**Review Of CAES Systems Development And Current Innovations That Could Bring Commercialization To Fruition.**

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## Abstract.

This paper will review the development of CAES technologies since the first application of a 290MW fast-start unit at Huntorf over 25 years ago. This is a non-recuperative unit allowing for 3-minute startup to support a nuclear plant. The only other operating unit is McIntosh at Alabama Cooperative, which is a recuperative system that improves the heat rate while operating at relatively low Combustion temperatures.

These are specialty design machines, as would be the next generation systems that are currently offered as a further improvement over earlier units. One reason for the slow adaptation of improved systems and Turbo-machinery is that it is always “first of a kind”. New Gas Turbine developments, such as higher temperatures and higher specific output have brought certain premature failures, which have made Insurance companies ask for higher premiums, and the financial community nervous about brand new concepts

Other innovations in both Bulk and Distributed CAES systems have by-passed the special machinery requirements and use state-of-the-art proven gas turbines in Hybrid configurations. Smaller systems would be adiabatic in compression and expansion allowing for full compensation of “green” energy storage.

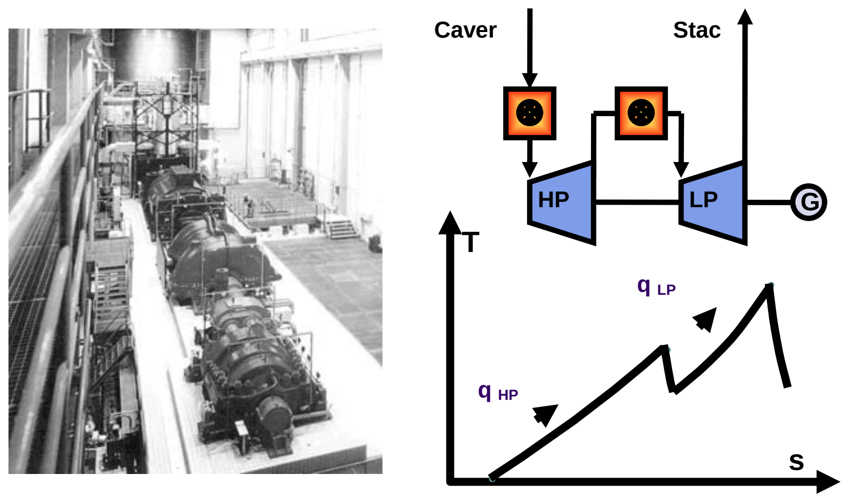
In Europe, there is concern about the large contribution of Wind Energy, and attention focused on the development of non-polluting Advanced Adiabatic CAES systems
(AA-CAES) This study was funded under an EC (European Commission) study involving Industrial partners and Universities. The proposed CAES sizes and requirements for Thermal Energy Storage from this study will be described.

Developers and power plant planners will gain confidence from these approaches to consider Bulk and Distributed CAES systems in serious terms as a benefit (value added) to the Energy supply market

## Introduction

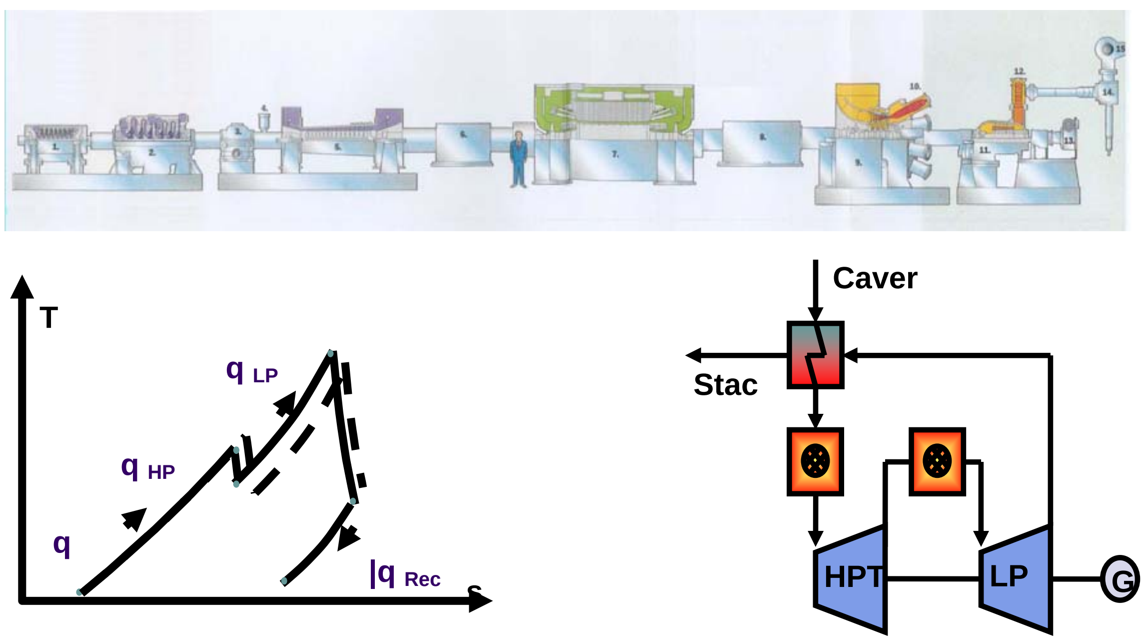
Stal Laval (1949 CAES Patent) and BBC in Europe did the early investigations for CAES; the Swedes were keen on hard rock cavern storage their geology favored this concept, BBC investigated salt caverns which were being used for NG storage. The purpose for the first unit Huntorf near Bremen was for a fast response unit to support a nuclear facility and provide black-start capability.
The use of heat recovery (HRU) was investigated at the time, air Recuperators were used on recuperative gas turbines at that time, but not at the pressures contemplated for CAES. The decision to eliminate the HRU at the expense of efficiency was to insure that 290 MW could be delivered in the shortest possible time.

This paper reviews the development of CAES technologies since the first application of a 290MW fast-start unit at Huntorf over 25 years ago. This is a non-recuperative unit allowing for 2.5-minute startup to support a nuclear plant. The only other operating unit is McIntosh at Alabama Cooperative, which is a recuperative system that improves the heat rate while operating at relatively low Combustion temperatures. Fig. 1 and 2




- 290 MW Peak Power at 50 Hz –

**Fig1. Huntorf Reheat Non-recuperative Power train with LP and HP compressors**




- Recuperator improves Power Generation Performance

Fig **2 McIntosh 110 MW Reheat /recuperative Power Train with LP and HP compressors**

In the US, BBC promoted the 220MW system and the first recuperative cycle, ordered in the early 80's by Soyland Cooperative, but unfortunately cancelled after discovering a fissure in the hard rock storage. The completed power train was shipped 1982. This was certainly a setback for CAES during the height of enthusiasm with EPRI as a catalyst.

BBC at the time developed a full range of recuperative CAES power plants ranging from 45 MW to 290 MW. The largest 60 Hz machines was the 220 MW unit, however BBC in studies with EPRI. Developed additional unit sizes of 45/50 MW and 60/100 MW to meet the projected market needs of smaller systems and lower volume caverns. One casing design served different generator ratings; the HP blading modified for site specifics. Remarkably, these units rivaled today's modern concepts with heat rate below 4000 Btu/kW/hr. It would not be until 1991 that Alabama Cooperative commissioned the first recuperative cycle at McIntosh; this smaller unit of 110MW incorporated a single shaft compression and power train by Dresser Rand. Turbomachinery developed and customized by ESPC Inc. using various compressor, expander, combustor and Recuperator components this initiative was EPRI driven. This included many studies for CAES applications, storage media and units as small as 25 MW.

These are specialty design machines, as would be the next generation systems that are currently offered as a further improvement over earlier units. One reason for the slow adaptation of improved systems and Turbo-machinery is that it is always "first of a kind". New Gas Turbine developments, such as higher temperatures and higher specific output have brought certain premature failures, which have made Insurance companies ask for higher premiums, and the financial community nervous about brand new concepts.

CAES interest was raised again in 1996 when CDC (CAES development Corporation) acquired the Norton limestone mine in Ohio with 338 Million cubic feet storage capacity at a depth of 2200 feet. Most OEM's were reluctant to participate as the potential for this project would be only for nine 300+MW sized units. Alstom (ABB at the time) after some initial studies decided to pursue the project and entered a study optimization phase with CDC. This optimization led to a compact power train with no HP combustor, one LP combustor and a duct fired HRU to maximize the kW output for unit of airflow. This concept was selected over the Hybrid GT/CAES cycle using a standard 180 MW combustion turbine and an air bottoming cycle for an overall power plant of 400 MW [Ref 1]

The compression train was separated and motor driven in order to utilize standard production air compressors. The expander incorporated a HP air turbine (IP steam turbine section) exhausting into the combustion section of a standard production Gas Turbine, avoiding new flow path designs. The combustion LP expander of a 90 MW GT direct coupled to the hot air expander on a single shaft provided an elegant design for a 300MW+ CAES power plant. (Fig 3)

The environmental impact study for the area required the lowest possible emissions; the HRU incorporated a Nox catalyst and CO oxidizer that met the criteria for permitting. The proposal, after the study phase, was submitted in 2002 resulting in endless contract term and Insurance negotiations. Unfortunately, the First Energy Bessie-Davis Nuclear plant incident dumped cold water on the project, as First Energy would have been a key player for the potential 2700 MW plant capacity. Full details of this exceptional opportunity for bulk energy storage at a strategic location have been detailed in several EESAT meetings.Sempra Electric now own the Norton storage facility. The Norton project [Ref 2] has gone through various iterations due to site space limitations and the need to reduce costs for the plant in a very competitive environment

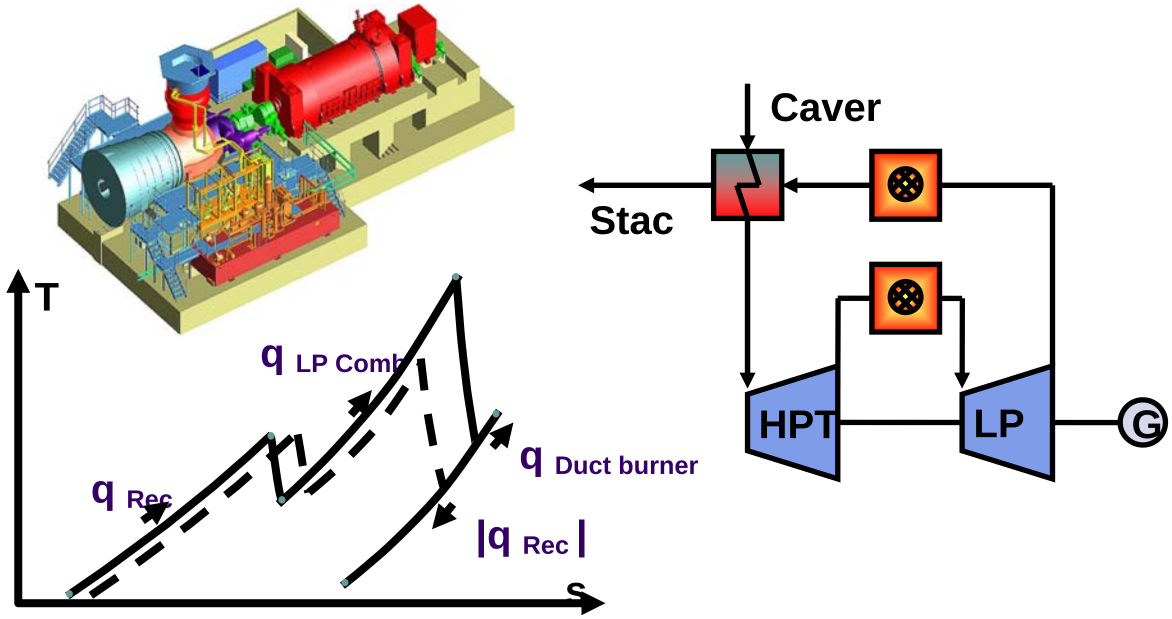



**Fig 3 CAES Recuperated power train with single DLN Low Pressure combustor**

In accordance with The Israel Electric Corporation concepts of a Novel CAES Cycle of 1994 and 1996 Patents using separate air expanders, ABB submitted proposals for the Mt. Sedom CAES project located near the Dead Sea for a 507 MW plant with salt strata storage. Single expansion and reheat expanders were proposed with the latter using 15 % less airflow to achieve 157 MW vs. 151 MW with 324 kg/sec airflow.
More recently made proposals based on Nakhamkin patents, similar concepts using standard production gas turbines with variations of inlet cooling or GT air injection optimized for site and storage specifics and off-peak or wind power costs

Other innovations in both Bulk and Distributed CAES systems have by-passed the special machinery requirements and use state-of-the-art proven gas turbines in Hybrid configurations. Lessons learned suggested a solution to use production gas turbines and recover the exhaust energy to heat the stored air before the expansion in a separate expander, adding an air bottoming cycle to the open cycle GT. The compression is now decoupled as well as the expansion cycle (ST Technology) these standard items substantially reduced the risk, allowed for shorter delivery cycles, but added some complexity in two electrical generating systems, however with a great deal of operational flexibility GT. Variations included Air Injection into the GT for additional capacity on hot days.

For Multi-MW projects from 100's to 1000's of MW CAES power plants using different Industrial Gas Turbine selections, such power plants can be tailored to storage capacity from smaller volumes from 10 to 20 million cubic feet, to large storage caverns such as Norton 338 Million cu/ft capable of sustaining 5400 MW. Production GT's from 45 MW to 185 MW F class machines will provide CAES power plants from 100 to 450 MW or multiples there of. One example of using a nominal 180 MW "F" class Gas Turbine currently a popular size for Peaker or Combined cycle units is illustrated in schematic form( Fig 4) This is a conventional bottoming cycle not unlike a CC power plant only using hot pressurized air for the intermediate pressure Steam Turbine which exhausts clean air to the atmosphere.

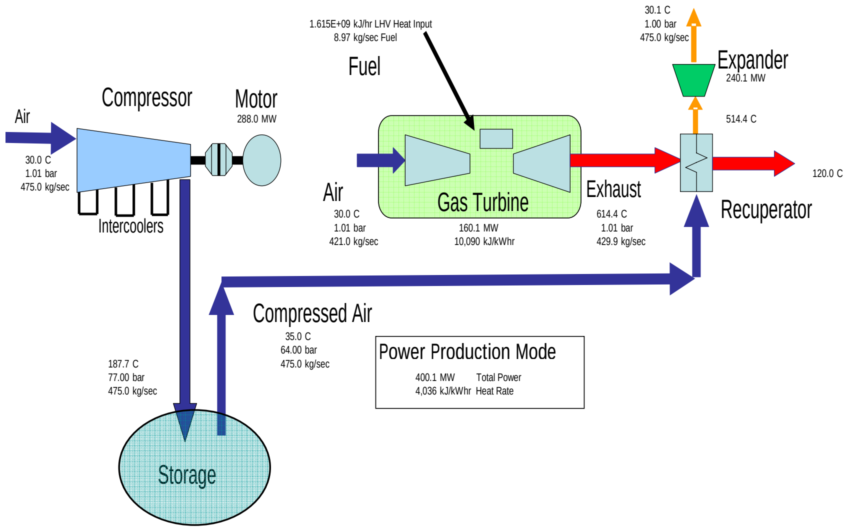



**Fig 4 Typical CAES Bottoming Cycle with GE 7241 Gas Turbine *(ESPC Inc.)***

The nominal 180 MW Gas Turbine produces only 160 MW on a 30-oC day, the high temperature exhaust flow of 430 kg/sec will heat the incoming pressurized air to 514 oC
The heated air expanded at a rate of 475 kg/sec produces 240 MW for a total plant capacity of 400MW. The heat rate is below 3900 Btu/kW/hr. Variations, with inlet air at 15 oC ,on an ISO day or cooled to that temperature on a 30 oC day with the expander exhaust air will increase the output to 427 MW with the expander contributing 253 MW .

The next interesting variation using an air expander with extraction of 50kg/sec after the HP section for air injection into the GT combustion plenum increase the output to 433 MW increasing the GT power to 193 MW on a 30 oC day. (Fig 5) illustrates this concept.
From these examples, it is clear that capacity and site conditions with storage volume can be optimized for economical power production. Wind generation integration with a wide selection of available industrial gas turbines can be readily applied to such projects for example the Iowa Energy Storage Project, moving the project for early production with installation of the open cycle gas turbines.

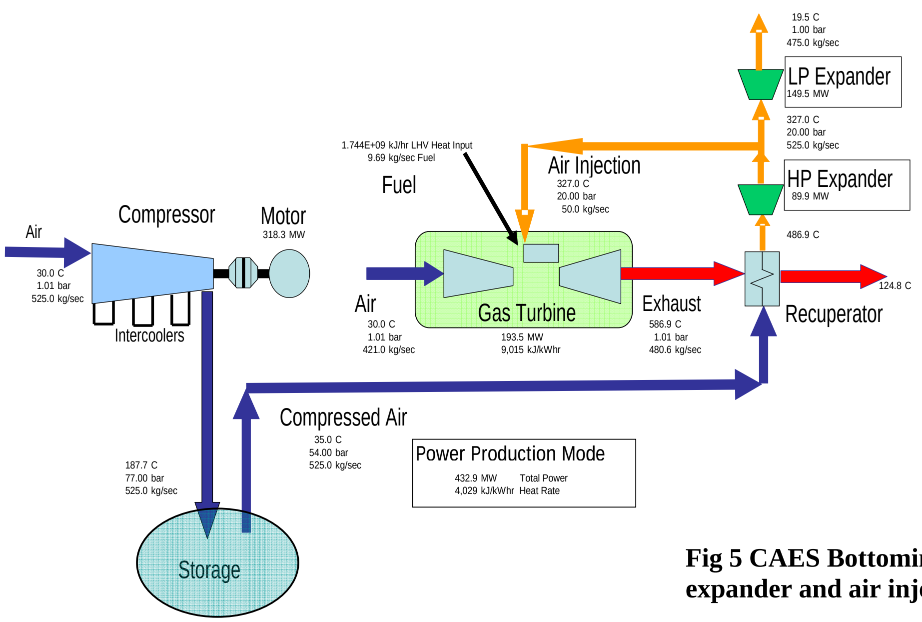



**Fig 5 CAES Bottoming cycle with HP&LP expander and air injection *(ESPC Inc.)***

Smaller systems would be adiabatic in compression and expansion allowing for full compensation of "green" energy storage, when coupled with Wind Energy. These systems in the 500 kW range support WTG's of 2.5 MW as well as multiple WTG's with increasing the expansion to 1000 kW or multiples there of. These systems such as EnisWind T-CAES use commercial production compressor and low-pressure turbo-expanders. Adiabatic expansion provides super-chilled cold air (-115 to -170 oF) for further use as in thermal energy storage (cold water) used for supplementing HVAC or cold storage facilities. For every one kWe generated one kW thermal is produced .Recent developments include freeze desalination, which can enhance sustainability of remote locations or islands producing fresh water from sea or brackish water. No fossil fuel is required and the economic benefits are great displacing diesel fuel. These concepts in more details presented at earlier sessions of this Conference.

These smaller CAES systems including small Gas Turbines depend on easily placed pipe or tank storage to serve distributed load centers. The stored high-pressure air is easily piped to the generating unit or multiple units located at large commercial or industrial building complexes. Pipe storage systems are common for NG and highly utilized in Europe to bolster delivery of gas during peak demands. (Fig 6)

Existing storage technology
Burried gas storage near Zurich, Switzerland
Operating pressure 1000 PSI

**Fig 6 Pipe Storage systems as standard practice in Europe**

In Europe, there is concern about the large contribution of Wind Energy, and attention focused on the development of non-polluting Advanced Adiabatic CAES systems (AA-CAES) This study funded under an EC (European Commission) study involving Industrial partners and Universities. [Ref 3] The proposed CAES sizes and requirements for Thermal Energy Storage from this study are described. These sizes were determined to be 30 MW, 150 MW and 300 MW; however, the TES systems need further development and cost optimization. These units will be deployed with thermal input until the TES technology can be fully developed. This will be a focus for the "green' industry.

**Conclusions**

CAES technology and the many variations from kW ratings to 100's of MW's, while none have recently been implemented, have had more investigation and development, than any other power system. These can benefit the grid and the drive for renewable energy, so heavily promoted and implemented across the USA and the world for that matter. The recent (August 2007) announcement by Shell/Luminant to bring 3000 MW of Wind Energy into the Texas market combined with CAES technology is an encouraging indicator for bulk energy storage. Mesa Power (August 2007) with 4000 MW of planned Wind Energy in Texas can certainly benefit from storage to provide the grid with stable power delivery (capacity) during periods of high demand.

CAES power plants proposed in Texas by Ridge Energy, such as Markham were environmentally permitted for construction, but not constructed caught by the Enron economic impact tsunami wave. The point is that Texas with a big wind energy resource is ready and able to implement CAES. The other high wind resource States should now plan similar action. The high demand (125 GW of projects at varies stages of development) for WTG's has caused a large backlog and combined with increasing commodity prices has dramatically increased the installed $/kW. Energy Storage such as CAES can bring more kW/hr production from the installed MW's to the grid and greatly enhance the projected growth to 30 GW by 2020. *(Latest forecasts that installed capacity of 12,200 MW at the end of 2007 will reach 31.6 GW by end of 2010)* Considering that a 400MW CAES plant installed competitively with Combined Cycle power plants at lower $/kW( current estimates $480/530/kW), consumes considerably less premium fuel, produces exceptionally low emissions for the kW/hrs of generation, has more flexibility of operation, we can expect progressive generating companies and investors to pay keen attention.

Developers and power plant planners will gain confidence from these approaches to consider Bulk and Distributed CAES systems in serious terms as a benefit (value added) to the Energy supply market.

**References;**

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