15 MW CAES Plant with Above Ground Storage – Distributed Generation based on Novel Concepts Developed by ESPC

Project Sponsored by EPRI

Presented by
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Energy Storage and Power Corporation
Presentation

• The 110 MW CAES Project for Alabama Electric Cooperative:
  – Concept, Design, Engineering, Operations
  – Lessons learned

• 15 MW CAES Plant with Above ground Storage:
  – Heat and Mass Balances
  – P&IDs
  – Lay Out drawings
  – Capital Cost Estimate
  – Summary
The CAES Technology
The 110 MW CAES Project
Alabama Electric Cooperative
General Electric 7FA CT Performance at Different Ambient Temperatures at Sea Level

- **Ambient Temperature: 59°F - ISO**
  - Gross Power: 172 MW
  - Heat Rate: 9,360 Btu/kWh

- **Ambient Temperature: 0°F**
  - Gross Power: 191 MW
  - Heat Rate: 9,350 Btu/kWh

- **Ambient Temperature: 95°F**
  - Gross Power: 150 MW
  - Heat Rate: 9,760 Btu/kWh

**Graphical Representation:**
- P 228, T 749
- P 250, T 713
- P 214, T 812
- T 2562
- M 1083
- M 984
- M 935
- M 898
- T 1116
- T 1079
- T 1141
- T 2562
- T 1079
Simplified Schematic of CAES Plant

Stores Wind Energy in the Form of Compressed Air

Off-Peak Wind/Renewable Energy

Compressors

Motor

Recuperator

Combustors

Generator

Peak Power Energy

Power Generating Expanders

Underground Storage
CAES Technology Features

CAES technology was developed as a load management plant with the prime purposes:
- To store the off-peak energy that is not needed and inexpensive and to increase load factor of base-load plants (Coal, Nuclear)
- To release this energy during peak hours when energy is needed and the price is high

The AEC’s 110MW CAES Project had been driven by two factors:
- Due to very low off peak loads, two 300 MW coal-fired plants during off-peak hours operated at very low loads with extremely high heat rates and sometimes had been shot down
- AEC had shortage of peak power

Project met all performance guarantees, costs and schedule and in successful operation for over 17 years.

Q: Why there were no other up w. CAES Plants built?
A: New Technology and No big motivations then cost of NG was then $2/M BTU and Coal $1.5/M Btu

The current development of Wind Power- the primarily uncontrollable energy source- requires the CAES plants to store wind energy produced during off-peak hours and distribute it with additional benefits during peak hours when energy is needed and cost of energy is high

Now NG Cost is $10/M Btu and possibly will go up.
Alabama Compressed Air Energy Storage Plant
Peak Power 110 MW; 26 hrs of continuous Power Generation;
Heat rate is 4000 Btu/kWh; Off-Peak Power 51MW, Capital Cost $600/kW
Schematic for AEC CAES Plant
(110 MW – 26 Hour)
CAES Concept and Parameters developed & specified by ESPC;
Compressors & Expanders delivered by DR;
Recuperator by SW;
HP/IP Combustors by AIT
Underground Storage- PB

Compressors (50 MW)
- HP
- IP-2
- IP-1
- LP
- After-cooler
- Intercoolers

Expanders (110 MW)
- LP
- HP
- Motor / Gen
- SSS Clutches

Salt Cavern Air Store:
- Distance to Surface = 1500 ft
- Height = 1000 ft
- Avg. Diameter = 156 ft
- Volume = 22MCF

Underground Storage Cavern: A Solution Mined Salt Cavern

Heat Rate
4100
Energy Ratio
0.81

Pressure = 650 psi
Fuel
Exhaust Stack
Recuperator
Alabama Electric Cooperative CAES Plant:
110 MW Turbomachinery Hall

From Left to Right:
Compressors, Clutch, Motor-Generator and Expansion Turbine
The 110 MW CAES Plant Engineering, Optimization and Delivery

ESPC developed, optimized and specified the 110 MW CAES plant concept based on available and/or newly developed components provided by various suppliers:

The reheat, intercooled and recuperated turbomachinery is based on:

• Compressors and expanders provided by Dresser Rand
• HP and LP combustors provided by AIT
• Advanced Recuperator provided by Struthers Well (patented by ESPC)
• Underground Storage by Parsons Brinkerhoff
• Control philosophy for operation and Safety

ESPC was conducting technical supervision of the project execution including:

• Supervision of the turbomachinery development by Dresser Rand
• Supervision of the HP combustors development by AIT
• Development of the test procedures
• Supervised performance guarantee tests and issued the Test Report
• Under contract with EPRI, ESPC recorded key plant parameters during 1991-1994 -three years after the project commercialization, and issued “Value Engineering” Report
EPRI was Co-sponsor of the CAES Project
Concentrating on R&D Issues:
Turbomachinery, Advanced Recuperator, Project Technical Supervision, the LP Expander TIT Increase

Ground Breaking Ceremony
Dr. R. Schainker, EPRI
Ray Claussen, AEC, VP Operations, Planning
Dr. M. Nakhamkin, ESPC

ESPC Received EPRI's Achievement Award
Unique Features and Components of the AEC’s Turbomachinery/Plant

The multi-component single-shaft turbomachinery train has the first of the kind unique features and unique components- all optimized and developed during the project execution:

- Reheat expander train with HP/LP combustors
- Intercooled Compressor train
- Advanced Recuperator
- Turbo expander and compressor trains are integrated with the underground storage
- Control Philosophy- Power Control by both HP/LP fuel and air flows

First of the kind Components with only single applications:

Dresser Rand:
- HP steam turbine converted into the expander and integrated with the HP combustors
- The industrial expander with increased TIT from 1350F to 1500 F that required the first time applied by DR nozzles cooling

AIT:
- Developed unique HP combustor (800 p.s.i.a and 1000F) uniquely operating at variable airflow
- Newly developed LP combustor (200 p.s.i.a 1600F) uniquely operating at variable airflow

Struthers Wells:
- Advanced Recuperator
Lessons Learned
Summarized in the published by EPRI’s “Value Engineering” report (produced by ESPC)

The 110 ME CAES project (with first of the kind unique features and unique components)- is unquestionably successful-
It met all performance guarantees, schedule and budget.

There are lessons learned:

The single-shaft turbomachinery train with multiple (9) components has some operational and maintenance complications
Conclusions: the separate components approach would provide operational and maintenance advantages

First of the kind components specifically developed for the CAES turbomachinery had a very limited power generation experience and had no operational and maintenance manuals for
Conclusions: use of off-shelf /standard components will resolve this issues.

The novel HP/LP combustors:
• Had no operational and maintenance manuals based on experience
• The HP combustor has inherently very high NOx emissions (app. 70 p.p.m.v.)
• The LP combustor is customized for this train and has higher than CTs NOx emissions
Conclusions:
• Novel HP/LP combustors should be avoided
• It is better to burn fuel in DLN combustors developed by OEMs

Single compressor train has limitation on use of available off-peak power
Conclusions: Multiple compressors provide operational and maintenance advantages
15 MW CAES Plant with Above Ground Storage
based on Novel CAES Plant Concepts
Developed & Patented by ESPC

CAES Plant Power:
– 30% of power generated by a Combustion Turbine
– 70% Green Power is generated by Air Expanders utilizing the stored (operating w/o combustors and utilizing the CT exhaust gas heat - the air bottoming cycle (similar to steam bottoming cycle for CC plants)

– The Overall heat rate is approximately 4000 Btu/kWh (vs. 10,000-11,000 by CTs)

The fuel is burned only in CT’s combustors (there is no additional fuel burners/combustors)

The storage is pressurized by multiple stand-alone off-shelf motor driven compressors

Significantly lower capital costs due to:
– Use of standard components
– No new components
– Simple construction & tuning up

Schedule time is within two years

The storage size is significantly reduced with associated storage costs
15 MW CAES Plant with Air Injection and Bottoming Cycle
Based on Taurus 60

Major components: CT, multiple Compressors; Recuperator; HP&LP Expanders

**Power Production Mode**

- **15.19 MW Net Total Power**
- **3953 BTU/kWhr Net LHV Heat Rate**
CTs Performance vs. Ambient Temperatures

GER 3567H

Figure 9. Effect of ambient temperature
Calpine Broad River Project
Where AI Validation Tests Conducted

PG7241FA with DLN (150.4 MW @ 95°F)

Humid Air Injection:
Measured:
• 18.3 MW increase @ 3.5% humidity, 95°F ambient
Predicted:
• 26.6 MW increase @ 5.5% humidity,

NO\textsubscript{X}:

• 9 ppm with DLN combustor
• 12 ppm with steam injection and DLN
• < 9 ppm with HAI and DLN

During testing there were no known operational limits that were exceeded. Specifically, during the testing all vibration, compressor (7241 Limits), emissions, combustion dynamics and generator temperature limits were not exceeded...The test criteria were met...
CAES Plant Power consist of 5.2 MW of CT Power and 10.6 MW Green Power
1 kWh of Stored Off-peak Energy Returns 0.78 kWh of Peak Energy
CAES Plant with Air Injection and Bottoming Cycle
Based on GE 7B CT

Major components: CT, Multiple Compressors; Recuperator; HP&LP Expanders

Power Production Mode
166.46 MW Net Total Power
3997.8 BTU/kWhr Net LHV Heat Rate
15 MW CAES Plant with Bottoming Cycle and Inlet Chilling
Based on Taurus 60

Major Components: CT; Multiple Compressors; Expander; Recuperator; Compressed Air Storage

Solar Torus 60 CAES; Storage & GT Inlet Air Cooling

Power Production Mode
14.52 MW Net Total Power
4373 BTU/kWhr Net LHV Heat Rate
CAES Plant with Bottoming Cycle and Inlet Chilling
Based on GE 7B CT

Major components: CT, Multiple Compressors; Recuperator; Expanders; Compressed Air Storage

- Compressor
- Motor: 96.54 MW
- Intercoolers
- Compressed Air: 86°F, 14.7 PSIA, 356 Lb/s
- Air: 86°F, 14.7 PSIA, 356 Lb/s
- Gas Turbine: 44.87°F, 14.7 PSIA, 535 Lb/s
- Fuel: 683.2 MMBTU/hr LHV, 8.82 lb/s Fuel
- Expander: 111.5 MW
- Recuperator
- Exhaust: 850.6°F
- Storage: 102°F, 1450 PSIA, 350.5 Lb/s
- Compressed Air: 95°F, 950 PSIA, 535 Lb/s
- Power Production Mode: 172.9 MW Net Total Power, 3951 BTU/kWhr Net LHV Heat Rate
15 MW CAES w. Above Ground Storage Lay Out Drwg
## Summary Table of Performance Estimates (w/o specific optimization)

<table>
<thead>
<tr>
<th>Description of Item</th>
<th>Air Injection</th>
<th>Inlet Cooling</th>
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<tbody>
<tr>
<td><strong>Civil/Architecture</strong></td>
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<tr>
<td>Site, Clearing &amp; Grubbing</td>
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<tr>
<td>Fence 440 LF w/2gates</td>
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<td>Slab on Grade w/ 2' Haunches</td>
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<td>Compressor Slabs (X4)</td>
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<td>Control &amp; Service Building</td>
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<td><strong>Sub-total</strong></td>
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<td><strong>Equipment Costs</strong></td>
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<td>Combustion Turbine</td>
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<tr>
<td>LP Air Compressor</td>
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<td>HP Compressor</td>
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<td>Heat Exchangers</td>
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<tr>
<td>HP Expander</td>
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<tr>
<td>LP Expander</td>
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<td>Compressed air Storage</td>
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<td><strong>Mechanical (installation)</strong></td>
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<td>Combustion Turbine</td>
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<td>LP Air Compressor</td>
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<td>LP Expander</td>
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<td>8&quot; Steel Pipe</td>
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<td><strong>Electrical and Controls</strong></td>
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<td>Misc. Electrical</td>
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<td>Field Mounted Instruments</td>
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<td><strong>Indirect Costs</strong></td>
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<td>EPC Contractor Profit</td>
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<td><strong>Total Capital Cost</strong></td>
<td><strong>18,583,000</strong></td>
<td><strong>$18,297,000</strong></td>
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Major performance characteristics of the 15 MW CAES/AI/Expander concept can be summarized as follows:

- The total CAES plant power is **15.2 MW** and includes the power of the Taurus 60 combustion turbine (augmented by the injected stored air) plus the additional power produced by HP and LP expanders utilizing the preheated stored air. The heat rate is **3960 Btu/kWh**.

- The CAES plant has two major power generation components:
  - The Taurus CT generating of approximately 5.2 MW (at 90F ambient temperature) with heat rate of approximately 12,000 Btu/kWh and
  - The green (w/o fuel consumption) CAES power is the **10.6 MW** that is the sum of approximately 9.9 MW, generated by HP and LP expanders plus the CT power augmentation by approximately 0.72 MW due to air injection.

- The off-peak energy storage:
  - The stored off-peak energy of 13.8MWh results in total generation of 15.2 MWh of peak energy, i.e. energy ratio is approximately 0.91
  - The stored off-peak energy of 13.8MWh results in generation of 10.6 MWh of green peak energy, i.e. energy ratio is approximately 1.3 or 1 kWh of the stored off peak energy generates 0.77 kWh of peak energy w/o using fuel.

- Above ground energy storage is sized for two hours of the continuous peak power generation:
  - Total energy generated is 30.4 MWh
  - Total energy stored 27.6 MWh

- Specific costs for this concept are **$1200-1300/kW**
Comparative Analysis of Generation Costs for Coal. CT, CC and CAES plants

Peaking Power Generation Options Comparison
Fuel Price @ $10 per MM BTU Gas (Coal $2)
ESPC with its subcontractors is delivering CAES projects on EPC basis. Estimated specific costs of the overall project including underground storage is approximately $550-600/kW. Delivery time is approximately 24 months, primarily controlled by a combustion turbine delivery.

These concepts are based on various combinations of the major standard/off-shelf components-existing or new combustion turbines, air compressors, air expanders and heat recovery recuperator—all integrated with a compressed air storage and engineered for specific operational, economic and geological conditions.

As it relates to the selection of a combustion turbine, customers have a choice of selection a combustion turbine based on their preferences and ESPC will design/engineer the CAES plant based on the selected combustion turbine. These h&m balances are based on GE7FA, GE 7EA and GE 7B CTs for 400 MW, 300 MW and 150 CAES plants respectively.

Suppliers of Off-Combustion Turbine standard components include but not limited to:
- Air Compressors: MAN Turbo, Dresser-Rand, and Ingersoll-Rand
- Turbo-Expanders: Major OEM’s with IP back pressure steam turbine technology; MAN Turbo, Skoda, Atlas Copco, and Hitachi
- Recuperator: RGP Engineering, Nooter/Eriksen, Deltech, and BHEL

ESPC has a number of qualified EPC contractors for delivery of CAES projects with typical warranties and guaranties and with typical commercial terms.
Technology Offerings

• ESPC offers the Power Augmentation - AI and CAES technology for licensing.

• ESPC delivers the AI and CAES projects on turn-key basis with typical performance guarantees.

• ESPC is flexible to cooperate with Customers in delivery the AI and CAES projects.

• Discussion of program

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