Available Compressed Air Energy Storage (CAES) Plant Concepts

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There is a significant interest in the Compressed Air Energy Storage power plants that are driven primarily by very extensive developments of the wind and other renewable resource projects and by the current emphasis on the coal/nuclear power plants (associated with very high current fuel/NG costs) – all requiring a significant load management.

These various applications require a flexibility of the CAES power plant concepts to meet variety of specific operational, economic and off-peak and peak conditions loads i.e.:
- Flexibility of the meeting a various magnitudes of load management demands- off-peak power availability and prices, peak load requirements and prices, operational specifics and economics
- Adaptability to specific limitations imposed by available geological opportunities
- Simplicity with high reliability and availability
- Reduction of specific costs and shorter lead time.

The paper summarizes a number on developed and patented by ESPC novel CAES plant concepts that will provide power generators with a number of practical and cost-effective choices. These concepts are based on various combinations of the following major standard off shelf components- existing or new combustion turbine, air compressors, air expanders and heat recovery recuperator - all integrated with a compressed air storage and optimized for specific operational, economic and geological conditions. Because both CT and CAES plants provide peak power, operations of CTs and CAES plants are practically coincidental. The total power of presented CAES concepts consists of the CT power generated with the CT’s heat rate and the incremental CAES power produced by extracted from the storage compressed air (that was stored during off-peak hours) with associated heat rate ranging for various concepts from approximately 0 to 4000 Btu/kWh heat rate. The fuel in these concepts is burned by CT combustors only.

In addition to flexibilities to meet a variety of load management and other specific requirements, these concepts are characterized by a simplicity, reliability and availability and significant reduction of specific capital and operating costs.

The illustrated in this paper performance and cost data for various CAES plant concepts had been developed by ESPC for the 300 MW CAES project located in the Shanghai area, China. The project is in an advanced development stage and optimized based on specific operational, economic and geological data with emphasis on the equipment manufactured primarily in China. These concepts will be analyzed as it related to performance and operational characteristics capital costs and compared to the Conventional CAES the power plant concept used by the existing Alabama McIntosh 110 MW CAES plant.
1. Background of the Current CAES Technology

The CAES concept has been well proven through the operating history of two existing CAES plants, one in plant in Huntorf, Germany and the first in the USA plant in McIntosh, designed for load management. The Huntorf plant is a 290 MW (designed and built to provide spinning reserve only) plant that started up in 1978. The 110 MW CAES plant is owned by Alabama Electric Cooperative, McIntosh plant and commenced operation in 1991. The successful operation of these two plants has demonstrated the technical viability of CAES technology in load management; spinning reserve, load following and intermediate power generation.

Energy Storage and Power Corporation (ESPC) developed the concept for the McIntosh plant, and was involved in all phases of project execution: feasibility study, engineering, construction, start-up, performance guarantee tests and three-year monitoring the plant operations. The simplified schematic of the 110 MW AEC’s CAES plant is presented on Figure 1.

Figure 1: Conventional CAES Schematic (McIntosh Plant)

Even though these two plants have been commercially successful, no additional CAES power plants have been built. ESPC believes that one reason for this is relatively high CAES plant construction costs ($700-800/kW) specifically for peak load operations. The second reason is that two major equipment vendors are offering only two CAES plant capacities: Dresser Rand -135 MW, and Alstom 400 MW. Both vendors have put together CAES concepts that are rigid
not only in the specified plant size but also in allowable operating flows and pressures, which affect the storage depth and volume. These restrictions make it difficult to adjust the plant specification to meet the needs of specific renewable plant capacities, operating modes and sites.

The experience of the AEC CAES project demonstrated the importance of the overall plant optimization including turbomachinery parameters, the storage available volumes and operating parameters and overall operating and economic data (like available off-peak power and costs, peak power needs and prices, fuel costs, etc.)

In response to these needs and challenges, ESPC has developed and patented CAES concepts that are flexible, simple, and reliable. They are based on utilizing off-the-shelf gas turbines, compressors, and expanders integrated into the CAES plant design with a significant cost reductions and shorter delivery schedule.

### 2.0 Description and Performance Characteristics of Novel CAES Concepts

As was mentioned above the illustrated below performance and cost data for various CAES plant concepts had been developed by ESPC for the 300 MW CAES project located in the Shanghai area, China. The project was configured with emphasis on the equipment manufactured primarily in China and therefore the CT used as a basic part of these concepts is the GE9171. Heat and mass balance models had been developed using the Thermoflex power plant modeling software.

**The CAES-Air Injection (CAES-AI) Concept**

The CAES-AI concept is based on the injection of the stored and preheated air directly into the compressor discharge plenum of a GT thus providing the GT power increase. The schematic of the CAES-AI concept with major performance characteristics are presented on Figure 2.1.

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**Figure 2.1 Schematic heat and mass balance for CAES-AI Concept**
CAES-AI concept has the following major components:

- GE 9171E CT (existing or new combustion turbine),
- Compressed air storage
- Multiple compressors for the compressed air energy storage charging during off peak hours, utilizing renewable sources
- Heat recovery recuperator (HRR)
- BOP systems

The GE9171E (designed for the maximum injected air flow and corresponding maximum power produced at very low ambient conditions like 10- 20F) at a typical ambient temperatures operations operates with significantly reduced inlet flow and reduced power. This shortage of the inlet flow in CAES-AI concepts is compensated by the injection of the stored airflow with associated increased of the CT power. Based on validation tests of the GE7241FA ESPC established the maximum injection flow allowable for the injection into GE7241 had been limited to approximately 12% of the combustion turbine inlet flow (Reference 1). The CAES-AI concept total power of 137.4MW with the heat rate of 9355 Btu/kWh (Figure 4.1) is the combination of the CT power of approximately 112MW with the heat rate of app. 10850 Btu/kWh and the additional CAES power of 25 MW generated by CT due to the injection into of the additional stored compressed air with the heat rate of app. 4000 Btu/kWh.

**CAES-AI with HP Expander Concept (CAES-AI-HPE)**

The schematic of the CAES-AI with the HP Expander concept with major performance characteristics are presented on Figure 2.2. The CAES-AI with HP expander concept is the CAES-AI concept with an added HP expander to utilize the pressure difference between the stored air pressure and the pressure at which the air is injected into the gas turbine.

**Figure 2.2 Schematic heat and mass balance for CAES-AI-HP Concept**
The CAES-AI with the HP Expander concept has the same components as the CAES-AI concept plus the high pressure expander. The stored compressed air is preheated in the HRR, utilizing the exhaust gas heat, and then is directed into the HP expander with the exhaust pressure being equal to the pressure required for the injection of the stored air into CT.

The total power of 145.4MW with 8700 Btu/kWh heart rate is a combination of the CAES-AI power of 137.4MW with 9355 Btu/kWh heat rate and the additional the HP expander power of 8.2 MW without any additional fuel consumption (heat rate is 0 Btu/kWh).

**CAES-AI Concept with the Bottoming Cycle Air Expander CAES-AI-BCE**

CAES-AI with the Bottoming Cycle Expander concept is the CAES-AI concept with the expander operating between the stored air pressure and atmospheric pressure. Air is extracted from the expander for air injection into the gas turbine. CAES

The schematic of the CAES-AI-BCE concept with major performance characteristics are presented on Figure 2.3. The CAES-AI-BCE concept has the same components as the CAES-AI-HPE concept with the following differences:

- The expander operates between the stored compressed air and atmospheric pressures
- The expander has an extraction of air with parameters consistent with the air injection into CTs
- The expander inlet compressed air flow is a subject for optimization and not limited by the injection flow into a CT.

![Figure 2.3 Schematic heat and mass balance for CAES-AI/Expander Concept](image)

The total CAES-AI-BCE power of 332.7 MW with 3800 Btu/kWh heart rate is a combination of the CAES-AI power of 137.4MW with 9355 Btu/kWh heat rate and the additional the bottoming
cycle HP and LP expander with the power of 200.5 MW without any additional fuel consumption (heat rate is 0 Btu/kWh).

**CAES Concept with the Bottoming Cycle Air Expander and Inlet Chilling (CAES-BCE-IC)**

The schematic of the CAES-AI with the Expander and Inlet Chilling concept with major performance characteristics is presented on Figure 2.4. This concept has the same components as the CAES-AI with the Expander concept with the following differences:

- There expander has no extraction for air injection into CT
- The expander is optimized to have the exhaust flow equal to the CT inlet flow and the exhaust temperature of approximately 10-15°C
- The expander exhaust is injected into the CT inlet.

![Figure 2.4 Schematic heat and mass balance for CAES/Expander/Inlet Chilling Concept](image)

The CAES power for the concept is the expander power plus the CT power increase due to inlet temperature that is lower than ambient temperature.

The total CAES-AI-BCE power of 327 MW with 3936 Btu/kWh heart rate is a combination of the CT power of 127 MW and heat rate of 10132 Btu/kWh (due to inlet chilling the increase from 112 MW with the heat rate of app. 10850 Btu/kWh) plus additional the bottoming cycle HP and LP expander with the power of 202.5 MW without any additional fuel consumption (heat rate is 0 Btu/kWh).

**CAES Concept with the Bottoming Cycle Air Expander (CAES-BCE)**

The schematic of the CAES-BCE concept with major performance characteristics are presented on Figure 2.5. This concept practically has the same components as the CAES/Expander/Inlet Chilling concept with the following differences:

- The expander is not sized to meet the CT inlet flow requirements and therefore has some flexibility in its sizing.
The expander exhaust is not directed to the CT inlet.
The CAES power is the expander power.

Figure 2.5 Schematic heat and mass balance for CAES/Expander Concept

3.0 Summary of Performance and Cost Analyses
Table 3.1 presents a summary of the performance data and estimated specific cost data ($/kW) for all concepts. All the capital costs for each of the CAES plant concepts analyzed in this study were estimated in 2006 dollars, for above ground plant based on some equipment on actual proposals or published prices. The salt dome underground storage cost estimates were based on escalated equations developed during execution of the AEC project.

The table and previous descriptions of the available CAES plant concepts demonstrate:

- They are simple and based on standard combustion turbine and off-shelf expander and compressor components
- CAES technology components are external to the CT and practically could be considered as the air bottoming cycle (similar to steam bottoming cycle for CC plants)
- They provide flexibility of the meeting a various magnitudes of load management demands- off-peak power availability and prices, peak load requirements and prices, operational specifics and economics.
- The CAES plant capacity could be met by a proper selection of CT and external expanders, injection rates and other components.

Table 3.1
Summary of Performance and Estimated Price Data for Various CAES Plant Concepts
These concepts can utilize existing CT-CC plants. They have significantly lower capital costs of approximately $450/kW. There is no additional fuel consumption except in a CT and therefore the emissions per kWh produced are reduced by a factor of two as compared to the CT. Schedule time is within two years. The storage size is significantly reduced with associated costs.