Second Generation of CAES Technology- Performance, Operations, Economics, Renewable Load Management, Green Energy

Dr. M. Nakhamkin, M. Chiruvolu, M. Patel, S. Byrd
Energy Storage and Power, LLC (ES&P)

Dr. R. Schainker,
Electric Power research Institute, EPRI

J. Marean,
New York State Electric and Gas (NYSEG)

Abstract: Compressed air energy storage (CAES) plants are designed to store inexpensive off-peak energy and return energy to the grid during higher priced on-peak time periods. This paper presents an attractive second generation CAES technology that has attractive performance, operational and economic characteristics as well as unique flexibility to optimize these characteristics to meet various “smart grid” operating and economic requirements for plants ranging from 15MW in capacity (using above ground air storage system) to over 400MW capacity using below ground geologic formations to store the compressed air. The turbomachinery in this new CAES plant design uses standard multi-size compressors, new or existing combustion turbines and separate expansion turbines. The emissions from this type of CAES plant has NOx levels in the single digits due to very low heat rate of approximately 3800 Btu/kWh and the storage efficiency is in the 80% to 90% range, i.e. app. 80% to 90% of the electric charging energy used during off-peak hours are returned during peak hours.

Today’s interest in more advanced CAES technology is driven in part by 1) the global spread of ‘zero emissions’ wind turbine generation, which typically can realize only 20-30% of nameplate capacity depending on time of day demand and prevailing wind, and by 2) the availability of low cost power from base loaded coal and nuclear plants during off-peak hours.

General Performance Information

Power: Plant capacity is scalable from around the 15MW level and to the 400MW-600 MW level, based on various standard combustion turbines, generating approximately 35% of the total CAES plant power. The expansion turbine(s) portion of the plant
produces about 65% of the total power from the CAES plant and acts as a bottoming cycle similar to a steam turbine system in of a combined cycle power plant.

**Heat Rate:** Approximately 3700-3800 Btu/kWh plant heat rate;

**Energy Ratio:** Approximately 0.65 to 0.75 kWh-In (off-peak kWh energy used to charge the storage system) over kWh-Out (CAES plant energy produced during the plants generation cycle).

**Operating Cost:**
- Fuel costs - Heat Rate (Btu/kWh) x Fuel Price ($/Btu)
- Off-peak energy costs - Energy Ratio (kWh-In/kWh-Out) x Price of Off-Peak Electric Energy ($/kWh-In)
- Fixed and Variable O&M Costs ($/kWh-Out)

**Reliability & Availability:** This second generation CAES Plant is based on standard /off-the-shelf components: namely, a combustion turbine module (new or used), multiple motor-driven compressors and multiple expanders-driving electric generators.

**No Newly Developed Combustors:** Fuel is burned only in the CT’s low NOx combustors with 5-9 ppmv NOx emissions. Thus, this type of second generation CAES plant does not need any specially designed high pressure combustor, which would be unique to the pressure level associated with the air storage system used.

**Emissions:** Combustion turbines with dry low emission (DLE) combustors have single digit emissions which are further diluted (on a per kWh-Out basis) in this type of second generation CAES plant, due to the extra power generated by the zero-emission “green” power generated by the expanders.

**Capital Cost:** Approximately $800-850 /kW for large plants using below ground air storage systems and approximately $1200/kW for small plants using above ground air storage systems.

**Grid Support:** During plant operation, practically instant load following from 30 to 100% of capacity and from cold shutdown approximately 70% of rated capacity can be achieved in less than 3-5 minutes of synchronous reserve demand.

Energy Storage & Power Corporation (ESPC) in close cooperation with Electric Power research Institute (EPRI) developed and optimized the original design concept and parameters of the 110MW first generation CAES plant built for Alabama Electric Cooperative (AEC) and conducted technical supervision of the project execution which went into operation June 1, 21991. The Alabama plant’s 110 MW CAES plant was specifically designed for AEC’s operational and economics requirements and was driven by load management of base-load coal plants characteristics.
The Alabama CAES plant was based on a single-shaft turbomachinery train with a number of unique components, which included diffusion type combustors (high pressure and low pressure) that are designed to operate at specific combustors air inlet conditions determined by an underground salt cavern storage system and with unique part load operations.

The current renewable (wind/solar) energy load management, power storage and generation requirements and smart grid variable requirements (arbitrage, regulations and synchronous reserve backup), as well as underground storage limitations, require a CAES plant designs with unique flexibility. Building on “lessons learned” from operation, performance and maintenance of the AEC’s CAES plant and other factors Dr. Nakhamkin has developed and patented a new second generation CAES technology (denoted CAES2). Compared to the first generation CAES technology in Alabama, the CAES2 technology is estimated to be less expensive to build, has lower operating costs, and has more flexible operating characteristics.

The CAES2 Plant Concepts General Description

Two 170-180 MW CAES2 concepts are shown on the Figure 1a and 1b and are built based on GE 7B combustion turbine and standard stand-alone major components that can be sized and integrated to optimize plant performance, operations, specific grid regulation and synchronous reserve requirements, economics and specific underground storage characteristics:

- A number of separate motor-driven standard off-shelf compressors with intercoolers to use the off-peak energy and convert it into the stored air energy
- New or existing gas turbine(s) with dry low emissions (DLE) combustors;
- A number of the bottoming cycle industrial air expanders (driving electric generators)
- Recuperator utilizing the combustion turbine exhaust gas heat for preheating the stored compressed air upstream of the bottoming cycle expanders
- Below or above ground compressed air storage with flexibility for capacity and parameters
Figure 1a. 170 MW CAES plant Concepts with Air Injection Power Augmentation
In general, gas turbine capacity (new or existing) represents approximately 30% of total CAES plant capacity. For example, if the grid requires a nominal 400 MW plant, the CAES2 design can be based on a 170-190MW-class gas turbine such as GE’s Fr 7FA model. Similarly, a nominal 250MW plant can be based on a 100MW-class gas turbine like the Fr 7EA. CAES2 concepts of various capacities are based on various combustion turbines but in principle are very similar to concepts presented on Figures 1a and 1b.

At the lower end of the power spectrum, say for a nominal 15MW plant, the design can be based on a 6MW-class gas turbine like the Solar Taurus 60. Whether small or large, the integration of the gas turbine into CAES2 plant design and operation is based on similar grid requirements (see Figure 1c).

CAES2 technology has gas turbines power output being augmented by 20-25% with injecting pressurized air extracted from the expander into the gas turbine upstream of the combustors. (Validation of air injection augmentation technology is discussed in detail in *Gas Turbine World’s* March-April 2002 issue.)
Alternatively, power can also be augmented by cold air supercharging the gas turbine, i.e. injecting the expander exhaust flow at much lower than ambient temperature (subject to optimization) directly into the gas turbine inlet.

The bottoming cycle expanders generate approximately 70% of the total CAES plant power without any additional fuel consumption and emissions. They have, as it was mentioned above, two alternative provisions for the combustion turbine power augmentation, by either a) the air extraction from the expander for injection into the gas turbine upstream of the combustors or b) injection of the expander exhaust flow at much lower than ambient temperature (subject to optimization) directly into the gas turbine inlet. The expanders could use standard off-shelf industrial expander’s suppliers and steam turbines standard modules replacing steam by air.

The recuperator preheats the stored air to approximately 900-1000°F depending on the gas turbine exhaust temperature and on plant optimization tradeoffs.

**Flexibility of CAES2 Technology for Optimization to Meet Smart Grid Operating Requirements and Economics**

**Off-peak and Renewable Energy Storage Operations Optimization**

In the storage mode of operation, specific grid characteristics -- off-peak energy availability and prices, requirements to provide load managements of intermittent, renewable and base-loaded plants, grid operation management -- provide the basis for:
- Optimization of multiple intercooled compressors, unit capacities and operating parameters,
- Evaluation of compressor transient operations, and
- The compressed air storage volume and parameters based on specific limitations established by the storage geological characteristics and depth.

EPRI studies indicated that approximately 85% of the US territory has geological formations that can accommodate underground compressed air storage that utilize below ground geologic formations.

Typically, for CAES operation, compressed air will be injected at a maximum pressure of approximately 1000-2000 psia and 100°F for storage (specifics depend on plant design and storage specifics).

Proper optimization of compressor sizes and numbers is critical to find the best combination of the lowest capital and operating costs. A typical compressor has a turndown ratio of app. 0.7, and the single 50MW compressor of the AEC’s project is not able to accept off-peak energy below 35 MW -- regardless of price and availability. Also, the compressor’s discharge pressure imposes limitations on allowable underground energy storage depth and pressure.
In the power generation mode of operation, specific grid characteristics -- peak energy requirements and prices, regulation and synchronous reserve demands – provide the basis for determining:

- Number of expander units and total plant capacity
- Gas turbine model and rated power output capacity
- Number of bottoming cycle expanders, unit capacities and parameters
- Recuperator duties and the air preheating temperature
- Gas turbine power augmentation technology
- Stored discharge air flow, pressure and temperature parameters
- Additional features (like optional duct burner) to meet specific grid ramping and spinning reserve requirements

**Flexibility for Peaking Power Delivery.**

**Flow Control.** CAES2 has flexibility to control/regulate the compressed air flow conditions can be regulated to meet a wide range of the power delivery requirements. For instance, the stored compressed air discharge pressure and flows could be throttled and controlled up or down to manage plant performance to a wide variety of ramping levels. Figure 3 demonstrates that the compressed air flow variation has significant affect on the bottoming cycle expander power, i.e. the increase of the extracted from the storage compressed air flow for the optimized for the 172 MW CAES2 plant (Figure 1a) by app. 40% will increase the total CAES2 power by approximately 10% above the design point power. On other hand the reduction of the compressed air flow will increase the duration of the electric power generation.

![Figure 2a. Flexibility for Peaking Power Delivery by Flow Control](Image)
**Sliding Pressure Operation.** As it was mentioned above, the stored compressed air pressure is changing from app. 1200-1500 psia to app. 800 psia and it is very practical to operate the expander train with the **sliding pressure** that allows generating additional peak energy practically without any modifications of expanders.

![Graph](image)

**Figure 2b.** Flexibility for Peaking Power Delivery by Sliding Pressure Operation

**Part Load Heat Rate and Energy Ratio.** The power CAES2 plants is generated by the combustion turbine and bottoming cycle expanders and that provide a flexibility to optimize performance parameters- heat rate and energy ratio- during the plant operations. Figure 3 presents performance characteristics of the CAES2 plant operation of at part loads that demonstrates practically constant and very low heat rate from 100% load to approximately 40% load.
Figure 3 Heat rate and Energy Ratio at Part Loads

**Duct Burners.** The expander also has built-in flexibility to generate power on its own when the gas turbine is not in operation. To meet specific regulation and synchronous reserve requirements, primarily during emergency operations, the CAES2 plant can increase its power output. Low NOx duct burners ahead of the expander inlet can be fired up to heat compressed air released from storage so that full expander output (typically around 70% of plant capacity) is available for grid dispatch within less than 3-5 minutes.

**Green Energy.** Approximately 70% of the CAES2 power is generated by the bottoming cycle expander(s) with no incremental fuel consumption.

**Power Arbitrage.** Buying less expensive off-peak energy and selling peak energy needed and with higher price.

**Enhancement of Operations and Economics of Renewable Resources.** This is materialized by the increase in load factor of renewable resources and the improvement in load management operations due to use of the CAES plant.

**Enhancement of Grid Operations:**
- Regulation - flexibility to provide load following in the range from 20% to 100% of the CAES plant capacity within 3-5 minutes
- Synchronous Reserve- sudden load response up to 70% of the CAES plant capacity within ~3-5 min

**Reduction of Fuel Consumption and Dependence on Imported Oil Prices.**
Peak power generated by CAES2 power plant has the heat rate of approximately 3800 Btu/kWh vs. heat rates of approximately 9500 Btu/kWh of state-of-the-art combustion turbines-prime deliverers of the peaking power. It results in approximately 50% reduction of the fuel consumption.

**Economics**

The CAES2 plant economics are based on relatively low capital costs and income generated by the sale of peaking power plus income generated by smart grid payments for regulation/ramping and synchronous reserve - minus costs of the off-peak energy stored.

In addition to pure economics of the CAES2 plant operations, there are additional external economical benefits associated with the CAES2 plant operations such as: increase load factor and economics of renewable energy sources and base-load plants (coal and nuclear).

The table below presents a summary of CAES2 plant characteristics and estimated capital costs of a 170-180MW CAES2 plant that utilizes an underground compressed air storage system (salt geology) and a 15 MW CAES2 plant which utilizes an above ground air storage system.

<table>
<thead>
<tr>
<th>CAES 2 Plant Parameters</th>
<th>170MW CAES2 plant w. Air Injection Power Augment</th>
<th>170 MW CAES2 plant w. Inlet Chilling Power Augment</th>
<th>15 MW CAES2 Plant</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total CAES2 Plant Power, MW</td>
<td>172</td>
<td>182</td>
<td>15</td>
</tr>
<tr>
<td>CAES 2 Expander Power, MW</td>
<td>108</td>
<td>118</td>
<td>9</td>
</tr>
<tr>
<td>Off-Peak Compressor Power, MW</td>
<td>71</td>
<td>73</td>
<td>6.9</td>
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<tr>
<td>Total Power Fuel Related HR, Btu/kWh</td>
<td>3771</td>
<td>3847</td>
<td>3900</td>
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<tr>
<td>Total CAES2 Plant Energy Ratio, kWh-In/kWh-Out</td>
<td>0.65-0.68</td>
<td>0.65-0.68</td>
<td>0.78</td>
</tr>
<tr>
<td>Estimated Specific Capital costs, $/kW</td>
<td>850</td>
<td>850</td>
<td>1200</td>
</tr>
</tbody>
</table>

The chart on the Figure 4 presents a comparative analysis of the generation costs of various power generation plants that indicates CAES2 is estimated to have practically the
lowest generation costs over the whole range of load factors even w/o considerations of additional external economical benefits.

Figure 4. Power Generation Costs for Various Plants vs. Load Factor

Conclusions

The CAES2 technology presented above is a second generation type of CAES plant with capital cost, operating cost, NOx emission, and ramp rate characteristics improved over those of the first generation CAES plant built in Alabama (circa 1991). Of particular interest today is the increasing amount of wind (and solar) power plants being built that have highly variable power output and operating characteristics. The CAES2 technology enables the cost-effective storage of energy from these types of variable power sources and the discharge of their “green energy” at ramp rates designed to meet the green and smart grid requirements of today’s electric grid.

References:

1. Vic DiBiasi, Publisher of Gas Turbine World Journal; “Second generation CAES technology has much improved economics, performance and operational flexibility to provide unique load management of renewable energy, smart grid regulation, synchronous reserve, demand power and peak shaving management;“Gas Turbine World, March-April, 2009


7. Dr. R. Schainker, Dr. M. Nakhamkin, Pramod Kulkarni “New Utility Scale CAES Technology” EESAT, 2007