Integrated Wind Turbine Generator (WTG), Transportable Compressed Air Energy Storage, Desalination And Mineral Recovery Systems

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Abstract

Two versions of compressed-air energy storage are discussed in this paper: (1) The basic Transportable Compressed Air Energy Storage (T-CAES) system that provides energy storage for later use, and (2) The Transfer Line Compressed Air Energy Storage (TL-CAES) system that, not only stores energy by means of compressed air for later use, but also delivers the stored energy to the user without the need for electric power lines. Also discussed in this paper is the use of the co-generated super cold air for desalination by a Eutectic Freeze Crystallization (EFC) method and for HVAC, as well as mineral recovery from the EFC residual brine.

In the first case, an engineering and economics study was performed for the use of T-CAES in an island scenario using a Wind Turbine Generator (WTG) as a power source and a T-CAES system as the method for storing excess energy. The objective in this study was to reduce or eliminate the dependence of the island's electric power supply on the use of diesel fuel, resulting in significant cost savings. Starting with a WTG as the power source, electric power in passed on directly to meet user demand. Excess power (energy) is diverted to T-CAES for storage. Any energy that is beyond the capacity of T-CAES is discarded.

Storage is accomplished by using the excess power to operate an air compressor to compress air in a storage tank at 1,200-psia. When needed, the compressed air is exhausted from the storage tank through a pressure control valve that delivers 200-psia air to the inlet of a turboexpander. As the air expands through the turboexpander, it rotates the rotor and shaft, as well as the turbogenerator that is mounted on the same shaft.

The exhausting air exiting the turboexpander is very cold (~ -150^{o}F). While the turbogenerator generates electric power, the very cold air is a "free" byproduct that can be used for HVAC, desalination and mineral recovery.

Typically, in an island scenario, high wind conditions are expected primarily during nighttime when power demand is low, and low wind conditions are expected during daytime when power demand is high. In such an environment, energy storage using T-CAES is economically ideal for load shifting. Unused nighttime energy is thus shifted to daytime use.

The super-cold air, co-generated during the operation of the turboexpander, is ideally for HVAC. However, when there is no use for the HVAC, the super-cold air is suited for desalination of seawater or brackish water using a Eutectic Freeze Crystallization (EFC) method, followed by mineral recovery from the residual brine. In addition, the cold air exiting the desalinator and mineral recovery system is still sufficiently cold to be used for air conditioning.

In this EFC process, seawater or brackish water is sprayed into a stream of the super-chilled air in a counter-flow direction or co-flow for the purpose of reducing the temperature of the seawater or brackish water droplets down to a temperature slightly above the eutectic temperature of the initial mixture (~ -6^{o}F). The net result is potable water and residual brine. The chilled air stream, now at near ~ -6^{o}F, is further used for air conditioning in a HVAC system.

As an outgrowth of the Eutectic Freeze Crystallization (EFC) process for using the super-cold air from T-CAES or TL-CAES operation to produce fresh water, residual brine is produced. This residual cold brine, containing water with high concentrations of salt and minerals, needs to be disposed of in an environmentally safe manner.

Fortunately, a workable method has been devised to further process the residual brine through an "open thermodynamic system" (fractional distillation) to crystallize the minerals in the brine. Recovered minerals have relatively high commercial value.

Background

The addition of a wind turbine generator to an existing diesel power generation system provides fuel savings that offset the additional cost of the wind turbine generator. These scenarios are particularly efficient when the wind power history coincidentally matches the demand power history.

For example, consider the four 950 kilowatt wind turbine generators that have been installed at the Guantanomo Bay Naval Station. Before the wind turbines were added, Guantanamo Bay was spending $31,000 a day ($24 a minute) on diesel fuel to run generators around the clock to produce electricity. Since the wind turbines went into operation they have been providing between 5 and 12 percent of the power the base uses. In a fortuitous coincidence, the time of day with the highest average winds coincides with the base's peak energy-usage period -- about 4 p.m. By this fortunate happenstance, wind power is the largest when loads are largest. The wind energy project is saving taxpayers $1.2 million in annual energy costs, and it reduced the consumption of 650,000 gallons of diesel fuel, reduced air pollution by 26 tons of sulfur dioxide and 15 tons of nitrous oxide and greenhouse gas emissions by 13 million pounds per year.

However, for the majority of islands that currently depend on diesel power generators, the wind history does not coincide with the power demand history. As a result, when using wind power, there are periods of excess power and periods of power deficits. The T-CAES energy storage system would allow storage of excess energy for use when demand exceeds available supply.

The regime of power vs. discharge time for various energy storage systems is shown in Figure 1. Although different energy storage systems are applicable to different regimes, it is clear that T-CAES applies to a regime that is most relevant to the island scenarios.

Compressed Air Energy Storage (CAES) System

A schematic representation of the T-CAES system is shown in Figure 2. Typically, in an island scenario, high wind conditions are expected primarily during nighttime when power demand is low, and low wind conditions are expected during daytime when power demand is high. In such an environment, energy storage using T-CAES is economically ideal for load shifting. Unused nighttime energy is thus shifted to daytime use.

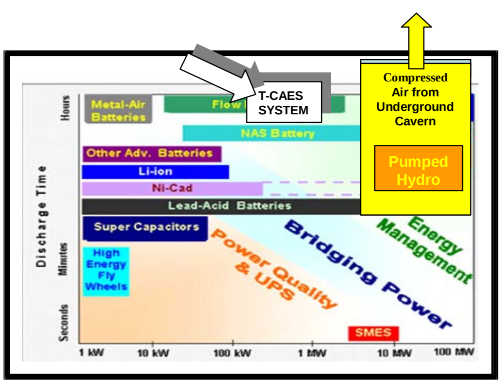

Figure 1. Regimes of Continuous Discharge Duration vs. Power for Specified Storage Systems

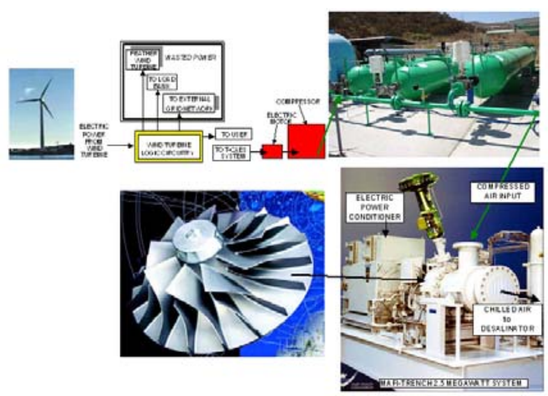

Figure 2. Description of Transportable T-CAES System

In the present analysis, two typical extremes of wind power history as a function of time were used for a 1.725 MW WTG. One was an idealized power history with repetitive 2-hour cycles of wind power. The other was a measured power history recorded for an island off the coast of Southern California, wherein there were long periods of low wind speed. The actual wind histories lie between these two extremes. The same demand power history was used in both cases. In these two cases, whenever wind power was in excess of demand, energy was being stored, and whenever wind power was below demand, the deficit was being supplied by the stored energy.

For the lower limit case, the cost of the T-CAES system is $5,545,505 and the diesel fuel savings over a 12-year period is $20,347,920. For the upper limit case, the cost of the system is $18,205,195 and the diesel fuel savings over a 12-year period is $17,234,733. The major difference in T-CAES system cost between the lower and upper limit cases is the cost of the storage tank.

Thus, in the lower limit case, the initial cost of the T-CAES system is paid off in 3.27 years. For the upper limit case, the T-CAES system is paid off in 12.67 years.. The greatest expense is the storage tank whose size can be reduced by a factor of 2, and, hence, the system cost can also be reduced by a factor of 2, by using waste heat at 250-psia and 450^{o}F air input to turboexpander. This is accomplished by a significant increase in turboexpander efficiency when the incoming air is raised to 450^{o}F.

It is significant to note that during T-CAES operation, for every 1 kW (electrical), 1 kW (thermal) is generated in the form of super-chilled air. The additional savings in HVAC or desalination costs, although substantial, was not included in the cost analysis. The addition of this source of energy would substantially lower the payback period (for the intermediate case, to ~5 years).

In the second application, the storage tank is replaced by a storage pipeline. In this case, the analysis was performed for the TL-CAES system, wherein energy is not only stored for later use, but also delivered pneumatically to the user 20 to 100 miles away by means of a 4-ft diameter pipe at 1,200-psig pressure, without the use of power lines.

The results of this analysis indicate that for a user requiring electrical power, the efficiency of the system is 9.9 SCFM/HP. However, for a user requiring pneumatic power, such as a pneumatic industrial park, the efficiency of the system is 4.0 SCFM/HP. Thus, only 40% of compressed air flow (SCFM) is required to generate the same horsepower for the pneumatic case as compared to the electrical case. Therefore, the same air volume in the tank can provide either 1.42 weeks of 10,000 kW power for the electrical case or 3.5 weeks of 10,000 kW power for the pneumatic case.

Combustor Powered Electrical Generator Supported by WTG and T-CAES Energy Storage System

This paper offers T-CAES as an energy savings system that not only functions to fill in demanded power during the lull periods in the wind speed history, whether diurnal or hourly, but also to co-generate chilled air. For every kilowatt of electrical power there is co-generated a kilowatt of thermal “chill” power that has several useful applications.

The chilled air can be used immediately for mixing with fresh-air and return-air in a Heating, Ventilation and Air Conditioning (HVAC) system for a large facility. Thus, if the stored electrical power is provided during the daytime to offset a peak electrical power demand that cannot be met by the wind turbine generator (WTG), the T-CAES system provides this electrical power. But in addition, the chilled air is directed into the HVAC and further reduces the electrical power demand. This reduction in demand, obtained in reducing the HVAC power requirement was achieved by using co-generated (free) chilled air

Figure 3 shows the flow rate of air from the storage tank required to produce a unit of power at 85% thermodynamic efficiency of the turboexpander. Figure 4 shows the range of input and output conditions for producing the extremely high flow rates of extremely cold air.

When the discharge pressure is 30-psia to assure that the discharge air has the energy to continue on through downstream ductwork or chambers, the super-chilled air can be between –75^{o}F to –128^{o}F, where the initially colder air produces a colder output air. The 200-psia to 30-psia pressure drop permits the use of a one-stage turboexpander.

When the discharge air is dumped into a large mixing chamber of a HVAC system, a two-stage turboexpander will exhaust –130^{o}F to –175^{o}F exhaust air.

Use of the “Free” Byproduct of Super-chilled Air to Produce Fresh Water and for HVAC

The super-cold air, co-generated during the operation of the turboexpander, is ideally suited for desalination of seawater or brackish water using a Eutectic Freeze Crystallization (EFC) method, followed by mineral recovery from the residual brine. In addition, the cold air exiting the desalinator and mineral recovery system is still sufficiently cold to be used for air conditioning.

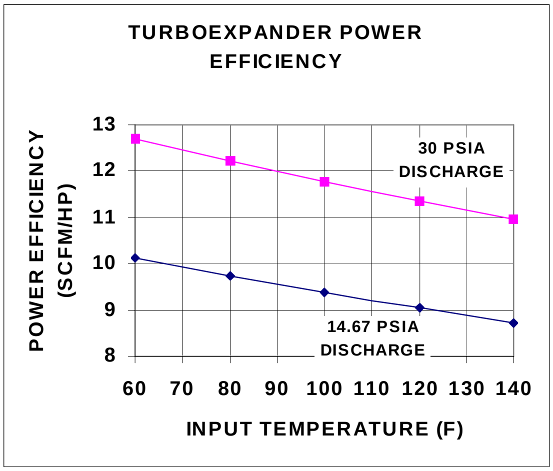

Figure 3. Turboexpander Required Mass Flow per Unit of Output Power Performance for a Range of Input Temperatures at 200-psia Input.

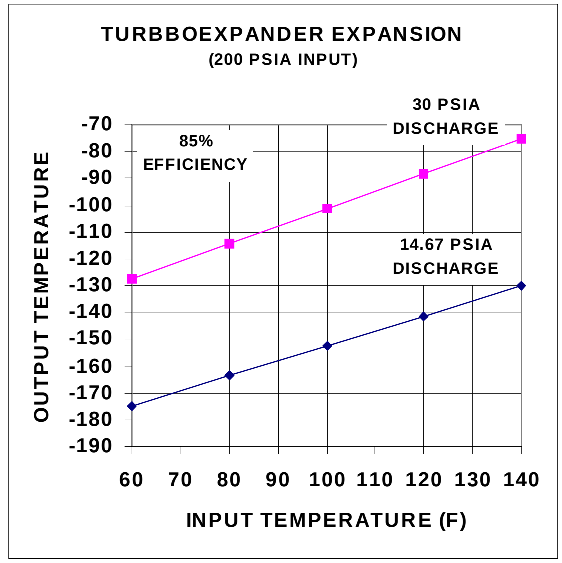

Figure 4. Range of Input and Output Temperatures for Producing the Extremely High Flow Rates of Extremely Cold Air.

In this EFC process, seawater or brackish water is sprayed into a stream of the super-chilled air in a counter-flow direction or co-flow for the purpose of reducing the temperature of the seawater or brackish water droplets down to a temperature slightly above the eutectic temperature of the initial mixture (~ -6^{o}F). The net result is potable water and residual brine. The chilled air stream, now at near ~ -6^{o}F, is further used for air conditioning in a HVAC system.

The chilling process of the salt-water mixture is shown in the phase diagram on the left side in Figure 5 by red arrows. As cooling of the salt-water mixture begins, nothing happens until the mixture approaches the freezing point of water (0^{o}C). At that point the red arrow splits into two arrows; one represents the pure ice/snow formation down along the boundary of zero salt concentration, and the other down the saturated solution path of steadily increasing concentration of salt. This is a “closed thermodynamic” system.

When the eutectic temperature of -21^{o}C is reached, both phases, ice/snow (0% salt concentration) and brine (23% salt concentration) coexist in equilibrium. However, any reduction in temperature below the eutectic temperature of -21^{o}C will initiate the precipitation of salt crystals along with the ice (pure water) crystals.

As an outgrowth of the Eutectic Freeze Crystallization (EFC) process for using the super-cold air from T-CAES or TL-CAES operation to produce fresh water, residual brine is produced. This residual brine, containing water with high concentrations of salt and minerals, needs to be disposed of in an environmentally safe manner.

Conceptually, recycling it back into the ocean in a distributed fashion should not be a problem. However, it may represent an environmental problem in the vicinity of the point of discharge in the ocean.

Fortunately, a workable method has been devised, as shown in Figure 6, to further process the residual brine through an “open thermodynamic system” (fractional distillation) to crystallize the minerals in the brine. Recovered minerals have relatively high commercial value.

The drawing in Figure 6 shows the Mineral Recovery System. It consists of the following components and features:

- Main Chamber (CEFC Tower)
- Multiple Stilling Chambers (nominally 10)
- Storage Tanks
    - Potable Water Storage Tank
    - Brine Storage Tank
    - Sludge Storage Tank
- V-Shaped Collection Trough around the outside perimeter of the system, connected to each Stilling Chamber and to the Potable Water Storage Tank for ice/snow collection and transport to the water tank
- Chilled-air input line from the turboexpander for chilling seawater, followed by further chilling residual brine for mineral recovery
- Chilled-air exhaust line from the Main Chamber. The exhaust air still has chilling potential, and may be used for HVAC.

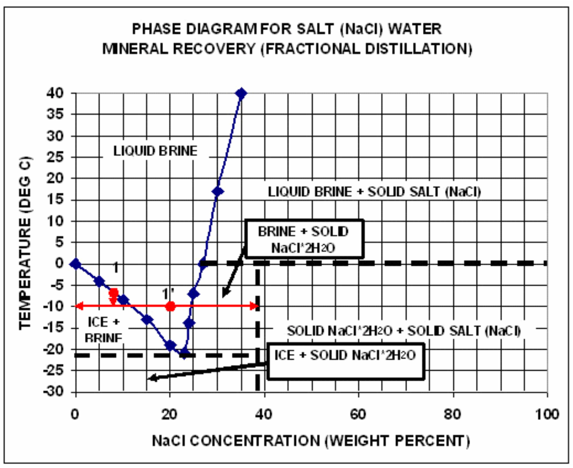

Figure 5 Saltwater Phase Diagram

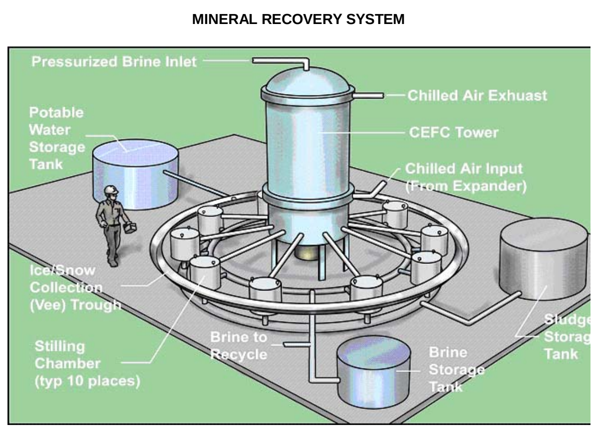

Figure 6. Mineral Recovery System

Conclusions

The following is a summary of the conclusions related to T-CAES, TL-CAES, the use of co-generated chilled air for desalination and mineral recovery, and for HVAC:

- Wind turbine generator (WTG) and T-CAES system, when supplemented by diesel Gen-Set, saves sufficient diesel fuel to pay for WTG and T-CAES system within 5 years

- Power sources (conventional combustion-driven, geothermal and nuclear power plants) that operate at constant power levels, day and night, can sell nighttime power at daytime rates using the T-CAES system.

- WTG farms, remotely located from the demand, can both, store and transmit energy using the T-CAES system. The 4 feet diameter pipeline transmission system is unobtrusive compared to tall tower power lines.

- T-CAES and TL-CAES provide enhanced system efficiency for pneumatic industrial parks that use compressed air directly to operate equipment

- T-CAES and TL-CAES systems have the option of operating at even higher efficiency by generating super-chilled air for HVAC only, without generating any electricity

- CAES systems are robust. There is greater than fifty-year lifetime for major components. There are no toxic or corrosive fluids for handling and later disposal.

- The turboexpander generates 1 MW of electrical power and co-generates 1 MW of thermal (chill) power. The exhaust air can be used directly in a HVAC system.

- The super-chilled air also has potential for use in thermal energy storage (time delayed HVAC), desalination and mineral recovery

- Batteries also store electricity. However, when compared to T-CAES and TL-CAES, batteries **do not**:
    - Transmit electricity over long distances directly to the user
    - Provide enhanced system efficiency for pneumatic industrial parks
    - Produce super-chilled air for HVAC
    - Produce thermal storage for HVAC
    - Offer potential for desalination
    - Offer potential for mineral recovery
    - Offer 50-year lifespan for major system components.

- TL-CAES system in combination with a turbocompressor/turboexpander device will supply HVAC to the interior of skyscraper facilities without exhausting hot air outside of the skyscraper, by-passing the need for further need for HVAC. This is a unique capability.