Adiabatic Compressed Air Energy Storage for the Grid Integration of Wind Power

Stefan Zunft, Christoph Jakiel, Martin Koller and Chris Bullough

***Abstract*--An increasing share of electricity from renewable sources is the stated aim of national and European energy policies. However, a grid-compatible integration of this fluctuating energy production to the European electricity systems is expected to be an issue in the mid-term – in particular in coast regions close to offshore wind farms. Large-scale storage technologies can substantially mitigate the expected shortages of balancing and transport capacities. The concept of Adiabatic Compressed Air Energy Storage is a promising candidate, representing a locally emission-free, pure storage technology with a high storage efficiency and a high application potential in Europe. This paper outlines the technology and reports on several areas of its development in the European "AA-CAES" Project. Intermediate results indicate the technical feasibility of the concept and good prospects for its economical viability.**

***Index Terms*-- Compressed air energy storage, Compressors, Turbines, Energy storage, Mechanical energy storage, Thermal energy storage, Wind energy.**

I. INTRODUCTION

THE dependence on imported energy is – besides the reduction of air pollutant emissions – one of the main driving forces for the development and increased use of renewable energy: The EU's energy imports are expected to rise to about 70% by the year 2030 compared to 50% today. This, together with a global energy demand expected to increase by about 30% by that time, makes energy prices likely to further rise and thus to burden consumers and economies in all regions [1].

To offset this development, the diversification of the energy mix towards renewable energy supply is a stated aim of the national and European energy policies: In 2001, the EU agreed on a target figure of 12% for the share of energy from renewables by 2010. To further promote this development, the March 2006 EU Spring Council decided to raise this target to 15% in 2015. The most probable growth is expected from wind energy at offshore locations.

However, recent studies indicate that with high shares of a fluctuating energy production the present grid infrastructure could represent an obstacle to this development. Such grid integration issues have in particular been investigated for the German electricity grid. Thus, current load balancing and transport capacities are expected to fall short after 2015 and beyond [2], [3].

The operation of storage power plants, when performing optimally and cost-effectively, can substantially mitigate such integration issues. They offer a CO_2-neutral supply of peak electricity and allow to make better use of scarce transport capacities.

In principle, pumped hydro storage plants are suitable for the supply of regulating and reserve power. Unfortunately, however, their current capacity cannot be significantly expanded because of geographic constraints. Storage plants based on compressed air in salt caverns are in contrast considered a viable alternative with comparable properties.

II. COMPRESSED AIR ENERGY STORAGE

The idea of storage plants based on compressed air is by no means new. In 1978, a first compressed air energy storage (CAES) plant of 290 MW capacity was built at Huntorf in Germany. In 1991 another 110 MW plant was built in McIntosh, Alabama. Both plants are still in operation today. In periods of low grid load they store electrical energy from base-load power plants or wind farms by means of compressed air. In this process electrically powered turbo-compressors fill underground caverns with compressed atmospheric air. At times of peak load, compressed air is drawn from the cavern, then heated and expanded in a modified gas turbine driving a generator.

Unfortunately, these "conventional" CAES plants still depend on the combustion of gas, for the released air must be heated prior to expansion. This also inherently limits the storage efficiency of the overall process. Because of this, and as a response to developments in terms of fuel prices and CO_2 certification, the so-called *Adiabatic* CAES concept seeks to overcome these drawbacks, representing a locally emission-free, pure storage technology with a high storage efficiency.

The basic idea of the Adiabatic CAES concept is to use a heat storage as a central element of the plant. This allows to supply the heat needed for the expansion process from the otherwise rejected compression heat and thus to avoid a gas

---

This work has been funded by the European Commission under Contract ENK6-CT-2002-000611. This financial support and the EC DGXII's involvement is gratefully acknowledged.

S. Zunft is with German Aerospace Center (DLR), Stuttgart, Germany (e-mail: stefan.zunft@dlr.de)

C. Jakiel is with MAN TURBO AG, Oberhausen, Germany (e-mail: christoph.jakiel@de.manturbo.com)

M. Koller is with ALSTOM Power, Baden, Switzerland (e-mail: martin.koller@power.alstom.com)

C. Bullough is with ALSTOM Power Technology Center, Leicester, UK, (e-mail: chris.bullough@power.alstom.com)

combustor: During the charge period the heat is extracted from the air stream and stored. When energy is required by the grid, the compressed air and heat energy is recombined and expanded through an air turbine (Figure 1 below).

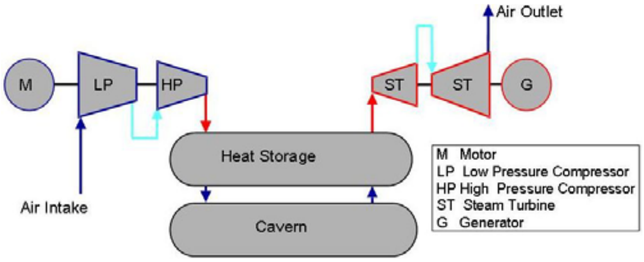

Fig. 1. Function diagram of an adiabatic compressed air energy storage power plant in single-stage configuration (basic layout)

Adiabatic CAES cycles have been discussed since the beginning of the 1980's. However, the technical specifications were seen as too ambitious at that time. Today's deregulated electricity markets, facing increasing cost of primary fuels and penalties for emissions and thus an increased penetration of fluctuating energy from renewable sources, lead to new assessments.

The EU-funded AA-CAES Project (Advanced Adiabatic Compressed Air Energy Storage) is investigating the technical potential of adiabatic technology, both for centralised and distributed storage; and has developed economic models able to predict market potentials of storage technologies. Thermo economic model efficiencies of >70%, and power related investment costs of <800€/kW have already been calculated for the 300MW Central Solution. Now reaching its conclusion, the Project has developed a viable conceptual design for the economically and technically most promising product based on AA-CAES technology.

III. TARGET APPLICATIONS AND SYSTEM DESIGN

Detailed studies of the economic basis for energy storage based on adiabatic CAES have been performed.

In order to ensure the market closeness of the system under development during this project, the technical investigation work is continuously accompanied by economic analyses. The individual technical options are evaluated not just in terms of their effects on efficiency and costs but also on their influence in respect of expected electricity sale revenues. This additional feedback accelerates the development process of market-ready total systems, which because of the large number of degrees of technical freedom is a complex task.

Qualitative descriptions of the potential markets for the usage profiles are the basis of such considerations. Here, the existing and projected generation and storage technologies in the target markets, their grid infrastructure, load profiles and size are significant factors. According to these, the Netherlands is particularly promising, with Germany, Belgium, Spain and Great Britain representing other promising locations [4].

Preliminary specifications for the design and interaction of the basic components (compressor, thermal store, cavern and air turbine) and the concept-specific components (e.g. intercooler, after-cooler) as well as the required operational strategy of the plant are therefore worked out in accordance with the most favourable sales revenues in which target market requirements and electricity trading prices are set and the investment costs are determined in a techno-economical iteration.

The three broad implementation scenarios are indicated in Table 1.

TABLE I
TARGET APPLICATIONS OF ADIABATIC CAES

Modus	Target application/ Strategy of Operation	Typical Size [MW]
Central Storage Device	Revenues from spot market price spreads and system services	300
Decentral Storage Device	Large windfarms: increase of full load hours, ancillary services, peak price sales	150
Island Solution	Combined wind/CAES system in island grid: saving of grid connection or gas turbine. Increased full load hours of wind turbines	10

Intermediate results of the Project suggest that it is an Adiabatic CAES Plant of about 300 MW capacity that has the best prospects, as significant economies of scale in combination with high efficiencies in the range of 70% and beyond can be achieved. Local flexibility opens up adiabatic CAES technology many potential applications, such as storage of wind energy close to the production site or storage of power surplus sited at main grid nodes. Further more, project results indicate a market potential in ancillary services, suggesting that Adiabatic CAES may be able to contribute reactive power for voltage control, tertiary reserve for frequency control and a black start ability.

An Adiabatic CAES plant of smaller size, next to a wind park, can increase the utilization of the wind energy by storing electricity at times when network congestion or the lack of power demand restrict the power feed into the grid. Without storage this electricity would have been lost. In addition, in countries where operators of wind parks units are charged for feed-in deviations, a storage plant can be used in order to hedge against unpredicted fluctuations of its power feed-in and thus help to avoid high costs for balancing power.

The remote island solution is typically a Mediterranean island disconnected from the mainland grid where storage increases wind energy utilisation, and saves the cost of grid connection or the need for an additional, separate gas turbine/ diesel generator.

The envisaged capacities are between 10 MW (island solution) and 300 MW (central solution). The key thermodynamic parameters of pressure and temperature for component design are limited to approx. 200 bar / 620°C, see Table II.

TABLE II
NOMINAL OPERATING DATA FOR TWO INVESTIGATED ADIABATIC CAES CYCLES

Configuration	Single-stage 300 MW	Two-stage 10 MW (island grid)
Capacity [MWh]	1800	120
Output [MW]	300	10
Pressure level [bar a]	100	15 / 150
Mass flow rate (charge) [kg/s]	220	20
Mass flow rate (discharge) [kg/s]	550	20
Intake temp. TES (charge) [°C]	620	450 / 450
Intake temp. TES (discharge) [°C]	20	20
Outlet temp. TES (discharge) [°C]	600	420 / 420

The areas of application for this type of power plant, all including the provision of tertiary regulation services, require a completely new fast start-up concept that allows the turbine/compressor train to be brought to full load within a few minutes. These additional operational requirements are also part of the optimisation and design process.

IV. DESIGN REQUIREMENTS

Although the technologies for the individual system components are available in principle, there are demanding requirements in terms of the actual design. Just as demanding is the optimisation of the free parameters for the overall system in terms of cost and efficiency aspects.

The design of the compressor train must be based on the needs of an adiabatic compression rather than the usual isothermal compression achieved by intercooling and aftercooling. The combination of high pressures and temperatures in the last stages together with the demand for high levels of efficiency and short start-up times requires solutions that are not covered by conventional compressor design.

The difficult design requirements for air turbines that are derived from steam turbines are high levels of efficiency over the entire operating range and quick start-up times to be significantly shorter than with current machines.

For the thermal energy store – a central element of the system – there are almost no technical exemplars with comparable operating conditions. This demands a basic screening of the applicable storage technologies. High pressure and temperature levels, large heat rates and temperature differences together with the capability to meet the operating conditions of compressor and turbine are – together with cost aspects – the determining specifications.

The storage of compressed air in underground caverns represents the state of the art. The various AA-CAES concepts require flexible designs in terms of storage volumes, pressure fluctuations and storage rates. Maximum overall efficiency levels require minimised pressure losses during storage and release from storage. A typical cavern size for a central storage is 150000 to 500000 m^3.

Several options exist for the creation of such caverns, where the solution mining of salt caverns is the most cost-effective one. Suitable salt formations are found in a broad band over much of northern Europe and locally in other areas of Europe.

V. COMPRESSOR TRAIN

Industrial compressors (e. g. Fig. 2) are already used at the two existing CAES plants, and due to their modularity and flexible structure are likely to feature in Adiabatic CAES, too. However, such industrial compressor trains are generally intercooled, and whilst high temperature compressor technology exists in for example gas turbines compressors, this is at generally lower pressures. Therefore, a new high pressure/ high temperature design is required, based on industrial compressors and allied to high temperature technologies of steam turbines and gas turbines. Short starting times, required for balancing energy have led thereby to the need to consider carefully the thermal ramp rates within the components.

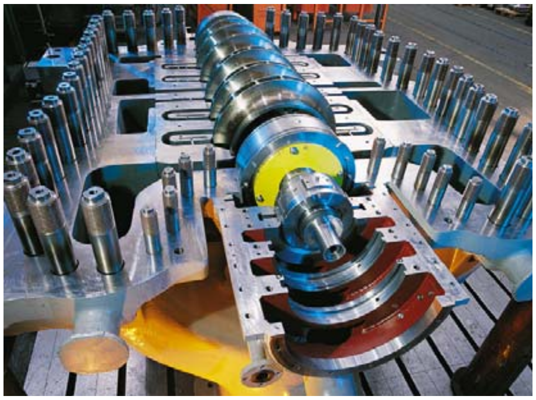

Fig. 2. Single shaft centrifugal compressor for industrial applications

In the first phase of project work various train concepts were designed and analysed for different power plant basic concepts and sizes, based on the economic scenarios described above. The arrangement of compressor casings, intercoolers and thermal storage devices as well as the compressor type and size and the number of stages are significantly affected by the power plant process and need to be re-determined for each individual scenario.

The most promising layout so far includes an intercooled low pressure compressor of axial type, whose output is led to single-shaft centrifugal machines with high temperature design (see Fig. 3). Multi-shaft centrifugal compressors are envisaged as an alternative, especially for small plant scaling. Although the adiabatic approach theoretically does not include intercooling, a realistic concept needs a small amount of intercooling to decouple charging pressure from the end temperature.

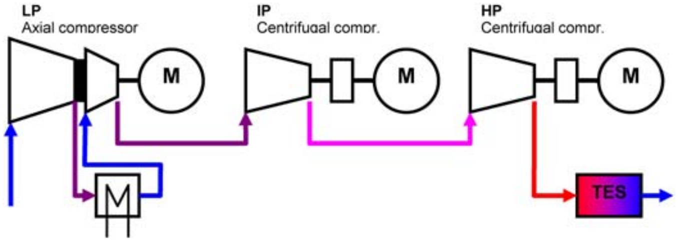

Fig. 3. Basic compressor train layout for a central storage in single stage configuration

Now, the available centrifugal compressor design principles are being developed further considering the requirements formulated here, e.g. using steam turbine casing concepts. In this development process a number of aspects, including materials, strength issues, shaft-hub connections and thermal expansions of the overall machine, are being investigated, and in all areas the extremely transient operation is taken into account.

VI. HEAT STORAGE

The thermal energy store (TES) is central to the operation characteristics of the plant and its performance is of decisive importance for the level of efficiency of the overall process. For the applications under consideration a thermal storage capacity of up to 2400 $\mathrm{MWh}_{\mathbf{th}}$ at high heat extraction rates and high uniformity of outlet temperature is required to allow a discharge cycle time of 4-12 hours. At the same time the temperature losses during charging and discharging need to be kept low to achieve high process efficiency levels.

The basic design concepts of the store allow free scope that was investigated, particularly in terms of costs and technical risks: Amongst the potential technologies, solid and liquid media thermal stores were investigated in greater detail. With storage media that have direct contact between airflow and storage material and thus avoid the use of heat exchangers, a large heat transfer surface can be provided particularly economically and therefore low heat transfer losses can be achieved. On the other hand this scenario requires a pressurised storage concept, which involves significantly increased costs for the container and requires innovative concepts for this component. Still, after a technology assessment this option turns out to be the most favourable solution, Fig. 4.

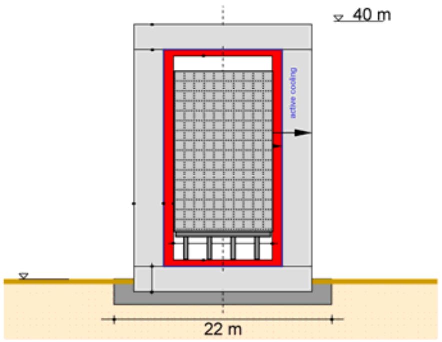

Fig. 4. Thermal energy store using a solid inventory in a pressurised containment

Solid stores or "regenerators" can be used with a large number of storage materials, e.g. natural stone, concrete, fire-resistant material and metals. These materials span a wide range of parameters in terms of thermo-physical characteristics and costs and thereby open up attractively priced design options. Durability aspects demand special attention here, for the storage has to withstand the operation conditions over a 30 years lifetime in daily cycles, Table III.

TABLE III
SHORTLIST OF CONCEPTS CONSIDERED FOR THE THERMAL ENERGY STORE

	Solid TES				
Concept	Rock bed	Cowper-Deriva-tive	Concrete Walls	Cast Iron Slabs	‚Hybrid' PCM
	direct	direct	Direct	direct	direct
Inventory Material	Natural stone	Ceramics	Concrete	Cast Iron	Ceramics or Salt

As a result of preliminary material tests, the range of candidates for the inventory has been narrowed to a few options that well endured the exposure to frequent cycles in a hot and humid atmosphere.

Special focus was on the assessment of various solutions for the pressurised containment. As a result it turns out that a modular setup of cylindrical structures made of pre-stressed concrete is an advantageous solution. A typical overall usable volume is 10,000 m^3 for a central storage plant.

Further work was directed at the design concepts for the high-temperature insulation, the active cooling of the structure and the arrangement of the inventory material.

VII. TURBINE

In general, the role of the air turbine is to convert the hot pressurised air into mechanical energy to drive a generator. For maximum efficiency early studies have shown that the turbine should be able to adapt to a range of pressures and mass flow from the cavern. Due to pressure variations in the cavern during operation and a load range from 40% to 100% the mass flow is likely to vary up to a factor of 3 and existing steam turbine control methods such as valve throttling are unattractive due to their efficiency losses. Therefore, adaptive stages, common in gas turbines, are being introduced into the air turbine designs, leading to the so-called sliding pressure air turbine. The main challenges for the designer have been to develop such stages at the very high pressures and relatively high temperatures. To proof the feasibility of this special design, a stress analysis with different load cases has been performed for the most critical parts. This analysis shows that the mean stress levels remain within creep limits.

Besides the introduction of adaptive stages, the turbine has to be optimised for fast start up in order to allow for participation in the regulation market. The basic requirement for the provision of tertiary reserve is a “go on-line” and “power-up” in less than 15 minutes. This is an order of magnitude faster than conventional steam turbines and could cause large thermal stresses and severely limit the turbine's life. To avoid this, a so called "warm keeping concept" has been developed that makes use of heating the rotor during periods of non-operation to temperatures close to those experienced during normal operation. A thermal analysis including LCF lifetime assessments has shown that this warmkeeping concept fully satisfies the requirement for fast start up and shut down without limitation of the design number of cycles (10'000).

To optimise power density, efficiency and costs the turbine design is "single casing", "single flow" up to a power level of 300MW, Fig. 5.

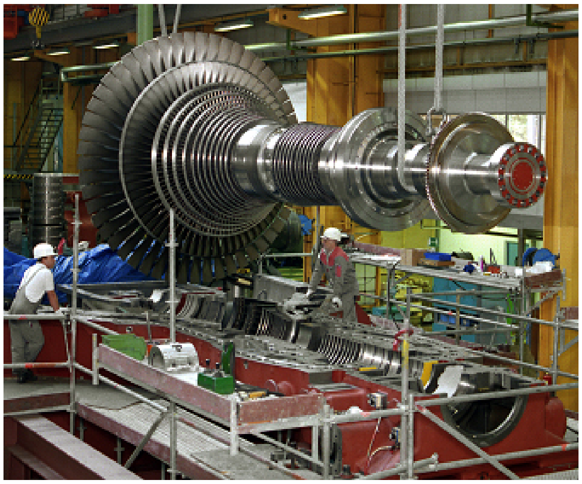

Fig. 5. Single casing, single flow turbine with high power density

VIII. SUMMARY AND CONCLUSIONS

To sustain a development towards a secure energy supply with a high share of renewable energy, its large-scale integration into the grid must be faced. Efficient and cost-effective electricity storage technology can play a key role here.

Adiabatic CAES plants are particularly well suited to substantially contribute to this development. They offer an emission-free storage of electricity with a storage efficiency comparable to pumped hydro. Different from the latter, it has a high application potential in Europe.

The EU project AA-CAES investigates the feasibility and performance of this technology and develops concepts for the most promising plant configurations and component designs. To accelerate the development of viable concepts, the work is accompanied by market studies.

Some of the findings of the project work include: Large-scale, central storage devices are best configured in a one-stage setup with moderate pressure levels. Such plants can reach storage efficiencies of 70% and beyond. This target application also has the best market prospects. Target applications with smaller capacities can profit from a two-stage configuration.

For all of the components suitable technical solutions could be identified. Though Adiabatic CAES is based on existing technology, its component specifications substantially differ from those of conventional CAES. For some of the components the technical realisation represents a challenging task. Continued development is expected to allow first demonstrations in the near- to mid-term.

Studies of the geographical and technical prerequisites reveal a large application potential in the European regions of future wind energy production. Preliminary market studies indicate good market perspectives for most countries in these regions.

IX. ACKNOWLEDGMENTS

The AA-CAES Project is comprised of 19 different partners, and the authors wish to express thanks for their co-operation and contributions to the Project, which this paper summarises. They are also pleased to acknowledge the support and involvement of the European Commission DGXII through the research contract ENK6-CT-2002-000611

X. REFERENCES

[1] European Commission: Green paper. A European strategy for sustainable, competitive and secure energy. Brussels, 2006

[2] DENA (Ed.): Energiewirtschaftliche Planung für die Netzintegration von Windenergie in Deutschland an Land und Offshore.. www.dena.de

[3] Brischke L.-A., Hoppe-Kilpper M., Tiedemann A.: Regel- und Reservebedarf bei Ausbau der Stromerzeugung mit regenerativen Energien bis 2015. ew No. 105, Vol. 1-2, 2006

[4] Gatzen C.: Modellgestützte Wirtschaftlichkeitsanalyse innovativer Speichertechnologien am Beispiel eines adiabaten Druckluftspeichers. 8. Symposium Energieinnovation „Erfolgreiche Energieinnovations-prozesse", Graz, Austria 2004

XI. BIOGRAPHIES

Stefan Zunft studied at the Universities of Hannover and Stuttgart, graduated as a mechanical engineer from the University of Stuttgart in 1991 and received his Ph.D. degree in 2002.

In 1991, he joined the Institute of Technical Thermodynamics of the German Aerospace Center (DLR). His research interests and his previous work in numerous international projects have been focussed on solar thermal energy and thermal processes in rational energy use. Currently, he is a research area manager of the industrial heat transfer and heat storage activities.

Christoph Jakiel studied at the University of Federal Armed Forces in Hamburg (Germany). He graduated as mechanical engineer in 1994 and completed his PhD in 1998.

Currently, he is development engineer and R&D project manager at MAN TURBO AG. His work focuses on the development of centrifugal compressors and turbines.

Martin Koller graduated as Physics Laboratory Assistant in 1967. After that, by continuing education he specialized in I&C and nuclear safety.

1982-91 he led the control and protection design for the bunkered emergency heat removal system and in 1994 he was acknowledged as engineer for nuclear safety in the nuclear power plant Beznau.

After joining ALSTOM in 1995 (ABB at that time) he was technical coordinator for refurbishment and upgrade of steam power plants until he moved to project management for diabatic CAES in 2001. Since 2006 he is group leader for system integration and process engineering in the steam turbine R&D department.

Chris Bullough graduated as a Metallurgist from the University of Birmingham in 1980, and gained his PhD from the University of Sheffield in 1987.

Joining AEA Technology in 1980, he also worked at ERA Technology moving to European Gas Turbines in 1995. He now works within ALSTOM Power at the Technology Centre in Rugby, where he is Head of the Design Support Group. His interests include materials technology developments for steam and gas turbines, and in providing metallurgical support of new and existing power plant.