New Compressed Air Energy Storage Concept Can Improve The Profitability Of Existing Simple Cycle, Combined Cycle, Wind Energy, And Landfill Gas Combustion Turbine-Based Power Plants

Dr Michael Nakhamkin, Ronald H. Wolk, Sep van der Linden,[1] Ron Hall, and Dale Bradshaw

Introduction

While combustion turbine manufacturers are steadily but slowly increasing Combustion Turbine (CT) efficiency by increasing turbine firing temperatures and improving the efficiencies of major components, there are a number of other approaches including various thermal cycle modifications that can reduce the cost of electricity.

One such approach is the Compressed Air Energy Storage (CAES) power plant where air is compressed using less expensive off-peak electricity and stored in the underground air storage cavern. It is later released for the power generation during peak demand hours. The first CAES plant in the US, the 110 MW Alabama Electric Cooperative plant at McIntosh, AL has been in successful operation since 1991. The application of this storage principle is particularly important for utilization of the renewable energy sources like wind energy, which could be produced at night and during other off-peak hours when electric power demand and prices are both low. The integration of the wind and CAES plants will improves economics of both plants – it allows selling the wind energy at peak price and it improve CAES plant economics by driving compressors with wind energy (when there is no demand) having the lowest costs. The same principles can also be applied to landfill gas generation facilities.

A second approach is to reduce the power consumption by the combustion turbine compressor that is directly driven by the combustion turbine expander and takes over 50% of its power. There are number power plant concepts like the CHAT and HAT thermal cycles that achieve these objectives by using the humidified air as a working fluid, thus reducing the specific air consumption and parasitic power consumption by compressors. Unfortunately these concepts haven't yet found attractive market applications to justify required combustion turbine modifications by turbine manufacturers. This paper presents the novel Compressed Air Energy Storage (CAES-CT) concepts that utilize the aforementioned two approaches and which are differentiated from the conventional CAES plants as follows:

1. The CAES-CT concepts utilize the existing reserve capacities of combustion turbine CT and Combined Cycle (CC) plants by injecting the stored air (similar to Steam Injection, without CT/CC any modifications.
2. CAES-CT concept avoids a) the complications and costs associated with development of highly customized specific CAES turbomachinery trains with reheat and recuperation; b) the costs associated with new projects development like site permits, licenses, etc.
3. The CAES-CT concept could be easily applied to meet a variety of the CAES plant power and storage requirements (without specific turbomachinery customization development efforts) by achieving required storage capacities through combining CTs of various capacities with various numbers of units.
4. The existing CTs as a rule present a state-of-the art proven technology with the highest performance characteristics and the lowest possible NOx emissions
5. The stored compressed air could be easily humidified before injection into CT/CC plants (with associated efficiency improvements and storage cost reductions) without the aforementioned complications associated with modifications of CTs.

The paper also will demonstrate advantages of the integration of the renewable energy sources with the CAES-CT concepts – large (100-300 MW) CAES plants with the underground energy storage in salt, hard rock and aquifer geological formations and small (5-15 MW) CAES plants with the air storage in the man-made storage vessels including the buried high pressure piping.

Novel Concepts Based on Use of Existing reserves of Combustion Turbine/Combined Cycle Power Plants (CAES-CT and CAES-CC)

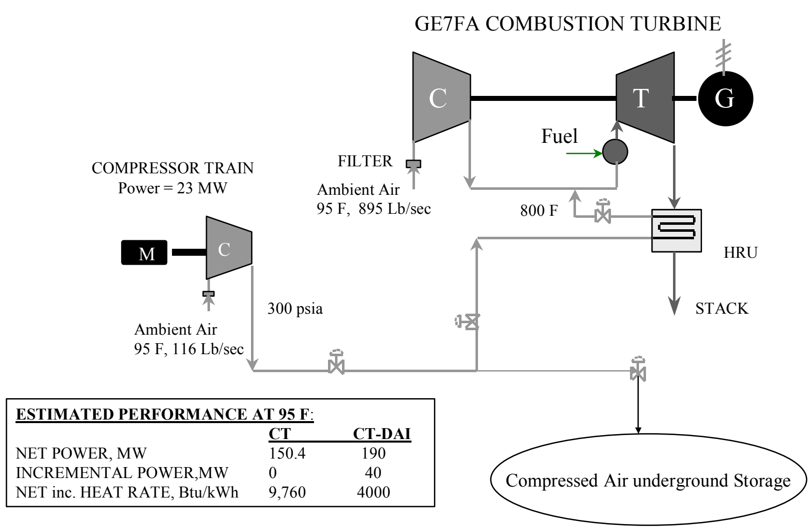
For the overwhelming majority of electric power customers (in the USA and abroad) power demands reach their peak during summer, when high ambient temperatures reduce the power output of combustion turbines and combined cycle plants to the minimum. The simplified explanation for reduced power production is that lower inlet air density, a result of the high ambient temperature, reduces mass flow through a CT with a respective reduction of the power produced. Similar situation exists at high elevations. Thus GE Frame 7FA CT nominally rated at approximately 174 MW at ISO

[1] brulinassoc@comcast.net

conditions (59 °F with 60% relative humidity), will produce maximum power of approximately 191 MW, when the ambient temperature is 0 °F, but will produce only approximately 150 MW at 95 °F. The significant power loss by a combustion turbine during high ambient temperature periods (when the price for replacement electricity is at its highest) requires a power generation company to install additional units to meet summer peak demands. Power losses for a combined cycle power plant during high ambient temperature operations are similar to those for a combustion turbine. Thus CT/CC plants operate for the most of the time with significantly lower than design capacities, which take place at low ambient temperatures. Therefore existing capacity reserves of CT/CC plants could be utilized for producing additional peak capacities via injection of the stored compressed air. This approach allows development of the CAES plants by adding only the air compression and storage facilities and avoiding highly customized and expensive turboexpander trains. This method was invented by Dr. Michael Nakhamkin of ESPC, as described in U.S. Patent #5,934,063 (Reference 1) and in Reference 2.

Figures 1a and 1b (including humidification) illustrate schematic diagrams and simplified heat and mass balances of the CAES-CT concept (with operating parameters), where the power of the GE 7FA-combustion turbine, operating at 95 °F ambient temperature, is augmented using compressed air stored in an underground compressed air storage system. The major components of the CAES-CT plant are as follows:

- A commercial combustion turbine with the provision to inject the externally supplied compressed air at any point upstream of the combustor. Engineering and mechanical aspects of the air injection for CAES-CT plants are similar to steam injection for power augmentation, which is a standard CT option provided by a number of OEMs;
- An auxiliary compressor train – a standard centrifugal compressor system consisting of commercially available off-the-shelf standard compressor modules and sized for the incremental airflow (and not for a full airflow) to be stored and later injected into a CT/CC plant;
- Compressed air storage, which could be underground storage in salt, hard rock or aquifer geological formations or above ground storage in various pressure vessels;
- Balance-of-plant equipment and systems including interconnecting piping, valves, controls and an optional recuperator.



ESTIMATED PERFORMANCE AT 95 F:

	CT	CT-DAI
NET POWER, MW	150.4	190
INCREMENTAL POWER,MW	0	40
NET inc. HEAT RATE, Btu/kWh	9,760	4000

Figure 1a. The CAES-CT Concept Based on The GE 7FA CT

This CAES-CT plant has three modes of operation:

- A conventional combustion turbine operation, where the CT is disconnected from the compressed air storage;
- A CAES mode of operation, where during peak periods the CT's compressor discharge air flow is complemented by the compressed air flow from the storage and injected upstream of the combustors. The compressed air from the storage could be optionally preheated in the recuperator and humidified. The storage is charged with the compressed air by the auxiliary motor-driven compressor during off-peak hours utilizing renewable resources or available nuclear or coal capacities.

- Power augmentation mode of operation, when a CT/CC plant power is augmented during peak hours by additional airflows supplied by the auxiliary compressor operating simultaneously with a CT/CC plant in the event that sufficient air is not available from storage.

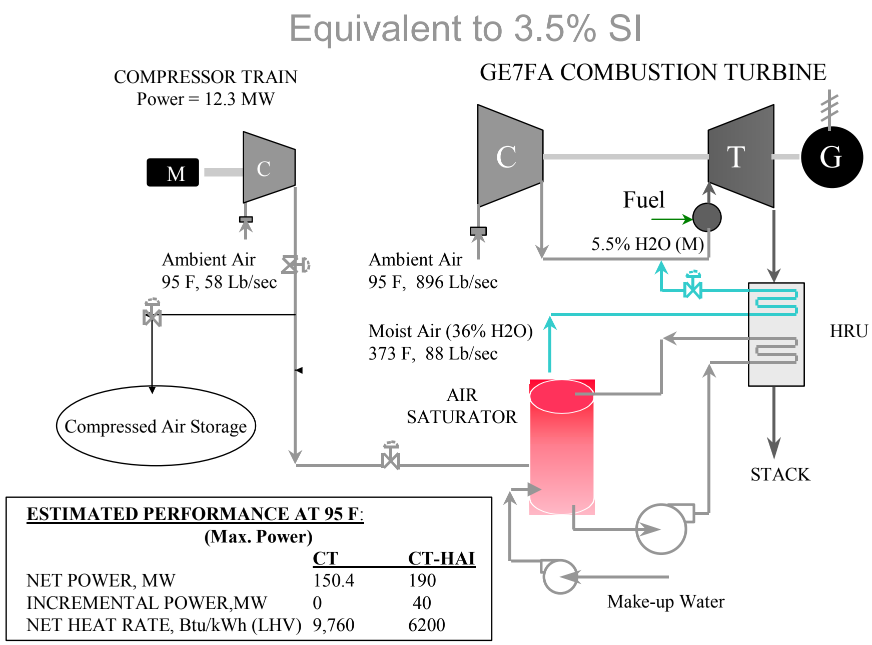


Figure 1b CAES-CT Concept with Humidification based on The GE 7 FA CT

Figures 1 a and 1b illustrate that the additional compressed air flows from the compressed air storage of 116 lbs/sec and 58 lbs/sec (with further humidification), respectively, being injected upstream of the combustors will increase the combustion turbine power output from 150 MW to 190 MW. The performance characteristics presented in Figures 1a and 1b should be considered as estimates only because the maximum amount of injected air, at any given ambient temperature, could be restricted, also, by a number of external limitations, like the electric generator maximum capacity and electrical system restrictions, etc.

The additional CAES plant capacity of 40 MW achieved by only one CT demonstrates that practically any required CAES plant capacity could be achieved by combining capacity reserves of various number of existing CT/CC plants. In addition to the power increase, the CAES-CT plant's heat rate, characterizing the fuel consumption in BTU per kWh produced, is significantly reduced to that typical for a CAES plant levels of approximately 4000 Btu/kWh for the CAES-CT plant and of 6200 Btu/kWh for cases with humidification. In spite of a higher heat rate for the case with humidification it is important to remember that based on the Figures 1a and 1b the humidification concept reduces the underground storage by a factor of approximately two (2) (as compared to the dry air concept) with corresponding cost and schedule savings. The operating cost of the CAES-CT plant in addition of the fuel, requires off-peak energy for the compressed air storage recharging with the compressed air. The fuel and energy related cost of electricity (COE) (without O&M costs) produced is calculated as COE, $/kWh = [Heat rate, BTU/kWh) x (cost of fuel, $/BTU) + (the off-peak energy for the storage recharging, kWh) x (cost of off-peak energy, $/kWh)]/ (total kWh produced in the power augmentation mode of operations). The CAES-CT concept could be similarly applied to CC plants with the difference that the CT is replaced by a CC. The CAES-CC plant operations are similar to the CAES-CT plant, the only difference is that in the CAES and power augmentation modes, the increased power of the CT will be complemented by an additional power produced by a steam turbine of the bottoming cycle due to additional the CT exhaust flow.

Engineering and Capital Costs

ESPC jointly with a consulting engineering company had performed the conceptual engineering and cost estimates for the CAES-CT concept based on GE Frame 7FA, with the compressed air storage sized for continuous six (6) hours operation with the incremental (CAES) power of approximately 40 MW. The overall plant has been optimized based on developed by ESPC program including concurrent optimization of parameters, performance and economics of the compressed air storage in a salt dome (with assumed characteristics), the compressor train and other equipment involved including the compressed air charging costs. The resulting storage requires approximately 3.8 million cubic feet (with depth of approximately 1000 feet and the maximum minus minimum pressure difference of 150 p.s.i.a.) with an estimated construction cost of $4 million (these data are based on prorating of actual parameters and costs of the underground storage in the salt dome for 110 MW CAES plant). The compressor train has been sized for two hours of compression for each hour of peak power generation at 95 °F, i.e. for half of the supplementary flow from the cavern (58 lbs/sec). Estimated total incremental cost for equipment and systems required for the conversion of the Frame 7FA combustion turbine into the CAES-CT plant with aforementioned operating requirements is approximately $8.5 million dollars, which is approximately $215/kW (40 MW additional power at 95 °F ambient temperature). This compares favorably with the approximately $600/kW specific cost for a turnkey installation of a large capacity CAES plant and it is, also, significantly lower than turnkey specific costs of a CT.

Above Ground Air Storage Facilities

ESPC conducted extensive exploratory engineering to develop a cost-effective aboveground compressed air storage approach. This approach allows the CAES-CT concept to be applied without considerations of local geology limitations. Various industrial pressure vessels, buried high-pressure piping and other alternatives were analyzed. As a result, the above ground compressed storage in the buried high-pressure piping was selected, based on the capital cost and other considerations. The conceptual arrangement of the sub-surface compressed air storage system is presented on Figure 2 and in References 4. The selection of the above ground storage resulted in the significantly higher storage pressure (to reduce the volume) and in the overall CAES-CT plant parameters and operations different from those for the underground storage. Optimized above ground storage systems are competitive with large underground storage facilities on the $/kW basis when storage capacities are limited to three (3)-five (5) hours.

Figure 7.

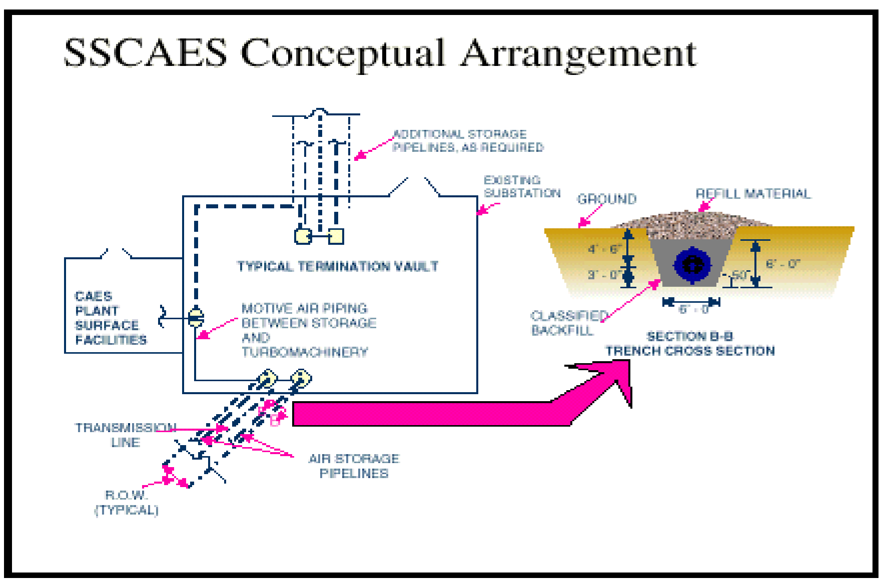


Figure 2. Conceptual arrangement of the Sub-Surface Compressed Air Storage

Small Scale Compressed Air Energy Storage with the compressed Air Storage Sub-Surface Facilities (SSCAES) Plant.

The development of the SSCAES plant is a joint effort of EPRI and ESPC with support from manufacturers and covered by the US Patent # 5,845,479 (see Reference 3) and described in EPRI's report (Reference 4). This section of the paper presents the latest performance and economics of small 8-12 MW CAES plants with the compressed air stored in the subsurface high-pressure vessels/piping. The engineering of the SSCAES plant was based on the Rolls Royce Allison (RRA) combustor/expander/electric generator (CEG) package. As typical for any CAES plant, the power generation heat rate is expected to be approximately 4000-5000 Btu/kWh. This does not include the power required for air compression, which is obtained from other sources (like wind energy, coal or nuclear plants) during off-peak hours, when electricity is inexpensive and available from other sources.

The SSCAES plant utilizes off-peak energy to drive motor-driven boost compressors to compress air and store the high-pressure air for expansion during peak demand periods. It could be practically located at any site regardless of the availability of specific geological formations required for a conventional CAES plant.

Wind Power Plants Integrated with Compressed Air Storage

One of the key economic issues that disadvantages wind power is that it is intermittent and therefore non-dispatchable. Since capacity credits cannot be obtained, wind power is at a significant economic disadvantage relative to other forms of generation. Another disadvantage is that in various areas of the United States and other areas of the world, as well, the velocity of the local winds and therefore the amount of power that can be generated does not peak at the same time that power demand peaks. If the wind typically blows during the late evening hours, wind power will only have a value equivalent to base load power in many areas, on the order of $15/MWh or less.

One approach to offsetting these deficiencies is to combine wind power with a CAES Plants and for small capacities with SSCAES plants. For wind energy integrated with SSCAES plant, as shown in Figure 3, electricity produced by wind turbines during periods of low demand is used to compress air that is stored in a pipe network of the type shown previously in Figure 2. Optimization studies indicated that the compressed air should be boosted by a system of compressors to the pressure of approximately 1500 – 2000 p.s.i.a and stored in the underground HP piping. When wind power is available and can be marketed, that power is supplied directly to the grid. At those times when wind power can be generated, but there is no market for the power, it is used to drive a compressor that injects air into a Sub-Surface pipeline network. That air is withdrawn during peak demand times and fed to a natural gas fired expander to deliver a total of 15 MW to the system. A heat recovery system is used to preheat the pressurized air by exchange against the hot expander exhaust. As shown in Figure 3, the humidification of the injected air reduces the amount of air that is required to be stored. This significantly reduces the investment required for both the air storage system and the compressor. The additional cost of the systems for humidification is small in comparison to these cost savings. The detailed cost and performance data are presented in the References 4 and 5. Specific costs are estimated as $550/kW for the SSCAES with the air humidification for peak power generation and arbitrary selected the four-hour period for peak power generation of and eight hours for charging the pipe network system. The heat rate is 6030 Btu/kWh (without accounting for the off-peak energy provided by wind). It should be noted that there is a 40 % reduction in the amount of natural gas burned to produce the peak power in the case with humidification as compared to a CT. This translates into comparable reductions in NOx and CO emissions. These economics can be markedly improved by integration of the wind-generated plant with the SSCAES-CT plant and with large capacity CAES-CT (with underground storage) due to significantly reduced costs associated with utilization of existing CT plants.

Landfill Gas Power Plants Integrated with SSCAES Plants

Landfill Gas (LFG) is generated by the anaerobic decomposition of municipal solid waste (MSW) placed in sanitary landfills. Its composition is about 55 percent methane (CH_4) and 45 percent carbon dioxide (CO_2) but also includes some oxygen (O_2) and nitrogen (N_2) from air introduced during the collection process. Usually, it is saturated with water vapor and contains trace amounts of volatile organic compounds and some other gases including chlorides. Methane and carbon dioxide are greenhouse gases. However, methane is considered 30 times more potent than carbon dioxide. Federal and most state regulations require the collection and control of LFG. If a landfill is of sufficient size to justify economic recovery of the energy contained in the methane, LFG may be successfully and profitably recovered. There are approximately 500 LFG energy recovery facilities in the United States and Europe. The practical economic life of most LFG energy recovery facilities is 10 to 30 years. The clean LFG could be used to fuel the SSCAES plant with similar advantages. For a given LFG production, the SSCAES-LFG plant will generate twice the amount of electricity, measured as kWhs, as compared to an ICE or a CT using the same amount of landfill gas fuel with a significant improvement in economics. The heat and mass balance for a typical SSCAES_LFG plant demonstrates the heat rate of 4,954 Btu/kWh, which is less than a half of the typical heat rate for the similar size ICE and CT plants of 11,000-12,000 Btu/kWh. The LFG storage allows concentrating the energy sale on times when it is needed and more valuable. SSCAES-LFG plants deal with small sizes of the CAES plants in the range of 10-30 MW, which is consistent with typical landfill sizes. Performance and capital cost estimates were generated for landfill sites of different sizes and the cost analysis and comparison were performed relative to the use of the simple cycle combustion turbine and ICE at the same landfill sites. (Reference 5).

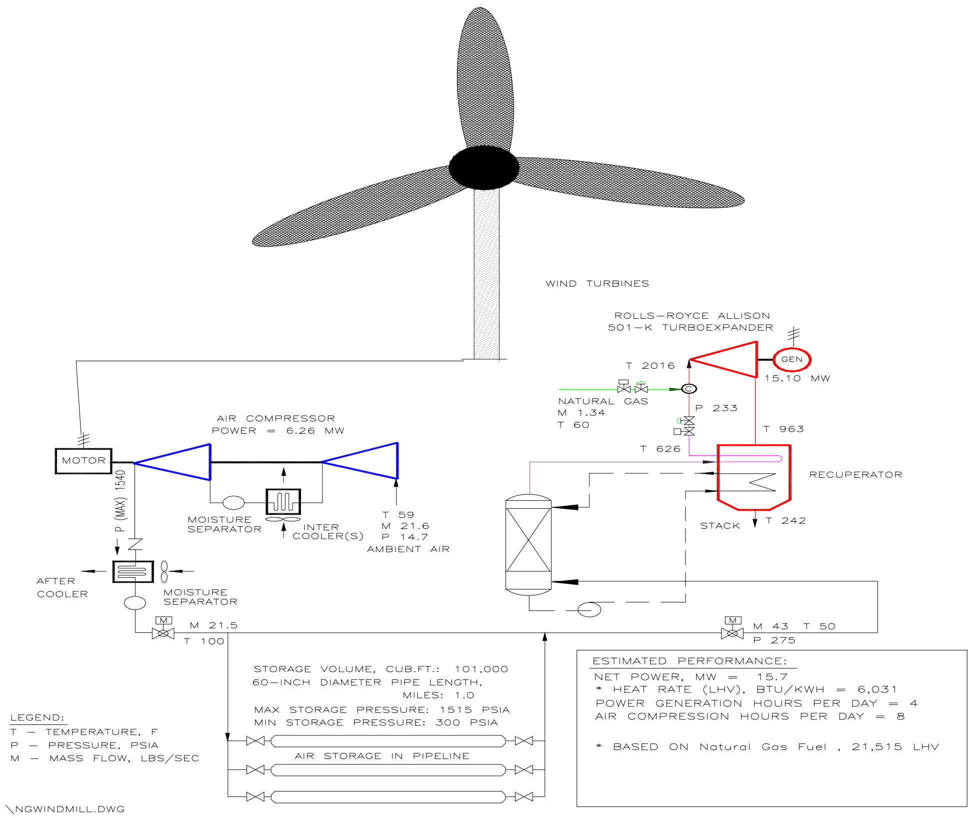


Figure 3. Heat and Mass Balance Diagram of an Integrated Plant with Wind Turbines, Compressed Air Storage, Air Humidification System and a Rolls-Royce Allison 501-K Turboexpander

Conclusions

Novel CAES-CT plant concepts have the following characteristics:

- The CAES-CT concept allows the CAES plant advantages to be utilized in the most cost effective and practical manner by utilizing existing power capacities of CT/CC plants without expenditures and complications associated with development of customized reheat turbomachinery trains;
- The air injection into a CT is mechanically similar to the steam injection for the power augmentation. The special compressor train for the storage charging could be provided by a number of OEMs and there are a number of companies capable of construction of underground storage facilities.
- By utilizing various numbers of CT's and their capacities one can achieve any specific energy storage requirements as well as peak power generation profiles.
- Specific incremental capital costs for the CAES-CT plant based on the GE7FA CT are estimated as $205 - 220/kW and are significantly lower than for other alternatives including the purchase of a new CT or CC plant. Also, fuel related heat rate is significantly reduced, and off-peak power consumption could contribute to improvement in the power generation system utilization.

SSCAES plant is based on the small capacity modified CTs with the compressed air storage in the man-made buried high-pressure piping. Specific costs of these plants of approximately $550/kW are competitive with other storage options.

These CAES-CT and SSCAES plant concepts are particularly effective when integrated with renewable energy sources: they allow collecting and storing the renewable energy whenever it is available and releasing it whenever the energy is needed at premium prices.

References

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