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An Analysis of an Advanced Compressed Air Energy System (CAES) Using Turbomachinery for Energy Storage and Recovery and for Continuous On-Site Power Augmentation as an Air Brayton Cycle

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A thermodynamic analysis is presented of an advanced CAES for Distributed Power Generation (DPG) that utilizes turbomachinery for energy recovery, but also gives continuous power generation to augment on-site power. The advanced CAES uses renewable energy such as wind power and solar PV in the power range of 1500 to 2500 kW plus recuperation of waste heat from the existing on-site prime mover to improve the utility of the energy storage system. The proposed system also utilizes battery storage to maintain high energy density storage, preferably without the need for costly electrical rectifying and inversion systems to improve the stabilization of power generation. This proposed system may be thought of as a "cross-over" system that combines CAES technology with electric battery storage technology, particularly if the stored electric power is used directly as D.C. power at an industrial facility. The direct use of stored energy from a battery as heat input to the proposed "cross-over" system also may be considered in some limited applications. The ideal application of the proposed system is for isolated DPG systems perhaps in remote sites utilizing "power islands" of renewable energy augmented with on-site fossil fuel prime mover, power generation systems. The proposed "cross-over" system enables higher reliability, faster response to transient power loads, and the efficient use of renewable energy, as well as heat recovery from conventional prime mover systems that are on site.

Keywords: Distributed Power Generation, waste heat recuperation, high energy density storage, renewable energy system.

1. State-of-the-Art Energy Storage System

The prevalent energy storage system in use today is based on battery technology. Electric batteries have a long history of storing electric energy, but such systems were typically devoted to small magnitudes of energy storage. The advent of significant renewable energy power generation by wind and solar, and the popular interest to couple this stored energy with the utility grid has encouraged the development of much larger battery storage systems, rated from 3 to 30 MW and 12 to 120 MWh.[1] The most effective battery technology to store unused but available utility spinning reserves uses lithium ion batteries together with inverters and rectifiers to be able to connect to the utility. The energy storage density of a lithium ion battery at 250-690 W-hrs/liter (100-265 WH/kg) has made it the most popular energy storage battery. The energy conversion and recovery efficiency is typically 70% over the 1,200 cycle lifetime of the batteries.

Over the past 5 years, there have been many entrepreneurial companies who have conducted both private and publicly funded research to design and implement 100% thermomechanical energy storage systems. The most common example of thermomechanical energy storage is the Compressed Air Energy Storage (CAES) system. A CAES is relatively simple in concept, but it is complicated in the design and execution of the concept to provide an economically viable and competitive energy recovery efficiency. This is particularly true when the CAES is scaled for use by electric utilities to store the electric power that is available for generation at reduced cost when the demand for the electric power is low. Such systems use axial or reciprocating compressors, depending on the storage pressures and the size of the storage. For example, large scale plants designed for the 21st century and using very deep caverns in the ground may have storage pressures as high as 70 bar,a. Earlier era CAES designs considered using only 13 bar,a to 20 bar,a but were limited by commercially available compressors which constrained their operating pressures and efficiency, and ultimately, the discharge temperature. The energy recovery cycle typically requires the use of a combustion system upstream of a turbine to reheat the stored, pressurized air before it enters the turbine. It is common to use an onsite gas turbine power generation unit or invest in a combustion system heater to heat the air stream to a high temperature before it is expanded in the turbine, thus improving power output.

It is generally accepted that CAES is more economical and efficient, compared to battery storage, over the total operating lifetime of the wind turbine or photovoltaic system. However, the major objective in developing a more economical system is to increase the energy density (often resorting to latent heat energy storage) and to increase the Energy Recovery Efficiency (E.R.E.) of the mechanical energy storage system. The E.R.E. is defined below.

$$E.R.E. = \frac{\sum \dot{W}_{out} \times \Delta Time_{discharging}}{\sum \dot{W}_{in} \times \Delta Time_{charging} + \dot{Q}_{reheat} \times \Delta Time_{discharging}}$$

Where:

$$\dot{W}_{in} = \dot{W}_{net\ compressor} + \dot{Q}_{auxiliary\ heat\ input} \times f$$

$$0 \leq f \leq 1; f = fraction\ of\ time\ that\ Auxilliary\ Reheater\ is\ used \quad (1)$$

[1] San Diego Gas & Electric Company Proposal and Awards, April 2017.

State-of-the-art designs for energy storage systems have several common elements. These elements are itemized here in order to then focus on how to improve upon these features.

1. Air in a vapor phase is typically the storage medium, although cryogenic energy storage is available commercially with a recent prototype developed by Concepts NREC. There is considerable interest in using a phase change material to store thermal energy in an effort to achieve a higher specific energy (Btu/lbm or kJ/kg). However, latent heat energy storage tends to be used only for low grade, heat energy storage and recovery. Energy storage systems tend to be open systems if air is the medium and/or if the medium can be directly used in the prime mover or industrial process. In the open systems, the compressed air is released into the inlet of a gas turbine combustor, thus avoiding the live parasitic compressor power while also enabling a more rapid start-up of the gas turbine from idle to produce power upon demand.
2. A very large storage reservoir is used, typically constructed from geo-physical phenomena; therefore, most energy storage systems are extremely large, utility energy (MWh) scale, and thus very costly with respect to the components, site preparation, and installation.
3. One or more compressors to compress the vapor phase and one or more positive displacement or turbomachinery expanders are used to recover the energy, and/or the compressed air is used directly in the prime mover.
4. The energy recovery from the stored fluid must contend with a negative pressure and temperature gradient as the storage medium exits the fixed volume storage reservoir. Thus, reheating of the medium and some means of flow and/or pressure control is essential to enable the expander to operate most efficiently and with the optimum high specific enthalpy change. In order to preserve or increase the overall efficiency of the energy storage system, the heat for the reheating necessarily must either be derived from a waste heat stream, or the prime mover engine must use some form of regeneration that consists of conduction and convection (e.g., regeneration) heat transfer between the fluid medium and a porous substrate matrix which has latently stored energy during the “charging” sequence of the energy storage cycle.

Several of the more common, recent entrepreneurial researchers who are developing alternative energy storage systems include LightSail Energy, Inc., SustainX, Inc., RWE Power AG, Energy Storage and Power LLC, Mitsubishi, and Air Products. There seems to be an unofficial consensus of contemporary developers of energy storage systems to integrate modular, sensible, or latent heat energy-based CAES with wind turbines and photovoltaic (PV) systems. The competitive technologies from these researchers store thermal energy by injecting water or foam into compressed air, or by using liquefied air. These approaches tend to be expensive to manufacture, involve significant changes to the compressor or turbine designs and still do not achieve the high energy storage densities available with state-of-the art battery technology. Other technical similarities include the use of a heat storage medium to store the Work of Compression and thus reduce the amount of energy needed during the energy recovery sequence to reheat the air flow rate into the turbine. Storing the heat of compression has the added benefit of reducing the storage temperature which helps to increase the energy storage density. Achieving the highest energy density but at the lowest cost and highest reliability possible is a major objective of CAES research. However, it is also understood that the energy per storage volume of the CAES must also be made less expensive, an objective that directly translates into a storage vessel that operates at lower pressures and temperatures. There is also consensus that it is critical that the inlet temperature of the turbine be kept as high as possible during the discharge phase of the energy storage system to improve the turbine efficiency and increase power output.

A new analytical approach to modeling the performance of a CAES has been taken and has been successful in identifying how the energy density of the CAES can be increased, at a lower cost, while increasing the turbine inlet temperature. The analysis presented in this paper enables a better understanding of the viability of integrating several forms of renewable energy to achieve the most effective thermomechanical-based energy storage system by using state-of-the art battery technology integrated into the CAES.

Concepts NREC's proposed alternative concept (Figure 1) may be considered a "cross-over" system, integrating a modular CAES with battery energy storage of power generated by renewable energy, but then continues to operate after the stored energy is depleted by using the heat energy from the on-site, prime mover, power generation system. The proposed system is thought to be suitable for use as a DPG system as compared to the historical CAES that have been designed for very large utility-scale energy storage. The energy stored in the battery and/or the energy released from the combustion of biomass is used to increase the turbine inlet temperature to maintain an acceptable E.R.E., as identified in the formulation that follows herein. Using stored electric power in this manner enables the use of a smaller battery during the discharge sequence of the energy storage cycle and eliminates the need for expensive frequency inverters and other power conversion and control electrical systems. In point of fact, eliminating the cost of such power conversion systems is the only reason for not converting the stored D.C. electrical power and having the inverted D.C. power connect directly to the utility grid. After the stored energy is depleted, the compressor and turbine subsystems continue to operate as an open cycle, air Brayton waste heat recovery system (after the typical 3- to 4-hour discharge sequence). This leaves 6 to 8 hours of power augmentation available for the user. The waste heat recovery is derived from the energy recuperated from the on-site gas turbine engine. Alternatively, the turbocompressor elements that serve as the means of storing (via the compressor) and then recovering (via the turbine) can continue to generate power using a combustion system that burns biomass or biogas.

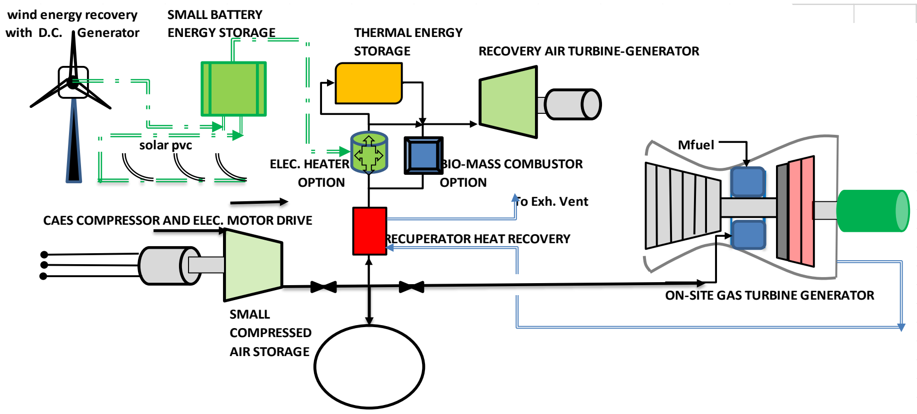

Fig. 1. Concepts NREC's "cross-over" system integrating a modular CAES with battery energy storage of power generated by renewable energy

1.1 Analysis summary and detailed discussion

Despite the cost (~\$200-\$250/kWh in 2018\$) [1] and limited cycle life time (5% per 1000 cycles) [2] of lithium ion batteries, they remain the most common energy storage medium for electrical energy, due to the high energy density that they provide to the system. The energy density of lithium ion batteries ranges from 100 to 265 Wh/kg (= 770 Wh/liter). This is considerably higher than what can be stored in a simple CAES, wherein energy is stored via the sensible heating of a substance to high temperatures and the CAES achieving the storage pressures by positive displacement compressors. An Exergy (or Availability) Analysis of several common fluids, including water, at a temperature and pressure above the ambient pressure and temperature (the "dead" state) has been completed and is shown in Figure 2. The shaded portion of the chart represents the range of the energy storage that is available from the lithium ion battery. The temperature used in the analysis corresponds to the saturation temperature of water at the given pressure. The results indicate that water as the storage medium has a higher specific availability (Wh/kg) than air, CO_2, or R245fa, the only refrigerant studied.

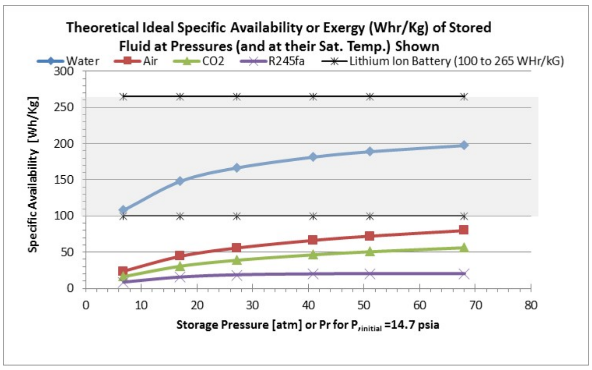

Fig. 2. Exergy (or Availability) Analysis of several common fluids

The high specific Available Energy for water as compared to the other fluids is due to the extremely high latent heat energy required to change the water from a liquid to a saturated vapor. Some preliminary conceptual studies have been done by Concepts NREC indicating that energy storage using the high latent heat energy of water can be done, but would require a very high-pressure containment vessel at temperatures above 350°C. For this paper, it is sufficient and necessary to observe from Figure 2 that the storage pressures for the CAES must be higher than 8 atm. For example, the compressor Pr must be greater than 8 for the energy storage densities to be comparable to that available with lithium ion batteries. However, it may also be observed that the rate of increase of the energy density decreases as the storage pressure is increased. From Figure 2, the rate of increase or slope of the curves (ΔAvailability/ΔP) appears to significantly decay at a storage pressure of 16 atm (Pr=16). To understand in more detail how to select a suitable design point for the CAES, Concepts NREC developed a new way of examining the optimization of a thermomechanical energy storage system that led to the development of the energy storage system shown in Figure 1.

An analytical expression for the Energy Recovery Efficiency (E.R.E. defined in Eq. (1)) has been derived for an Air Energy Storage System, assuming that air can be treated as a perfect gas. Two derivations were developed. The first derivation determines the E.R.E. as a function of the storage pressure, but with the assumption that no additional energy is added to the turbine inlet stream during the recovery of the stored energy. The second derivation develops an expression for E.R.E. as a function of pressure ratio, but then considers the effect on the E.R.E. of the addition of heat energy to the inlet turbine air flow rate to increase its temperature. It is preferred that the necessary heat input to the pressurized air before it is input into the turbine be derived from a renewable energy source. The renewable energy could include the combustion of biomass or biogas, for example. However, it is also possible to use electric power derived from wind turbines or photovoltaic cells to heat the compressed air entering the turbine. However, the use of electric power in this manner should weigh the savings in the cost of rectifying and inverting the D.C. electric power against the thermodynamic exergy destruction that results when the electric power is not returned directly to the utility grid. Both derivations use the state point temperature parameters that are defined by the air process paths, as illustrated in Figure 3 below. The ambient air (T1) is compressed during the "charging" sequence and heated to T2 by the energy of compression. The temperature of the stored energy may decrease to T_{cooled} due to heat transfer from the storage system. The magnitude of this heat transfer loss is dependent on the design of the storage system.

The measure of the magnitude of the temperature reduction is identified by a new parameter defined as:

$$Rc = \frac{\left(T_3 - T_{1,ambient}\right)}{\left(T_2 - T_{1,ambient}\right)} \tag{2}$$

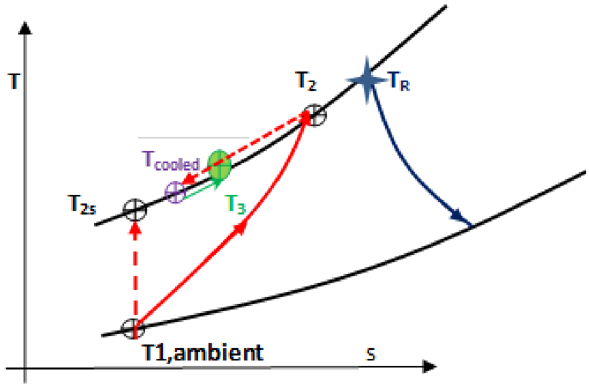

Fig. 3. Process path for air during Charging and Discharging sequence

The Temperature Recovery Effectiveness (Rc) is a parameter used to indicate the degree of temperature recovery (T_3) that is required before the stored fluid enters the turbine. As diagrammed in Figure 3, the elevated discharge temperature, T_2, from the compressor may cool to temperatures between T_2 and $T_{ambient}$ before the recovery sequence from the stored energy is initiated. This is due to the loss of some of the thermal energy to the environment if the energy is stored for prolonged periods of time. It is also possible that the work of compression has been intentionally removed to increase the density of the stored air. The heat energy that is removed must be stored in some manner that can be easily recovered to reheat the air as it is delivered to the turbine during the energy recovery sequence. If the work of compression is recovered completely and no heat is lost to the environment during the storage period, then this value would be equal to 1. However, during the normal fluid extraction process from the storage vessel, the pressure of the fluid in the storage vessel is dropping due to the extraction of fluid during the Energy Recovery sequence. Analysis can also show that, as the air is rapidly discharged from the storage vessel, the temperature of the air remaining in the tank continues to be reduced. Depending on the size of the vessel and the initial storage pressure, the value of Rc can range from 0.6 to 0.9. The lower range is more representative of a smaller vessel as may be used in an energy storage system in applications for Distributed Power Generation. Ultimately, the cooling of the remaining air in the storage vessel increases the need for the turbine inlet temperature to be boosted to a higher temperature during the Energy Recovery sequence, if the E.R.E. is to be maintained at an economically acceptable level.

If no additional heat energy from an external source is added to the flow stream entering the turbine during the Energy Recovery sequence, then the instantaneous[2] E.R.E. is calculated using the equation shown here:

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[2] The E.R.E. equation is best described as providing the instantaneous value for the E.R.E. at the end of the Charging Sequence and at the initial moments at the start of the Energy Recovery Sequence when the pressure ratio across the compressor and turbine is equal. At all other times during the charging and discharging of the stored energy, the pressure ratios are changing. However, the E.R.E. equation is thought to be a simple, closed form equation that can accurately represent the transient ratio of the total work of compression and expansion that must otherwise be integrated over the charging and discharging periods as required in Eq. (1). An alternative is to consider using the mean effective pressure ratio, Pr_{effect}. for each of the compressor and turbine Pr in

$$E.R.E. = B \times \eta_{turbine} \times \left[Rc + \frac{\eta_{compressor}}{A}\right]$$

Where:

$$A = (Pr, compressor)^{\left(\frac{k-1}{k}\right)} - 1 \;\; ; B = 1 - \left(\frac{1}{Pr, turbine}\right)^{\left(\frac{k-1}{k}\right)}$$

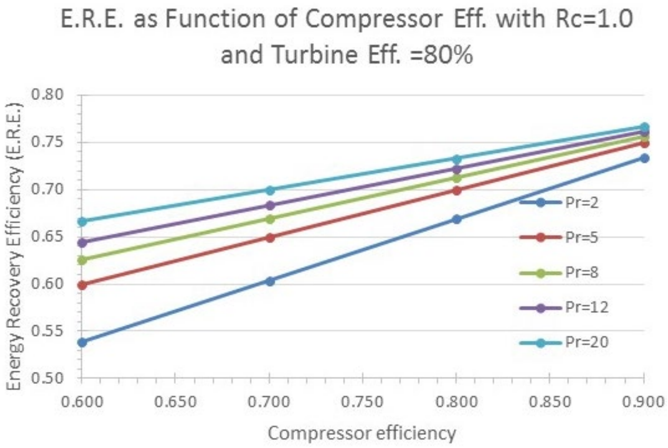
With:

$$Rc < 1 \; and \; k = 1.41 \tag{3}$$

Figures 4a-c present the results from a parameterization of the Energy Recovery Efficiency (E.R.E) with respect to the compressor and turbine efficiencies and Rc. Perhaps the most striking observation to be made from Figure 4 is the independence of the E.R.E. as a function of the stored pressure (equivalent to Pr) at pressure ratios above eight (8).

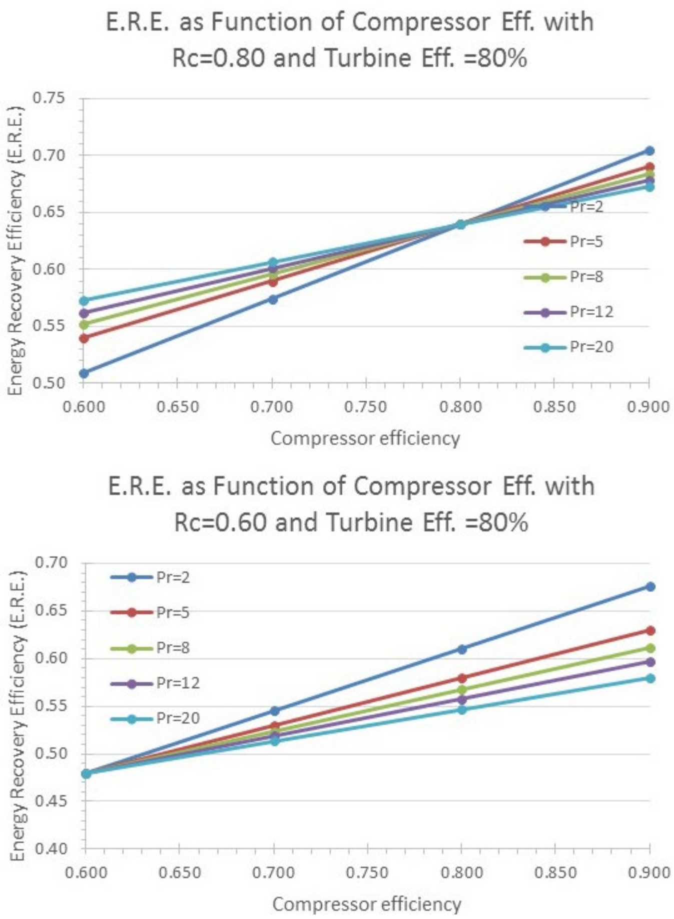
Thus, to maintain a competitive E.R.E. for modular systems (e.g., thermomechanical energy storage systems designed for smaller, Distributed Power Generation systems), it may be sufficient to store energy at pressures of less than 8 atmospheres, but then utilize the advantages of the inherently high energy densities available with battery storage and/or biomass[3] combustion to maintain or improve the E.R.E. during the Energy Recovery sequence by increasing the temperature at the inlet to the turbine as high as possible.

Such a system, see Figure 1, suggests that the typical availability of an on-site gas turbine (or other power generation prime mover) affords the opportunity to provide continuous recuperation of the waste exhaust gas heat by the proposed turbomachinery now considered able to provide not only energy storage and recovery, but also continuous power generation to augment power from the prime mover at the user's site.



Eq. (2). The same correction may also be considered for the part-load efficiencies of the compressor and turbine, replacing the efficiencies with weighted average efficiencies during charging and discharging.

[3] Biomass consisting of carbon-hydrogen bonds is an example of very effective energy storage.



Figs. 4a-c. Results from a parameterization of the Energy Recovery Efficiency (E.R.E)

A very interesting and important observation can be made by careful study of Eq. (2) and Figures 4a-c. If the compressor efficiency is equal to the Temperature Recovery Effectiveness (Rc), then Eq. (2) evolves into a much simpler relationship between E.R.E. and turbine and compressor efficiency, as shown here:

$$E.R.E. = \eta_t \times (R_c \equiv \eta_c) \tag{4}$$

As may be observed in Figures 4a-c, this equation leads to a definitive result that, when compressor efficiencies can be made higher than Rc, the E.R.E. is increased with LOWER pressure ratio, Pr, not higher. This observation provides the most compelling evidence and reason for achieving as high an efficiency for both the turbine and compressor as can be designed, taking full advantage of the current state of the art for turbomachinery design software and advanced machining practices (including Additive Manufacturing).

To determine the effect of providing energy input to the turbine during the energy recovery sequence on the E.R.E., a modification of the E.R.E. equation, Eq. (2), is required with the introduction of another new parameter, Rr. The Recovery Factor, Rr, is a measure of the relative magnitude of the amount of energy added to the fluid to increase the temperature, T_R, of the fluid that is entering the turbine during the energy recovery sequence. It is defined as shown in the equation below with respect to T_3 and T_2 (which were previously illustrated in Figure 3):

$$Rr = \frac{(T_R - T_3)}{(T_2 - T_3)} \tag{5}$$

It is noted that Rr can have a range from zero, when $T_R = T_3$, to greater than or equal to 1 when $T_R \geq T_2$. The choice of the temperature, T_R, is constrained by the availability of other "free" waste heat, as may be available at the user's site, the materials used in the turbine, or the electric resistance heater. Electric resistance heating is assumed to be used only if the electric power is directly available from live wind or photovoltaic renewable energy sources at the user's site or from battery storage, and only if the renewable power generation is never intended to be connected to the utility, with the consequential savings in the complexity and expense of power conditioning systems (such as voltage inverters or the expense of compliance with the local regulatory requirements for power generation systems).

The modified E.R.E. (net) equation that accounts for the energy added to the system during the energy recovery sequence is shown here with respect to the same parameters defined previously:

$$E.R.E._{net} = \frac{T_R}{T_{ambient}} \times \frac{B \times \eta_{turbine} \times \eta_{compressor}}{A \times [1 + Rr - Rr \times Rc]} \tag{6}$$

Using this equation with T_R= 900R, 1200R, 1400R and 1800R, the Net E.R.E. for the integrated system of Figure 1 is shown in Figure 5. As expected, the $E.R.E._{net}$ is less than the previous E.R.E., because the energy that is added to the system to increase the inlet temperature to the turbine must be accounted for as given by Eq. (1). However, while Eqs. (5) and (6) are thermodynamically correct in accounting for the additional energy, an argument can be made that IF the energy that is added to the system is "free", that is, derived from a waste heat source that otherwise would not be recovered or from a renewable energy source such as wind or PV, the E.R.E. efficiency could be recognized to be much higher and independent of the inlet temperature, T_R, and in fact is calculated using Eq. (2) with T_3 set equal to the desired turbine inlet temperature, T_R. This value of E.R.E. is also presented in Figure 5 for an Rc=80% and turbine and compressor efficiencies of 85%.

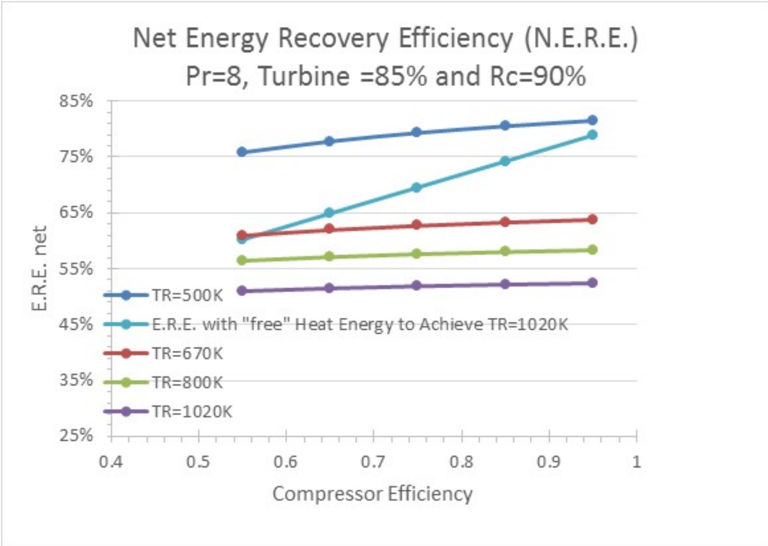


Fig. 5. Value of E.R.E. for an Rc=90% and turbine efficiency of 85%

1.2 The cross-over energy storage system: continuous power generation after stored energy recovery

The proposed use of a modular (i.e., smaller) Energy Storage and Recovery System for the Distributed Power Generation market using turbomachinery components and the reheat subsystems as shown in Figure 1, can serve as an air Brayton cycle system that enables the continuous generation of power after the stored energy has been depleted. The turbocompressor subsystem can produce a net power output using the waste heat recovered from the onsite prime mover such as the gas turbine engine or a biomass combustor as shown in Figure 1, assuming that inlet temperature to the turbine can be increased above a critical minimum temperature, $T_{R,min}$, that thermodynamically has the air Brayton cycle efficiency, given by Eq. (7), greater than zero (0).

$$\eta_{brayton\ cycle\ power\ rccovery} = \frac{\left(\frac{T_R}{T_{ambient}} \times \frac{B \times \eta_t \times \eta_c}{A} - 1\right)}{R_R \times (1 - R_c)} \tag{7}$$

The minimum temperature, $T_{R,min}$, as determined from Eq. (8), is displayed in Figure 6 as a function of Pr for the turbocompressor system.

$$\frac{T_{R,min}}{T_{ambient}} = \frac{P_r^{\left(\frac{k-1}{k}\right)}}{\eta_t \times \eta_c} \tag{8}$$

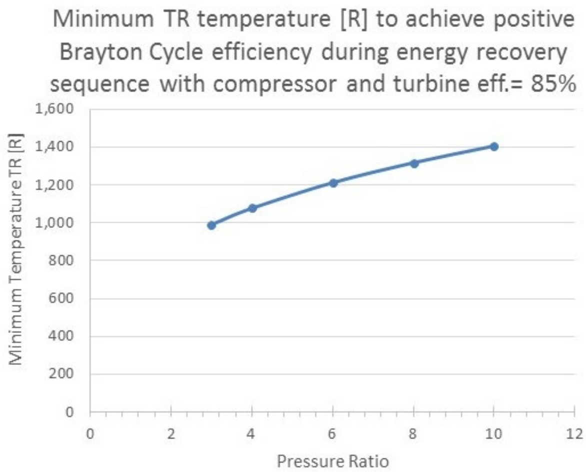


Fig. 6. Minimum temperature, $T_{R,min}$

The calculation of cycle efficiency, using Eq. (7) for several turbine inlet temperatures, T_R, is shown in Figure 7. It is interesting to note the optimum cycle efficiency is a function of the system Pr and the temperature T_R, and this serves as an engineering design tool for selecting the design point for the system.

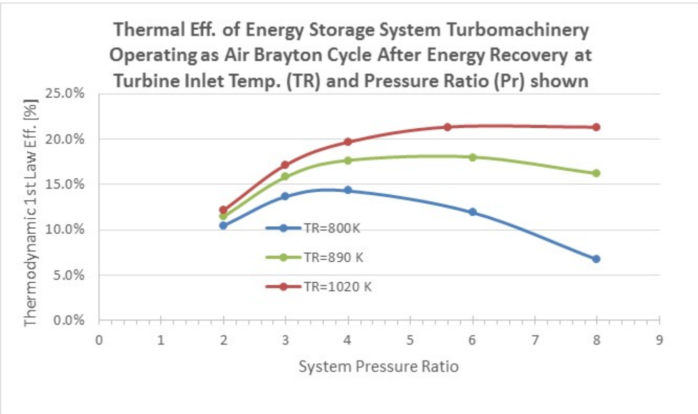


Fig. 7. Calculation of cycle efficiency for several turbine inlet temperatures, T_R

2 Case Study

The following Case Study provides an example of the application of the formulations presented in this paper, including estimates of the size and speed of the turbocompressor for a Distributed Power Generation system that uses CAES with the continuous power option.

Consider the siting of the proposed "cross-over" CAES-battery and open Brayton cycle engine alongside a 1,500 kWe-rated wind turbine. The wind turbine is assumed to have a 65% utilization factor. That is, on average, 60% of the rated power is consumed by an electrical load that is connected to the site. Therefore, up to 35% of the rated power is available to be generated, but perhaps cannot be used due to a lack of demand. For this Case Study, it is assumed that half of this capacity, equal to 20% of the rated power, is subject to energy storage using the proposed CAES-battery/Brayton cycle system. The balance of the wind turbine's capacity is assumed to be unavailable due to lack of wind. It is determined that 900 kWh of energy is available for storage. The CAES uses a storage pressure of only 8 atms, a very typical and safe pressure by industrial standards. It is determined that the compressed air is stored in five spherical vessels, each with a diameter of 10 meters. A single compressor rated at approximately 750 kW will provide the compressed air in approximately 1-2 hours. This accounts for one half of the stored energy required, and the balance is provided by 2,000 kg of Li-ion battery. The worksheet that summarizes these data and the output from the system analysis are shown in Figure 8.

Using the equations presented herein, the E.R.E. for the system is calculated to be 67%, assuming a Temperature Recovery Effectiveness, Rc, equal to 70%. This E.R.E. is very competitive and provides an increase in the confidence that the system can provide at least half of the stored energy in the event of a failure in either mechanical or electrical parts of the system. The combined CAES-battery energy storage system also enables instantaneous power to be generated via the electrical system until the turbine part of the Brayton system is brought up to operating speed.

When the stored energy from the CAES and battery is depleted, the "compressor-turbine-motor/generator" configuration can continue to provide continuous power generation. This configuration is the familiar Brayton cycle, as shown in Figure 9, and utilizes the exhaust gas waste heat from the combined compressor-turbine system that now functions as a gas turbine. To operate as a Brayton cycle-gas turbine during the discharge sequence, both compressors shown in Figure 9 are engaged in parallel to provide the necessary flow rate through the turbine. The waste heat energy from the proposed Brayton cycle turbine can be augmented by an external auxiliary heat input derived from either the combustion of conventional fossil fuels, biomass, or the waste heat from other prime mover engine(s) that may be installed on the site.

For this Case Study, a three-stage, 25,000 rpm axial turbine with a third-stage diameter of 300 mm would be appropriate. A preliminary analysis for the compressor design indicates a radial compressor with a diameter of 0.3 m operating at the same speed. 25,000 rpm would suit this application.

The benefit of this system is clear: the investment in a compressor and a turbine for the purpose of energy storage and recovery can be utilized as a continuous power generation system that conceptually is available in the event the CAES is not available.

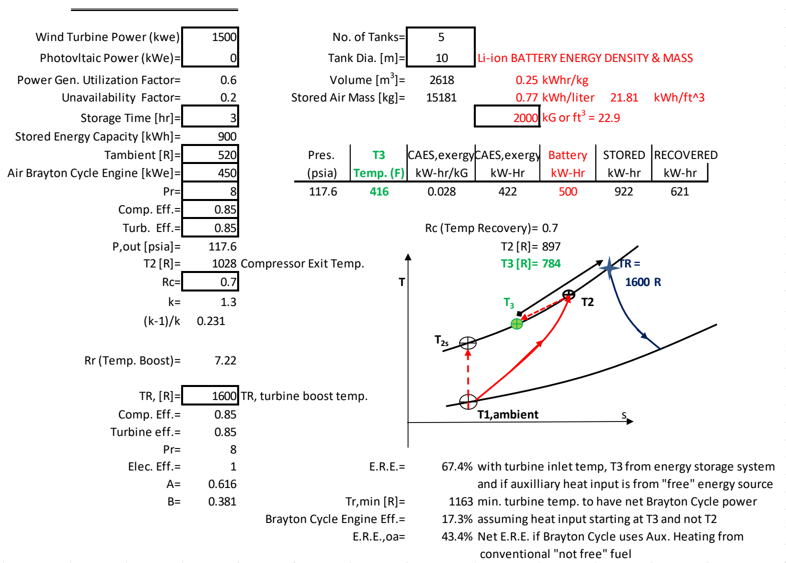
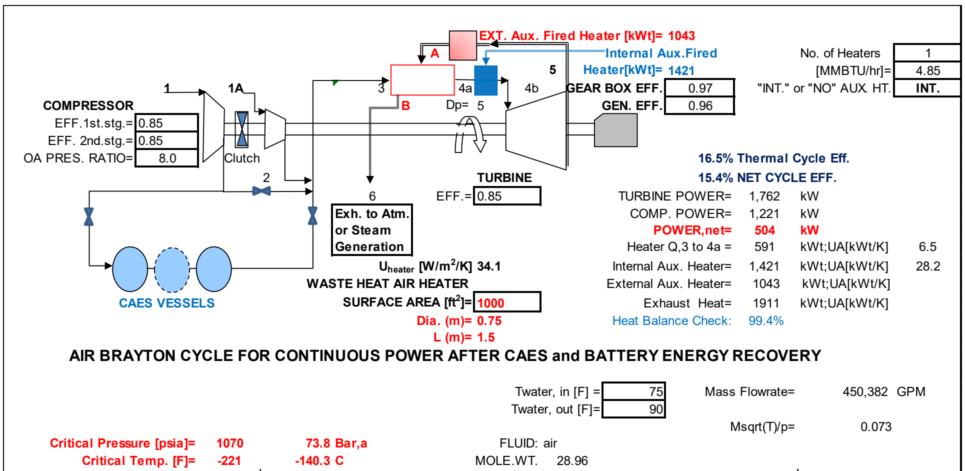


Fig. 8. Summary of data and output from the system analysis



	1	1a	2	3	4a	4b	5	6	A	B
Pres. bar,a	1.0	1.0	8.1	8.1	7.7	7.7	1.0	1.0	1	1
Temp. [K]	299.7	299.7	580.8	580.9	711.6	967.1	587.9	748.3	810.8	748.3
Enthalpy [KJ/kG]	300	300	587	587	726	1009	594	765	834	765
Temp. [C]	26.7	26.7	307.8	307.9	438.6	694.1	314.9	475.3	537.8	475.3
Density [kG/m³]	1.18	1.18	4.85	4.84	3.78	2.77	0.60	0.47	0.44	0.47
Mass Flow [Kg/s]	2.13	2.13	4.25	4.25	4.25	4.25	4.25	4.25	4.25	4.25
Volume Flow [Nm³/hr]	6338	6338	12677	12677	12677	12677	12677	12677	12664	12664
Pipe Size Estimate (mm)	274.5	274.5	191.4	191.7	216.8	253.3	543.8	613.5	634	613

Fig. 9. Proposed Brayton Cycle engine as may be applied to “Cross-over” CAES-Battery Energy Storage

Conclusion

The proposed "cross-over" system enables higher reliability, faster response to transient power loads, and the efficient use of renewable energy, as well as heat recovery from conventional on-site prime mover systems. The system is particularly well-suited for applications where there are numerous but relatively small "power islands" in a Distributed Power System. It is also proposed that the use of an induction generator and not a synchronous generator with the Open, Air Brayton cycle will greatly reduce the controls programming required for maintaining the cycle on line. With an induction generator, synchronizing electrical gear and the monitoring of voltage and frequency is not needed for the Air Brayton power system as this is maintained by the local utility electrical system. Similarly, the power control of the Air Brayton Cycle does not need to involve a speed governor or fuel control valve. The power output is simplified by the having the Air Brayton Cycle operate at its maximum depending on the availability and magnitude of the waste heat and/or bio-fuel. A simple proportional control algorithm will monitor the power output and turbine inlet temperature and reduces the delivery of bio-fuel or waste heat to the heat input heat exchanger of the Air Brayton Cycle.

The next step in CN's study would be a cost analysis for the proposed cycle. However, the extent of the cost analysis would be greatly affected by the use and power output of the wind turbines, photovoltaic solar panel, and/or the type of power prime mover used at the site. The cost analysis must also include a stochastic model of the prevalent wind and/or solar conditions as well as the hourly electric utility power usage at the site or as serviced by the connected utility.

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