Turbomachinery Solutions for Advanced Adiabatic Compressed Air Energy Storage

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Abstract

The growing concern about the role of man-made CO2 emissions with respect to global warming, in combination with the large increase in energy demand spurred by developing nations and a growing global population that is foreseen over the next 15 years have recently turned attention to potential CO2-neutral energy supply solutions.

Grid-compatible integration of typically fluctuating electrical energy sources, like wind and solar power, will be important in order to support the goal to reduce CO2 emissions. However, this will require substantial adjustments to the grids and power plant systems in order to cope with the upcoming new boundary conditions imposed by substantially increased utilization of renewable energies.

To respond to this imperative, GE and RWE Power have started to investigate new technologies for large-scale storage of electrical energy in Adiabatic Compressed Air Energy Storage power plants.

This concept offers efficient, local zero-emission storage based on compressed air held in underground caverns. The compression and expansion of air with turbomachinery help to balance power generation peaks that are not demand-driven on the one hand and consumption-induced load peaks on the other, allowing the optimal use of both traditional fossil fuels and renewables.

Before this concept can be implemented, however, numerous technical issues must be addressed, mainly in the field of turbomachinery and the heat storage device. This paper describes today's technical capabilities of turbomachinery equipment, and evaluates the need for further development based on the requirements of advanced CAES technology. Ongoing development activities are described and initial results presented.

Introduction

The third generation of Compressed Air Energy Storage (CAES) is getting ready to solve a core challenge in renewable energy production. They could act as large-scale storage for electricity that is produced from renewables in a fluctuating and decentralized way and feed it into the network when needed.

Traditional natural energy sources such as wood, coal, gas and oil are available whenever needed. With renewable energies, the situation is different: wind and sun energy supply is unsteady and available also at times when it is not needed. This has forced operators to partially shut down their wind turbines at night, because otherwise they would overload the network. During this time, they could produce valuable, renewable power that could help to balance daily peaks on the grid. The solution is storage of renewable energy in times of surplus and distribution at peak demand. Such storage solutions already exist. The most widely known technology is the hydraulic pumped storage, which has a high storage efficiency of well over 70%. The major disadvantage however for this technology is that it depends on a suitable location.

A solution less dependent on the location is the CAES power plant. Here, ambient air is compressed by electrically driven compressors and stored under pressure in a salt dome. When energy is needed, the storage can release the air used to drive an air turbine to generate electricity and distribute it to the grid.

In the first generation of CAES (Huntorf, Germany, 1978), a significant amount of energy is lost during the process. The heat generated during the air compression process has to be rejected to the ambient before pressurized air can be stored in a subsurface salt cavern for later use. Upon air expansion, heat has to be reapplied to the process by pre-heating the compressed air with the combustion of natural gas to achieve an optimal turbine efficiency.

The second generation of compressed air energy storage uses a recuperator, which utilizes waste heat from the turbines discharge for pre-heating the compressed air reducing the amount of fuel required.

The next logical step is to store the heat produced during air compression and use this heat for air heating during the production phase without any addition of fuel. This so-called adiabatic concept is exactly the approach being investigated by a consortium from RWE Power, GE Oil&Gas and GE Global Research.

The Advanced Adiabatic Compressed Air Energy Storage captures the heat produced at the compression of the air and stores it in a Thermal Energy Storage (TES). Later, the accumulated heat heats up the released compressed air prior entering the air turbine. Since this new process does not need any fuel, this third generation will have zero local emission release, an efficiency close to the hydro pumped storage power plants one, and represents efficient storage capacity for places where hydro plants cannot be built for geological, topographical or other reasons.

RWE – GE Project

Adiabatic compressed air energy storage technology was evaluated previously in the European research project "AA-CAES", which was completed in 2006. The resulting conceptual designs of the four main plant components (compressor, heat storage, cavern and air turbine) helped to identify some key technical risks as well as a substantial need for additional development efforts, particularly for the "adiabatic" compression and the heat storage device. Unfortunately, all endeavors to implement a follow-up project have failed so far.

As a consequence, RWE (previously a partner of the EU FP5 AA-CAES project) and GE agreed to initiate a collaboration on this subject and perform a feasibility study, leveraging GE's broad expertise and product portfolio across energy, aviation, and oil & gas related turbomachinery. RWE's subsidy ESK as well as the German Aerospace Centre, DLR, supported the project with cavern and thermal energy storage (TES) data. Differently to the previous EU project, the work was performed against the background of the desire to install a demonstration plant based on GE's turbomachinery portfolio and the special expertise of ESK for the cavern and of DLR for the heat storage device.

Adiabatic CAES (as illustrated in figure 1) is avoiding the inefficiencies of rejecting the compression heat to the ambient as much as possible by using the TES. Thereby, heat generated during the compression process during the energy storage charging phase is conserved in the thermal energy storage between charge and discharge, and used to heat the cold air coming from the gas storage during discharge prior to entering the air expander. Since no fuel input is needed, this concept is able to achieve significantly higher energy storage efficiencies, and has no associated emissions to the ambient. In the evaluated concept, the outlet temperature of the compressor is maintained above 600°C and the corresponding compression heat is stored in the TES consisting of an arrangement of solid materials, typically ceramic bricks or natural stones. Trade-off analyses between costs, performance and operability of the overall plant were done to define the most economic cavern operating pressure levels, which turned out to be roughly in the same order as the two commercial units in Huntorf and McIntosh.

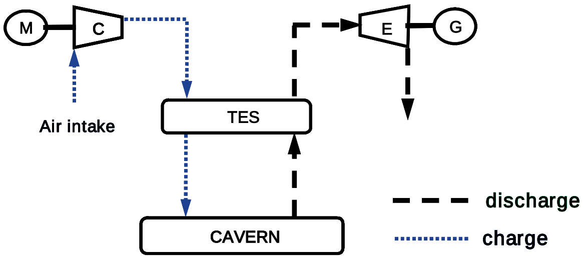

Figure 1 - Basic advanced adiabatic compressed air energy storage process layout

The system design of the AA-CAES plant was aiming at a daily energy storage load cycle. Based on economic assessments by RWE the plant capacity was chosen to be in the range of 1000 to 2000 MWh in order to supply or store power to or from the grid of about 200 MW for several hours at specific plant investment costs of less than 1000 €/kW. Considering participation in the day-ahead spot market as a baseline operating scenario, a high overall plant efficiency of 70 % at nominal operation is targeted, which is significantly larger than the overall plant efficiency of the existing diabatic CAES plants in Huntorf and in Alabama. For further participation in the balancing power market, additional flexibility and performance requirements in part load operation are being assessed.

Compression Phase

A large air flow amount is required during the storing phase, coupled with a discharge temperature above 600°C.
To accomplish such requirements, several compression train architectures were analyzed in order to accomplish the best compromise in terms of performance, operability, reliability, maintenance and cost.

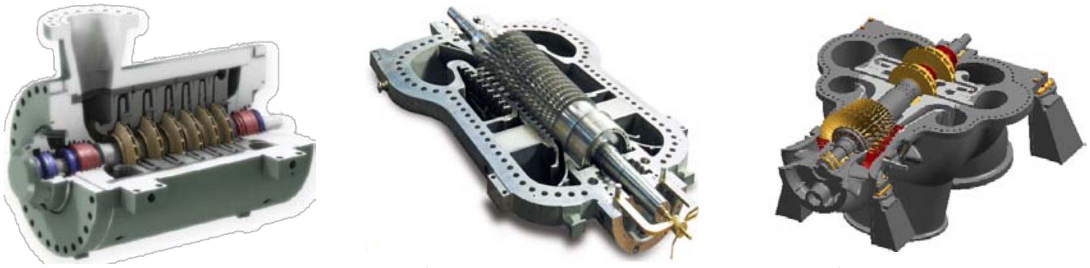

Figure 2 - Barrel compressor (left), axial compressor (center) and axial-centrifugal one (right)

Many arrangements were preliminarily evaluated, leveraging GE Oil & Gas broad experience on process compressors (figure 2). Some included axial compressors or axial-radial compressors, others were composed by two or more radial machines, with a variable number of machines and their sizes, hence a variable number of compression trains depending on plant size selection.

A modular arrangement, composed by more compressors in parallel, was found a promising option to allow high flexibility and plant availability (if one turbomachinery or train is out for maintenance, the plant will continue to work), at the expense of slightly higher footprint and cost.

The final compression train design will include probably an axial or axial-radial compressor, which will include components from the well proven GE Oil & Gas gas turbine axial compressor technology, followed by one or more centrifugal compressors.

One of the possible choices is the use of the GE10 gas turbine axial compressor (scaled up), it will help to meet the high efficiency requirement still allowing a large operability of the compression train, by the use of 3 stages of variable guide vanes. Furthermore, being the axial compressor designed for gas turbines in mechanical drive and generator drive applications, there will be no need to redesign to satisfy daily start operation.

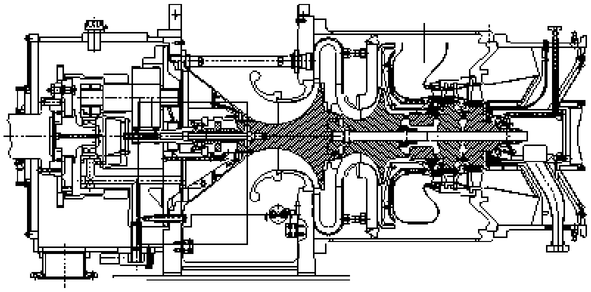

Figure 3 – PGT2 Cross Section

The main challenges in the design of the last centrifugal compressor(s) of the train are:

1) the high discharge temperature needed to guarantee the highest cycle efficiency
2) the compressor's daily cycle operation required by the grid fluctuations.

Due to the high discharge temperature, the off-the-shelf centrifugal compressor design will need to be carefully reviewed and modified. To do so, GE Oil & Gas referenced back to its previous experience on gas turbines and some projects were high temperature compressors where designed.

Examples of those are an 8-stages barrel air compressor designed for an ammonia plant with a discharge temperature of 400°C in operation since 1982 and the PGT2 gas turbine (see figure 3). The compressor of this 2MW gas turbine running at 22500rpm (with very high peripheral speed) is composed by 2 centrifugal stages with a pressure ratio close to 13, and a discharge temperature about 400°C.

First verifications were initiated to identify areas of such further development needs. Among them:

- Bearings. They need to be carefully kept at the right temperature; because of that a special cooling scheme will have to be developed.
- Clearances. As general statement, higher temperature requires to increase the clearances, but it's even true that greater clearances mean higher chargeable secondary flow, hence lower stage efficiencies.
- Rotor Assembly. In a traditional centrifugal compressor, the bonding between impellers and their shaft is guaranteed by the interference between the two parts. The maintenance of the interference may instead not be guaranteed at high temperatures. Therefore different assembly solutions of the impellers/shaft are under evaluation. One of the more attractive proposed solutions consist in the replacement of the standard shrink on

impellers with impellers coupled together by a central tie-rod or various tie-bolts. Such solution is directly leveraged from gas turbine technology.

- Sealing System. Being the outlet temperatures close to those of gas turbine applications, the upgraded arrangement and materials shall be derived from those. Trials to manufacture an impeller capable to withstand very high temperatures are being conducted.

It is important to highlight that all the upgrades proposed are thought to operate in a large range of ambient conditions, while still being able to meet high performance requirements of the AA-CAES cycle.

Expansion phase

To match the fairly large expansion ratio and the cyclic operation of the air turbine (daily start-ups and shut-downs), various expansion train solutions were analyzed, starting from steam turbine or gas turbine technology, single unit or multi-unit train, single flow or back-to-back configurations, each with a wide span and speed of response, giving the operator maximum flexibility to manage the load aspects in an efficient, cost effective and reliable manner. High speed and low speed solutions (from 3000 to 10000rpm) have been considered and compared to obtain the best overall train efficiency.

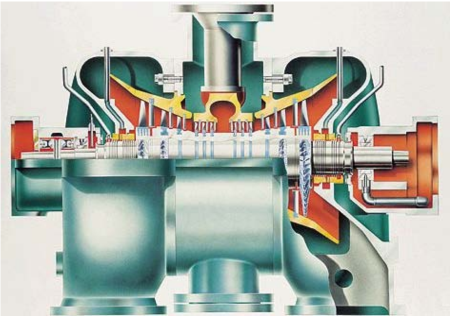

Figure 4 – Back to back Turbine

The back-to-back configuration has the advantage of reducing the axial thrust to be compensated or supported by axial bearings, hence reducing also turbine losses. On the contrary, its mechanical arrangement is more complex (figure 4).

Even if a standard steam turbine derived solution (figure 5) would have an intrinsically lower efficiency versus gas turbine technology and longer start-up time (typically one order of magnitude bigger than a typical gas turbine one), it would still offer the possibility to well manage large mass flow variations, typical for a CAES operation.

In order to improve the efficiency of a steam turbine derived expander, a possible solution would be to modify the standard design with the introduction of IGVs (Inlet Guide Vanes), to replace the steam turbine intake partialization valve.

Furthermore, steam turbine typical inlet temperatures are lower the ones required by AA-CAES application. Steam turbine main components, as the casing and the rotors, have to be assessed and optimized to operate at higher temperatures.

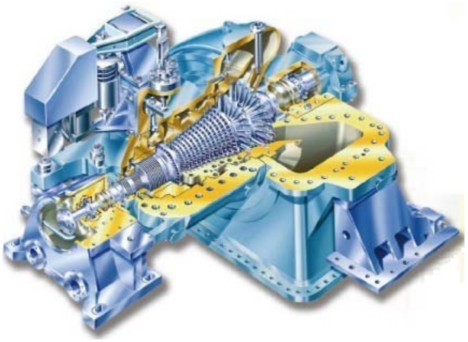

Figure 5 - Industrial Steam Turbine

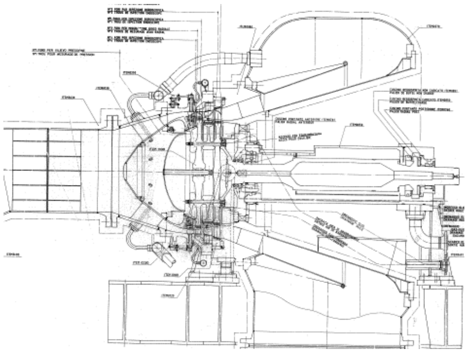

Figure 6 – Axial Expander

A gas turbine derived solution, may offer a higher efficiency, but it would need to be optimized for managing the required large variation of mass flows. Its design features could be leveraged from some successfully fielded expanders based on the PGT25 power turbine architecture. Figure 6 shows, as an example, an expander in operation since 1989 (Ambes), rated at 16MW, running at 5500rpm, with an inlet temperature of ~476°C.

Whichever solution will be pursued in the next preliminary and detail design phases, special attention will be dedicated to allow the air expander protection and its fast maintenance (i.e. reduced leadtime for rotor replacement):

Trip valves:

They are integral parts of the rotating equipment protection system, which is located at the main gas inlet of the turbine to quickly shut off supply airflow when an emergency operating condition occurs.

AA-CAES application requires severe operating condition of these and no off-the-shelf solutions are available today. Studies are ongoing with valve suppliers to understand modifications needed and cost.

Filters:

The expander utilizes previously cavern stored and then TES heated air; this air could contain salt particle, refractory material debris, water droplets, chemical species that are both corrosive and erosive in nature. Design of turbo-machinery in such an environment poses many challenges, the most important among them is to protect the rotating, stressed material from this type of hostile environment.

Air will probably need to be filtered to protect the air turbine. In fact after only a few months of operation, the Huntorf plant experienced serious corrosion problems and high levels of rust were found in the filter upstream of the gas turbine [3]. This caused shutdowns shortly after the start up of the power station. Alabama McIntosh plant had a severe damage in 2005 to the low pressure turbine, some blade were severely damaged, while some blades and nozzles sustained minor or no damage. It was not clear if caused by blade failure or foreign object damage [11].

Such high-temperature filter might be a crucial factor for normal plant operation. Metallic filters for hot gas cleaning exist already in the market, but they are really expensive and not reliable enough: an alternative solution is being pursued by GE Oil & Gas, by the use of more traditional separators and special coatings/hardenings for the gaspath components of the air expander.

Next step of project will include even a detailed flowpath component assessments to evaluate the application of surface hardening thermal treatments, application of hard material layers, anti oxidation coatings and water extraction via water removing groves. GE Oil & Gas will leverage the experience acquired in design, operation and maintenance of steam turbines and turbo-expander for geothermal applications.

Plant Layout

In terms of plant layout, it would be possible to use the same integrated electric motor-generator philosophy of the two existing plants in Huntorf and McIntosh or separated trains for the compression and the expansion phases.

The integrated electric motor/generator solution offers the following advantages:

- the connection between expander and compressor may allow the compressor to be started up and run up to synchronous speed using the turbine (after start-up, air turbine can be shut down). Hence by implementing such an arrangement, the motor-generator needs no special starter.
- A decreased capital cost when compared to the separate drive arrangement, reducing cost of generators, cabling etc.

On the contrary, having a single shaft for compressor, expander and electric motor/generator may imply reduced availability of one of the two phases (compression or expansion) while the other is under maintenance: this may be solved with the introduction of clutches upstream and downstream of the motor-generator.

GE O&G has contacted SSS to investigate this concept.

Plant performance optimization

Together with turbomachinery layouts, several operational parameters were preliminarily investigated, in order to identify the most promising solution in terms of efficiency and operability.

In particular, having an intercooled compression phase with the intercooler located at low pressures increases the overall efficiency. ISO ambient conditions were assumed for these initial performance assessments. Real gas behavior was accounted for using real gas equation of states for air and steam.

During the next steps of the project, efforts will be concentrated around the most promising technical solutions, in order to further optimize plant operability and transient performance.

Further analyses will be carried out using the turbomachinery technology curves to investigate the maximum cycle pressure and temperature, the impact of cavern size on operation and plant efficiency, the compression and intercooler staging, the expansion and heating staging [4].

Waste heat recovery systems addition will be considered as well.

Conclusion

The expected developments in the electricity markets will likely call for extended capacities of electrical storage in the future. Due to a lack of sufficient appropriate sites for hydro-pump storage plants, Adiabatic CAES appears a promising alternative for large scale large capacity power storage solutions.

Compared to earlier approaches, which in principal have already proven the technical feasibility of adiabatic CAES concepts, the RWE-GE feasibility study is based on GE's existing turbo machinery equipment to enhance the prospects of successful realization.

An overall plant efficiency close to the 70% design target seems to be achievable. However, numerous turbomachinery features need to be studied and addressed, mainly linked to the high compressor discharge temperatures.

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