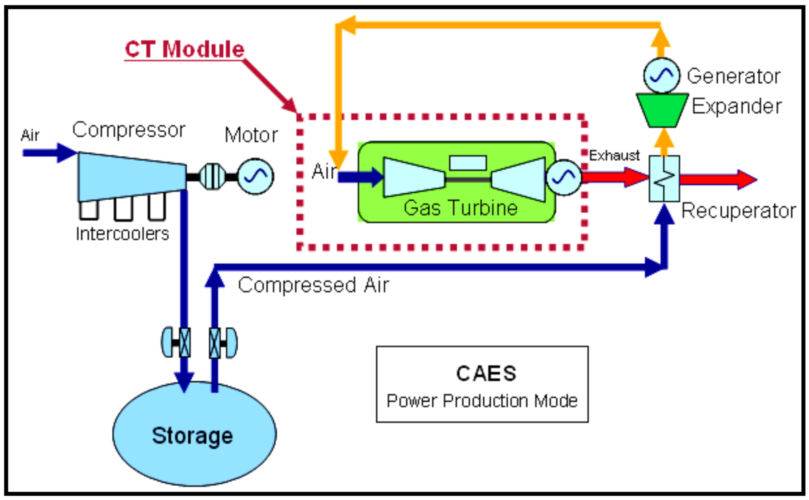

Figure 2: Second Generation CAES Plant Design Option Called the "CAES Expander & Inlet Chilling" Option, Since The Outlet From The Expander (Which is Chilled Air) Goes To The Inlet Of The Combustion Turbine

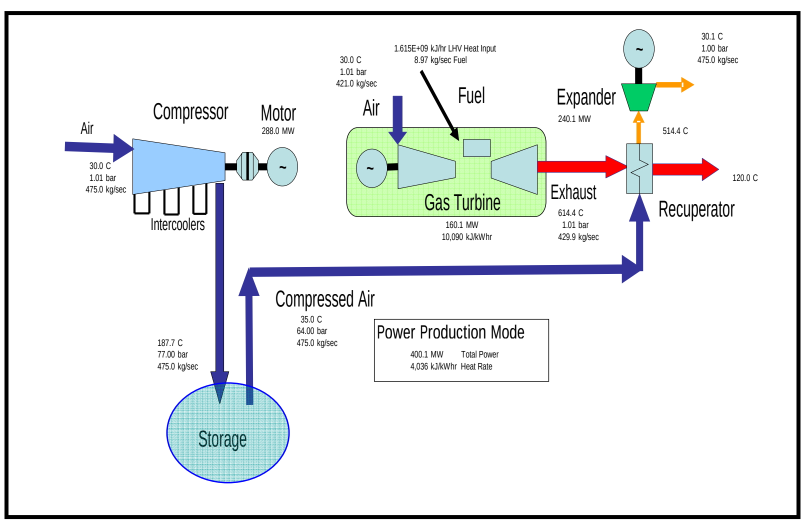

Figure 3: Schematic for the CAES - Expander Plant Option (Note: The Stored Air Does Not Go Through A Combustion Process)

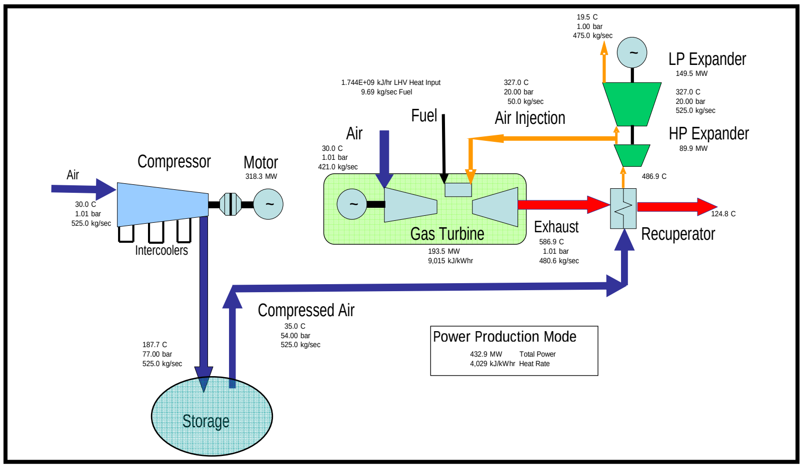

Figure 4: Schematic for the CAES-AI Expander Option

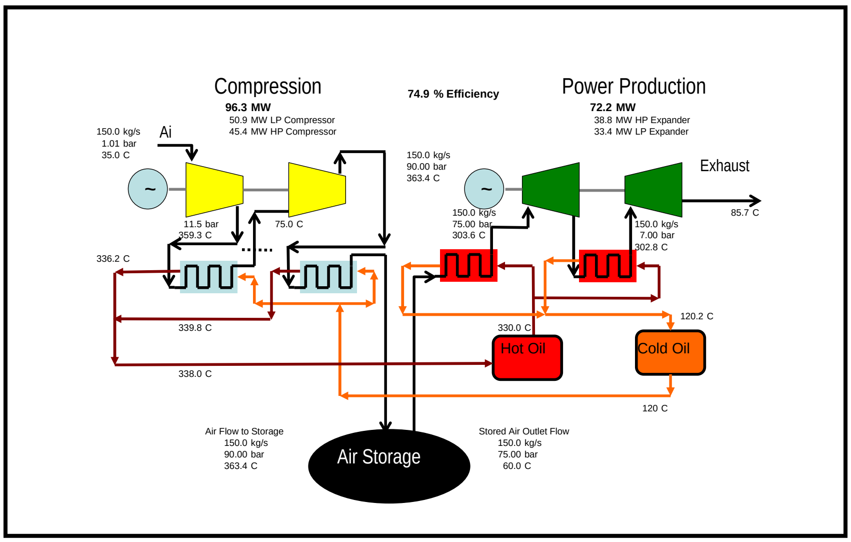

Figure 5: Schematic for the CAES Adiabatic Plant Option

Conclusions and R&D Opportunities To Deploy CAES Plant Options

The major R&D associated with California underground air storage formations revolve around field testing cyclic air storage systems in at least two types of air reservoirs (namely, one for a depleted gas field and one for a depleted oil field). First, core samples should be acquired and investigated with respect to any geochemistry associated with storing air in these formations. This can be done using standard autoclave systems on core samples taken from the depleted gas/oil sites, which can be obtained from the local State Geologic Survey, or if necessary, by drilling into the underground formation with a small bore drilling rig to obtain “clean” core samples for the needed geochemical investigations.

Analysis of the specific characteristics of new CAES plant options, as well as the no-fuel adiabatic option, was driven by a desire to simplify the overall plant equipment layout and connections, and use standard components and systems wherever possible. Even so, there are a number of R&D efforts required to ensure reliable and cost effective CAES plants for implementation in California where there is a growing renewable portion in the future State generation mix.

Most if not all of the R&D issues associated with the new second generation CAES plant options could be effectively addressed by demo projects with well thought-out test procedures to apply the demo projects results to a variety of CAES plant options, differentiated by size and equipment module additions.

These demo projects could easily utilize existing old small capacity combustion turbines to reduce capital costs and plant capacities of the demo plants. These demo projects would allow integrating various CAES plant configurations with the above ground storage systems as well, with about two to three hours of continuous generation. Also, special "hybrid" demo designs could be built to address various CAES plant options including the adiabatic option. This would allow results of the "hybrid" demo project to be applied to a variety of plant design options and geologic opportunities throughout the State.

A major characteristic of most of the new CAES options show that they are based on a combustion turbine module; and therefore a demo project could be based on any available existing combustion turbine a California utility makes available, or is willing to contribute to a CAES demo project. Also, the amount of air in the exhaust stream of this combustion turbine used in the demo project can be much smaller than all the exhaust air available, since all the demo project has to do is provide a proof of principle to the thermodynamic and performance characteristics expected. For example, the demo plant need only be about 1 MW to 5MW's if it only uses a portion of the exhaust air for heating the stored air; or, the demo plant could use all the exhaust air flow and produce 50MW to 100MW of output depending on the size of the combustion turbine the host utility provides for the demo project.

The specific R&D topics related to the new CAES options described herein are as follows:

- Investigate the performance of a combustion turbine that uses injected stored compressed air, as it relates to practical implementation of the second generation CAES plant options identified
- Perform trade-off/optimization studies of various new CAES plant options for a variety of sizes and specific renewable energy requirements requiring regulation and ramping duty, as it relates to power and storage requirements
- Analyze the adiabatic option based on the latest technological developments/costs of thermal heat storage oils, and perform innovative engineering analyses to use these thermal media
- Perform cost optimizations and field testing of above ground air storage systems based on the latest high pressure gas pipeline technological developments. Include in these analyses a cost-effective design using prefabricated concrete and/or reinforced fiberglass piping, as well as previously EPRI studied low cost carbon steel piping. The R&D field/lab tests should focus on cyclic induced heating, cooling and corrosion stresses. Also, the field/lab test R&D activities need to verify the overall energy output over energy input efficiency index during multiple charge-discharge cycles.
- Perform trade-off analyses of alternative below ground storage media, including porous media and salt layer media, with emphasis on storage media performance under planned CAES operating cyclic conditions.
- Analyze CAES plants using a variety of fuels including biomass fuel, low-BTU gas, Number 2 fuel oil, and mixtures of hydrogen and natural gas
- Analyze adding a synchronous condenser feature to appropriate CAES design options since +/- VAR injection is needed in California as more wind or other renewable generation plants are put into service (i.e., analyze the cost-effectiveness of "exciting" the synchronous compressor motor so it can also be used as a synchronous condenser)