Compressed Air Energy Storage (CAES) Coupled with Gas Turbine Air Injection (AI) Makes Renewables and Wind Power More Economic

Dr. Rodney Gay (ESPC, Solvang, California, USA); RodneyGay@ESPCinc.com
Dr. Michael Nakhamkin (ESPC); Septimus van der Linden (Brulin Associates)

This paper describes the way to maximize the economic benefit of renewable wind energy while increasing the capacity and flexibility of the power generation system via integration of three technologies: compressed air energy storage (CAES), gas turbine power augmentation with air injection (AI) and wind power.

Wind power suffers from the fact that its output fluctuates so greatly and in an unpredictable manner such that its power cannot be considered to be controllable and available when the system needs it. Compressed air energy storage (CAES) is practically the only proven technology capable of storing thousands of MW-hrs of the wind energy during off-peak hours, and distributing approximately 135% of the stored energy during peak hours. The problem is that though the CAES technology is more economical and practical as compared to other alternative storage techniques, its capital costs of approximately $700/kW to $800/kW require significant spread between the peak and off-peak power prices to make it cost effective. The main component of these capital costs is relatively expensive, custom-built turboexpander train with reheat and recuperation and the intercooled compressor train.

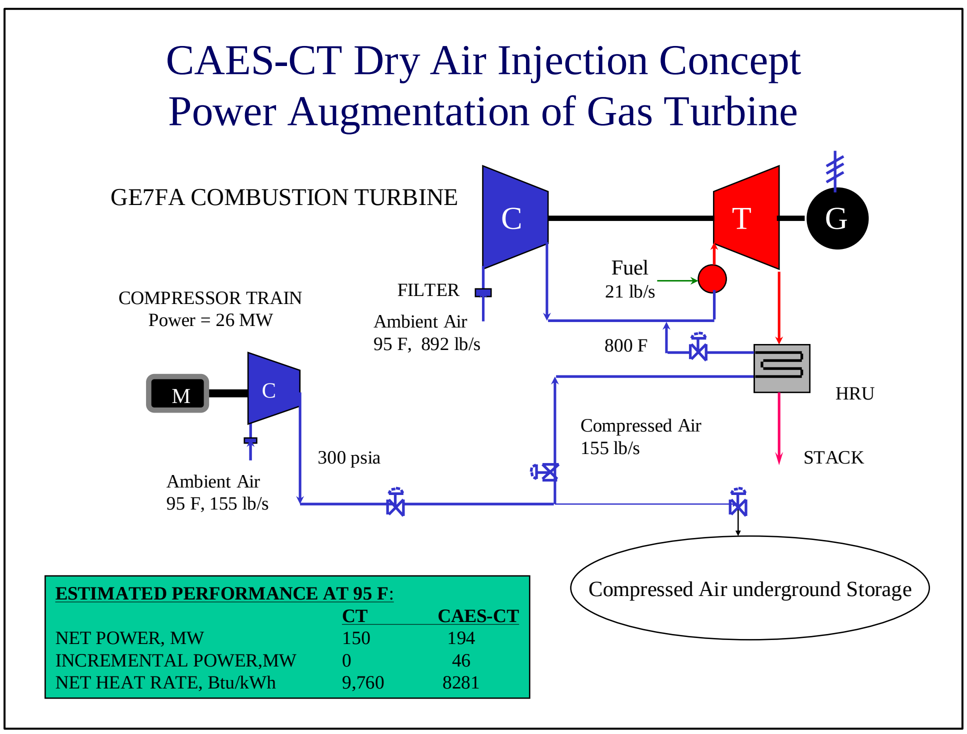

Figure 1: CAES-CT System, Stored Compressed Air is injected into Gas Turbine

The CAES technology combined with the with AI technology where the stored air is injected into existing combustion turbine (CT)/combined cycle (CC) plants for power augmentation significantly reduces specific costs of this CAES-CT or CAES-CC concept as compared with conventional alternative with custom-built CAES turbines. The power capability of CT/CC plants is increased when the stored compressed and optionally heated (by the exhaust gas) air is injected into the existing engine at a location upstream of the combustors. The compressed air from the air storage facility will be mixed with the air from the gas turbine compressor and heated in combustors to the normal gas turbine combustor exit temperature, and thus increasing the CT/CC plant capacity by 25-35%.

The advantage of air injection for gas turbine power augmentation is that existing CT/CC plants can be utilized with little or no modification to the engine itself. The CT/CC retains the flexibility to operate with or without the injection of compressed air. Thus, the energy from wind power can be stored and then utilized when it is most economical without losing capability of the CT/CC to operate independently, when appropriate, without the power augmentation with the stored air injection.

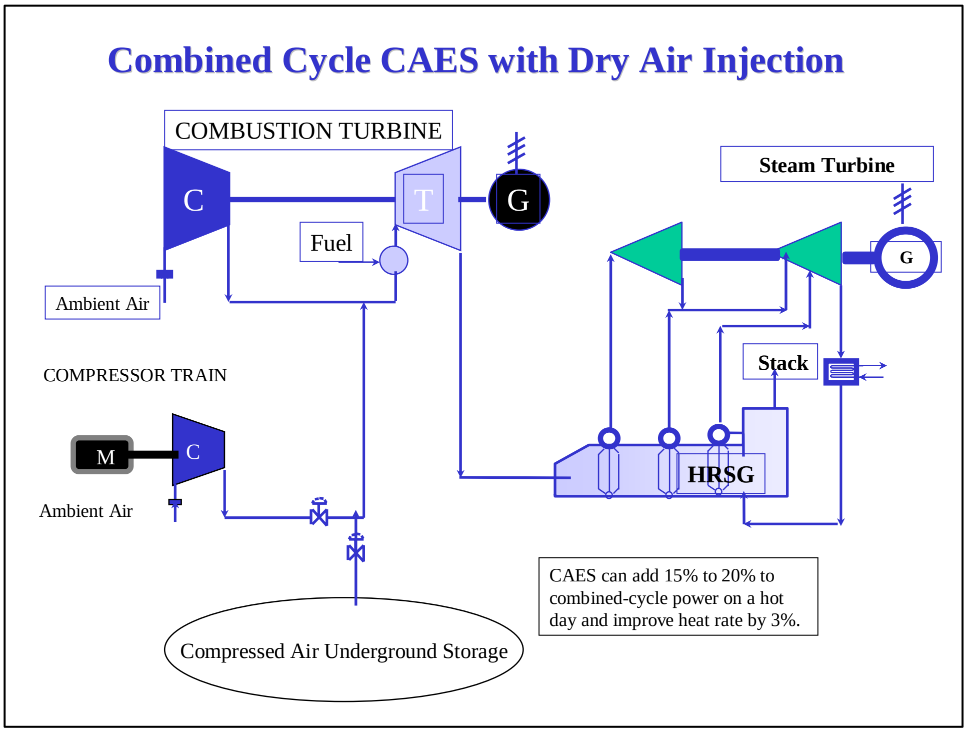

Figure 2: CAES-CT Technology applied to a combined-cycle (CC) power plant

The Alabama CAES (McIntosh) plant cost approximately $600/kW in 1991. These costs were made up of:

- Custom-built Intercooled Compressor: $110/kW
- Salt Storage Facility: $70/kW
- Custom Turboexpander: $330/kW

A CAES-CT power plant utilizes air injection into a gas turbine instead of a custom turbo expander. A power plant based upon the CAES-CT can be built for $250/kW to $650/kW, depending upon the availability of a gas turbine for use as the power production engine. The estimated costs for a CAES-CT plant are:

- Gas Turbine is free if an existing engine is available, or costs approximately $300/kW if a new gas turbine must be purchased for the power plant.
- A less expensive “off-the-shelf” compressor may be used because of the lower operating pressure of the gas turbine; costs are less than $100/kW.
- Salt storage facility may be more expensive than for conventional CAES because of higher specific air consumption and because of the potential for lower storage pressures; costs will be less than $100/kW.

The CAES-CT system has several distinct operating characteristics that are different from a conventional CAES plant. Operational differences between a CAES-CT and a conventional CAES power plant are:

- **Lower Operating Pressure of CAES-CT**
  - A gas turbine (CT) operates at constant expander inlet pressure of 10 bar to 16 bar depending on model, while the Alabama CAES turboexpander operates at inlet pressures approximately from 800 psia to 1200 psia (54 bar to 82 bar).
  - Standard "off-the-shelf" compressor may be used because of the lower operating flows and pressure.
  - Lower operating pressure increases the specific air consumption of the power production cycle; that is, more compressed air is required to produce a given amount of power.
  - Larger potential delta-pressure, from max to min in the storage volume, potentially allows a smaller storage volume.
  - If high maximum storage pressure is used in storage volume to reduce storage size, the overall cycle efficiency will be reduced due to throttling losses from high storage pressure down to CT operating pressure.
  - If lower maximum storage pressure is used in storage volume, the volume must be larger, but the overall cycle is very efficient.
- **Higher firing temperature of CAES-CT improves efficiency**
  - GE 7FA fires to 2550 F combustor exit temperature, this improves the efficiency of the power production cycle and reduces the specific air consumption (the mass of air required to produce a unit of power).
  - Conventional CAES plants use custom-built turboexpanders which are not of the latest technology used in gas turbine engines. The Alabama CAES plant fires at only 1600 F, reducing the efficiency of the overall cycle.
- **CAES-CT Can Produce Power When Storage is Empty**
  - Makes CAES-CT the ideal backup technology for intermittent wind power.
  - Conventional CAES plant cannot produce power when the storage volume pressure goes below its minimum allowed value.
- **Lower NOX Emissions**
  - Higher pressure combustors of conventional CAES plants tend to generate more NOX.
  - Modern gas turbine DLN combustors emit single-digit NOX in parts per million of the exhaust gas.
- **Not all the power from CAES-CT comes from stored compressed air**
  - Less than half of the CAES-CT power production is from the compressed air, power is always produced from air driven through the standard gas turbine air compressor.
  - Overall heat rate of the CAES-CT will be higher than that of the CAES plant during power production mode, because some of the power is produced at standard gas turbine or combined-cycle heat rates, while some of the power is produced at the very low heat rates (4200 Btu/kWh) that are characteristic of compressed air power production.

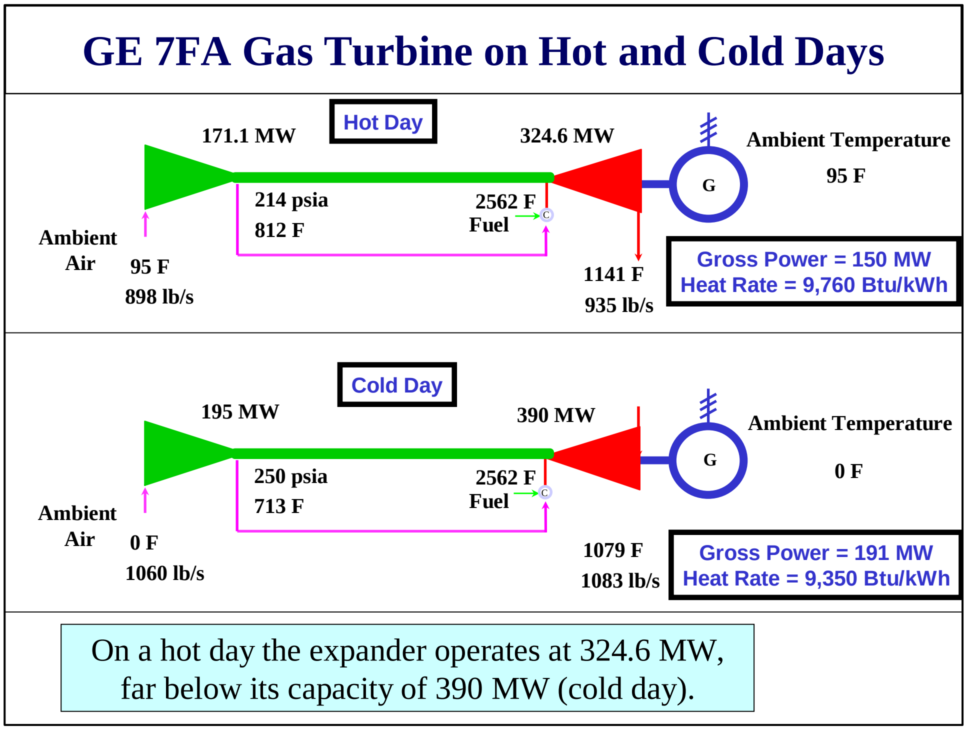

Figure 3: Gas turbine operating data on a hot day compared to that on a cold day

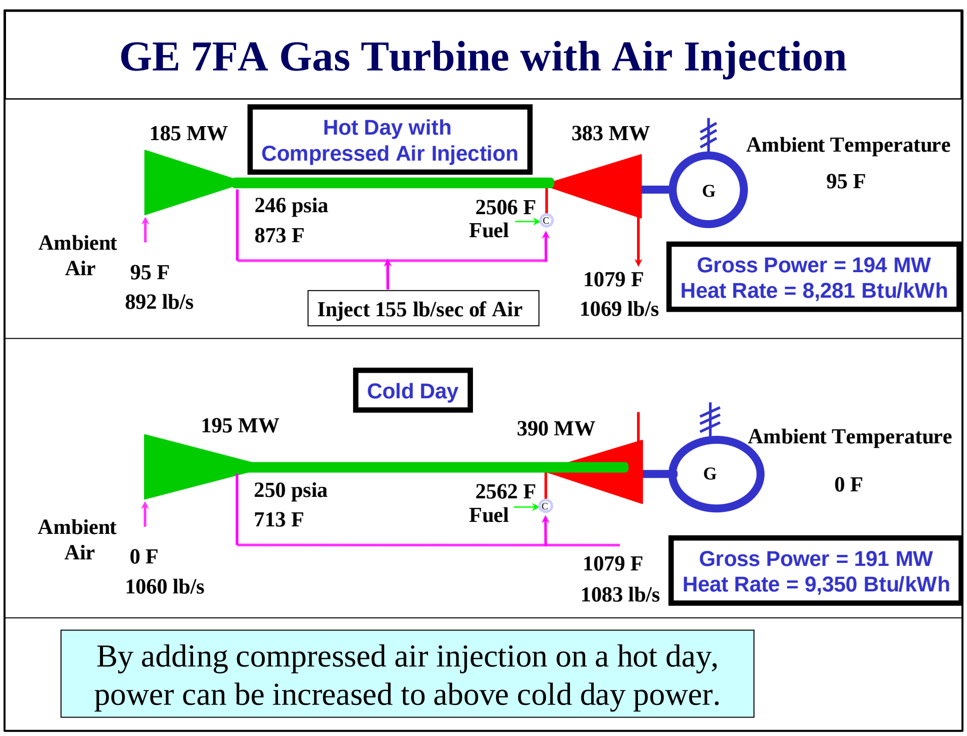

Figure 4: Gas turbine operating data with injection of compressed air on a hot day compared to cold day operation

Figures 3 and 4 compare gas turbine operation on hot and cold days to operation with injection of compressed air injection. Figure 3 shows operating data of a GE7FA gas turbine on hot and cold days. The engine generates 150 MW on a hot day (90 F), while it generates 191 MW on a cold day (0 F). The reason that power is higher on a cold day is that the cold day has a higher inlet air flow rate (1060 lb/s versus 898 lb/s). The inlet air velocity is approximately the same as on a hot day, but the mass flow rate is higher on a cold day because of the higher air density.

Of particular interest is the fact that the expander power on a hot day (324.6 MW) is only about 83% of its power on a cold day (390 MW). The expander is running at part load on a hot day.

Air injection technology brings the gas turbine up to full load on a hot day by injecting air into the compressor discharge gas stream. The effect is to bring the combustor and expander up to their design operating conditions on a cold day. The impact of air injection is to make the expander run at cold day conditions, increasing the gas turbine power and improving the heat rate.

The existence of inlet guide vanes on most industrial gas turbines allows a reduction of power produced by the "normal" CT/CC operations. The CT's compressor flow can be reduced by as much 35% to 40%. The use of inlet guide vanes permits the injection of a greater mass flow of stored-compressed air. This increases the share of power produced by the stored compressed air with very low heat rate and that results in improved overall efficiency and economics of the CT/CC plant with the stored compressed air injection. Unfortunately, when the CT compressor flow is reduced and the pressure ratio is increased by compressed air injection, the CT compressor moves towards the surge limit. Therefore the flow reduction achievable by closing inlet guide vanes is limited by compressor surge restrictions.

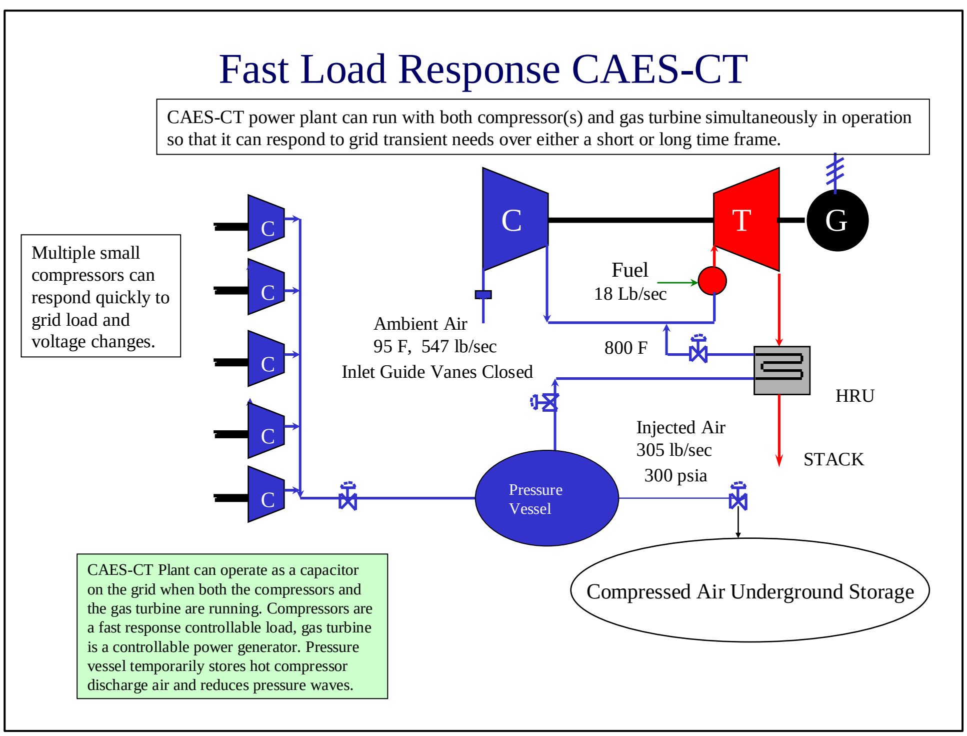

Figure 5: CAES-CT system designed to respond quickly to grid voltage or frequency changes

An important issue with wind power and other renewable sources of electricity is their impact on grid frequency and voltage control. These generation sources tend to be intermittent, and therefore tend to make the transmission system less stable. CAES-CT offers a partial solution to this problem.

CAES-CT has the unique operating characteristic that the air storage compressor can optionally run at the same time as the power producing gas turbine. If the air flow produced by the storage compressor(s) is greater than the rate of air consumption by the gas turbine the storage volume pressure will rise, otherwise the storage volume will be losing pressure.

The CAES-CT system has a controllable load (the air storage compressor) and a controllable generator of electricity (the gas turbine), and a storage volume that lets the system run as either a net power producer or a net power consumer for an extended period of time. This system is essentially a capacitor on the electric grid, and can be used for control as well as load scheduling.

Figure 5 illustrates equipment changes intended to improve the frequency response of a C AES-CT system. The single air storage compressor has been replaced by multiple smaller compressors in parallel. Small compressors have a faster response time than larger compressors and it is possible to trip one of several operating compressors very quickly to respond to a sudden loss of electric supply to the storage compressors. Such a sudden partial loss of power would happen if one wind turbine out of several operating wind turbines suddenly stopped producing power. A CAES-CT system located next to a wind turbine farm could absorb the loss on one or several wind turbines without the transient being felt on the grid.

To further improve the time response and the cycle efficiency of a fast-response CAES-CT system, a pressure vessel could be used in addition to the underground storage facility. The small size of the pressure vessel and its proximity to the gas turbine will allow fast response of the storage volume to sudden changes in the compressed air requirements of the gas turbine. In addition, when the CAES-CT system is operating with both the storage compressors and the gas turbine in operation, the pressure vessel would provide a more direct link between the storage compressors and the gas turbine, without the pressure and thermal losses associated with the underground storage facility.

SUMMARY

CAES-CT system has several advantages over alternate energy storage technologies:

- The Lowest Specific Cost (250-650$/kW)
- Size of Power Generation Flexibility (1 MW to 100’s of MW)
- Potential for Large Storage Quantities (100’s of MW-hrs are possible)
- Shortest Delivery Times (9-18 Months)
- Can Generate Power even when Storage Volume is Empty
- Practically No Development of New Technology
- Flexibility for Lower Pressure Storage
- Short or Long Response Time

CAES-CT has the following unique characteristics:

- Power Generated Does Not All Come form the Stored Compressed Air
- Natural Gas or other High Temperature Fuel is Required
- The Gas Turbine Must be Located Near the Storage
- Large Storage Facility Locations (salt deposit, abandoned mine, or aquifer) are Limited