Advanced Adiabatic Compressed Air Energy Storage for the Integration of Wind Energy

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Abstract

The large-scale generation of electrical wind energy is planned in many countries, but the intermittent nature of its supply, and variations in load profile indicate a strong requirement for energy storage to deliver the energy when needed. Whilst pumped hydro storage, batteries and fuel cells have some advantages, only compressed air energy storage ("CAES") has the storage capacity of pumped hydro, but with lower cost and less geographic restrictions. Existing *diabatic* CAES plant lose heat energy from the cycle during compression, and which must be re-generated before the compressed air is expanded in a modified gas turbine. *Adiabatic* CAES, on the other hand, uses a separate thermal energy store during the compression part of the cycle. During the generation part of the cycle the thermal energy store is used to reheat the air, which is then expanded through a sliding pressure air turbine. This storage technology offers significant improvements in cycle efficiency and, as no fuel is used, it generates no CO_2. This paper describes the work of 19 partners within the "AA-CAES" Project (Advanced Adiabatic – Compressed Air Energy Storage : EC DGXII contract ENK6 CT-2002-00611) committed to developing this technology to meet the current opportunities in the market.

Keywords: Energy storage, adiabatic, CAES, grid integration, wind energy, balancing power, economic modelling, electricity markets.

Introduction

The proportion of electrical energy generated from wind and other renewable sources is set to rise significantly in many countries. The goal for the European Commission is 20% by the year 2020 [1,2], and the largest proportion is likely to be contributed from offshore wind farms. Whilst it is reasonable to assume a steady evolution in wind turbine capacity, efficiency and reliability, the major obstacles to utilising a high proportion of wind energy lie in its intermittent nature, and its integration into the grid. Put simply, the power put onto the grid must exactly match the load required by industry, businesses and domestic consumers. Even without the introduction of further renewable energy sources, some national grids are experiencing problems associated primarily with load balancing, indicated by the price volatility in their electricity markets.

Prior to the advent of the renewable energy sector, balancing power was typically provided by peak-lopping gas-turbines (sometimes termed hot-spinning reserve, as the turbines are kept at or close to their optimum operating temperatures to improve availability, and to avoid damaging thermal cycles). Where possible, pumped hydro plant is also used, having excellent characteristics for balancing by both extracting from, and supplying electrical energy to the grid. Unfortunately, however, the capacity of pumped hydro storage is constrained by geography, and in most developed countries there is only limited prospect for further development.

Most other forms of electrical energy storage (batteries, flywheels, supercapacitors, fuel cells) have limited storage capacity, and are more suited to providing distributed storage or for voltage stabilisation. However, in 1978 the world's first compressed air storage plant ("CAES") of 290MW capacity was built at Huntorf in Germany [3]. In 1991 a 110MW plant was built in McIntosh, Alabama [4], and several other sites throughout the world are being considered for development. In a CAES plant, excess power on the grid is used in an electric motor to drive a compressor. The compressed air is cooled, and used to fill a large cavern to a pressure of typically 60-70Bar. At times of peak demand, compressed air is drawn from the cavern, heated and then supplied to a modified gas turbine. The energy from the compressed air, together with that supplied from combustion processes drives the turbine stage, and is thus converted by an electrical generator and re-supplied to the grid. In some ways, the cycle is similar to that

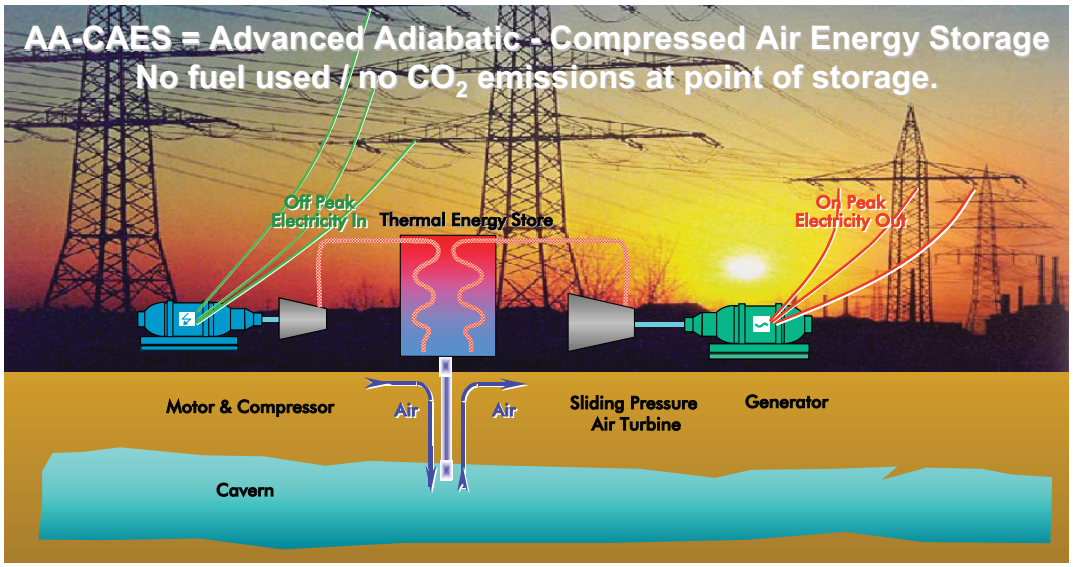

Figure 1. Schematic arrangement of the main elements of an Adiabatic CAES plant

of a gas turbine, except that the air from the compressor is cooled, stored and reheated before it is burnt in the combustor and expanded in the turbine.

Adiabatic CAES Concept

The storage efficiency of the *diabatic* CAES plants just described is reduced by cooling of the air before it enters the cavern, and by reheating the air prior to burning it with the fuel. In the *adiabatic* cycle described below the heat energy is extracted and stored separately before the compressed air enters the cavern (Fig. 1). When energy is required by the grid, the compressed air and heat energy are recombined, and expanded through an *air turbine*. This *adiabatic* CAES benefits from higher storage efficiencies and, notably, zero CO_2 emissions and is being developed within the "AA-CAES" Project (Advanced Adiabatic – Compressed Air Energy Storage), funded by the European Commission under contract ENK6 CT-2002-00611, reference [5].

The favourable characteristics of Adiabatic CAES cycles have been known for about 30 years. With the increasing penetration of renewables into the energy market leading to opportunities in market, and the advances in knowledge in diabatic CAES in the meantime, the time is now right to develop the technologies that will enable Adiabatic CAES to be built. The AA-CAES Project addresses: adiabatic or quasi-adiabatic compressors able to deliver compressed air at sufficiently high temperatures (~650° C) and pressures (~ 10 to 20 MPa); heat storage devices enabling effective adiabatic CAES technology; expansion turbines enabling fast start-up, high power-ramps, and high efficiency over a broad range of inlet pressures. It couples these component developments with generation of basic data allowing for accurate process simulations and traceable performance tests for turbo machinery and heat storage devices; a reliable economic model describing all benefits of electrical-energy storage; and study of geological and geographical constraints.

The approach is to evaluate very different technical solutions in a first phase, to concentrate on 2 - 3 technically and economically viable solutions for different market scenarios in a second phase and to establish a conceptual design for the economically most attractive product in the third phase of the project. Emphasis early in the project is given to the critical issues of market and economic analysis and to the critical technical issue of the heat storage device.

Economic Basis for Energy Storage

There are potentially many requirements for mass energy storage within the grid of the developed countries within Europe. Perhaps in an ideal situation a storage technology with zero losses could be used to allow plants to run at full capacity, balancing the load and distribution of power onto the grid. Even without a truly loss-less storage technology, mass storage of electrical power can ease congestion on the grid, and reduce the need for additional transmission grids. Storage also flattens the load demand curve, and therefore enables thermal power plants at medium load to operate at duty point with maximum efficiency.

Higher percentages of electricity being generated from wind power in particular, leads to less predictability of supply of wind power onto the grid, that can change by a few hundred MW in less than one hour, and by up to a GW in a day. (Source: E.ON, data from December 1999.) In the deregulated markets in Europe the effect of increasing percentages of wind power is clearly evident in the market price in electricity that can vary by a factor of 10 within

Modus	Strategy of Operation	Size
Central Device	Revenues from Spot Market Price Spreads and System Services	300 MW
Decentral Device	Large windfarms Increase of Full Load Hours of WEG Ancillary Services Peak Price sales	150 MW
Remote Island Solution	Combined Wind/CAES System on autonomous Island; savings of grid connection costs or Gas Turbine Increase of Full Load Hours of WEG	30 MW

Table 1. Strategies for Adiabatic CAES (WEG = Wind Energy Generation)

the day. The spot market volatility is increased due to the fluctuating power output from installed wind power units; this effect is enforced with higher penetration of WEG in a power system. Additionally, the demand for regulating and reserve power for frequency control is enhanced significantly with a higher percentage of non-dispatchable power sources.

Within the AA-CAES Project we have performed detailed studies of the economic basis for energy storage based on adiabatic CAES, and the three broad implementation scenarios are indicated in Table 1. Within a central Adiabatic CAES plant revenues are raised from the price spreads, and daily / weekly / seasonal storage scenarios were considered. With a decentralised plant, the storage is performed at or close to large windfarms, utilising a greater number of full load hours of the wind farm, providing ancillary services, and the possibility of selling the wind power at the peak price. 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.

Present studies within the Project suggest that it is the central Adiabatic CAES plant that has the best prospects commercially, as significant economies of scale can be achieved and higher efficiencies. The central Adiabatic CAES plant can also provide storage of wind energy, yet be close to the load or sited at nodes in the grid, offering good flexibility in its usage. Further more, our work has shown a market potential in ancillary services (depending on

Ratings from +++ to ---	Baseload Techn.	Peakload Techn.	CHP Must-run	RES Non-dispatchable	Storage	Interconnector	Load Structure/ Volatility
Germany	+++	+	++	+++	-	--	0
France	+++	-	---	--	-	-	0
Italy	---	-	+	0	---	-	0
Spain	++	++	+	++	--	--	0
Netherlands	--	++	+++	+	+++	++	+++
Belgium	++	++	0	--	-	0	++
Sweden	+++	++	+	--	-	---	--
Norway	--	--	--	--	---	+	--
Denmark	--	-	+++	+++	++	---	--
UK	++	++	-	0	-	+	0
Alpine	++	--	++	-	---	--	0

Table 2 Factors affecting the opportunities for adiabatic CAES in several European countries. [Ranging from +++ (highly favourable), through 0 (neutral influence), to --- (highly unfavourable)]

the eventual plant characteristics), suggesting that Adiabatic CAES may be able to contribute reactive power for voltage control, secondary or tertiary reserve for frequency control, and a black start ability.

A decentralised Adiabatic CAES plant, next to a WEG unit, 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-in into the grid. Without storage this electricity would have been lost. In addition, in countries where operators of WEG units are charged for feed-in deviations, like Spain (depending on the chosen tariff system) or the UK, the decentralised plant can be used in order to hedge against fluctuations of his power feed-in and thereby avoids high costs for balancing power. The remote island solution is also thought to be commercially viable, particularly where overall generating capacity falls below 5MW.

The UCTE[1] countries within continental Europe, have energy markets that differ markedly for many reasons, including: the generating mix (type, age, percentage of renewables); load patterns (industrial and domestic use, requirement/availability of different heating systems such as must-run combined heat and power); geographical factors (extent, capacity and maturity of grid, availability of pumped hydro storage); interconnectivity (links to other national grids, contracts etc.); and political initiatives eg to encourage renewables use. Such matters have been studied in detail with respect to market opportunities for Adiabatic CAES [6] and are summarised for several countries in Table 2. The factors that improve the opportunities for Adiabatic CAES are:

- Cheap base load technology tend to result in higher price spreads
- Expensive peak load technology similarly boosts the price difference
- Must-run technologies, in particular combined heat and power (CHP), lead to lower off peak electricity prices
- Non-dispatchable power (wind, solar) production increases market volatility due to uncertainties in supply.

The factors that reduce the opportunities for Adiabatic CAES are:
- Availability of rival storage technologies, for example pumped hydro storage.
- Availability of import/export capacities from other grids will reduce price spreads.

It will be clearly seen that the Dutch electricity market is the most promising for mass storage whereas, for example, Italy, Norway, Sweden France and the Alpine countries are much less promising. A series of economic calculations have been run using the national spot market prices for the years 2001 and 2002, and a range of storage capacities, Figure 2. The calculations demonstrate that the opportunities are greatest on the Dutch market, with a plant storage capacity of about 3000MWh.

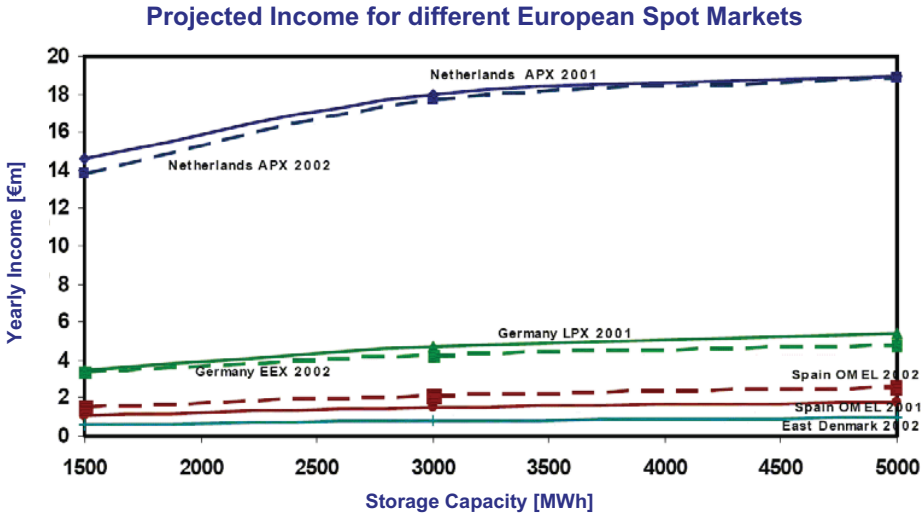

Figure 2 Calculations of the Income from European Spot Electricity Markets and different Storage Capacity

[1] Union for the Co-ordination of Transmission of Electricity

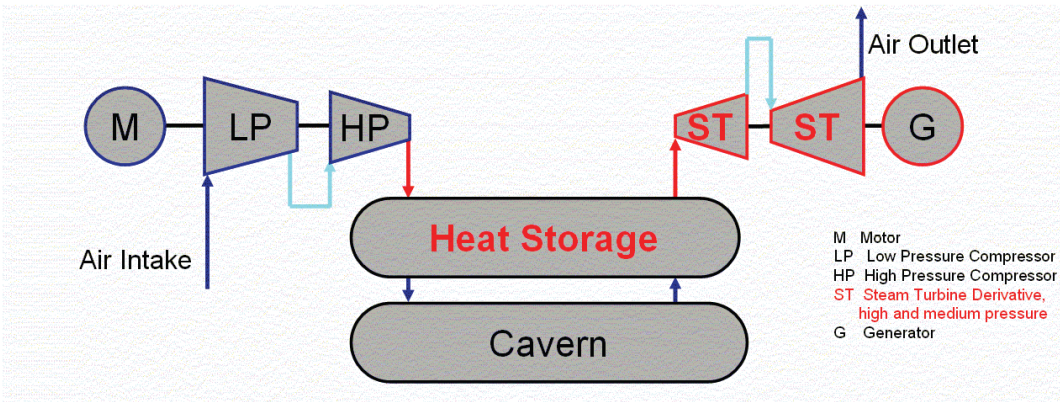

Figure 3 One of several Adiabatic CAES cycle concepts considered within the AA-CAES Project

The Development of Adiabatic CAES

The research into the user requirements and market conditions for Adiabatic CAES have continued alongside detailed research into the optimum arrangement of plant, and the design of the individual components. With efforts concentrating on Central Device of 250 to 300MW capacity, a full set of cycle simulation studies have been carried out to calculate cycle characteristics and performance. For example, one stage and two stage designs have been examined (for example Figure 3), with and without compressor intercoolers, with caverns of different sizes, and with differing storage statuses, and operational requirements and calculations performed to find the cycle with optimum flexibility, highest efficiency and lowest capital cost. Furthermore, the effects of uncertainties in the input parameters have been evaluated using performance sensitivity analyses.

Of course, the four main components of an Adiabatic CAES plant share many of the characteristics of existing or planned (diabatic) CAES plant. However, the specification for each component is intimately related to the load and operational profile of the storage device (capacities, ramp rates etc). The following sections are therefore intended to summarise the development goals, current work and results highlighting similarities and differences compared to existing CAES technology. The project partners are particularly well placed to develop this technology, as together they are world leaders in diabatic CAES, having designed and built the first plant at Huntorf[2], and with the recent development of improved compressor, an industrial gas turbine and recuperator with higher cycle efficiency available for new installations.

Compressors

Industrial compressors (eg Figure 4) are already used at the two existing CAES plants, and due to their modularity and flexible structure are likely to feature in Adiabatic CAES. However, such industrial compressors 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 (particularly materials) e.g. of the steam turbine.

Within the AA-CAES Project, a range of compressor train concepts has been studied, based on the economic scenarios and end-user requirements described earlier. These have particularly affected the size, capacity and ramp rate of the compressor during the charging cycle. Short starting times, required for balancing energy have, of course, led to the need to consider carefully the thermal ramp rates within components. Results from the initial studies are now being taken forward in greater detail to optimise such matters as low pressure intercooling, and compressor layout. The most promising design so far includes an axial flow low pressure compressor, whose output is intercooled, and then delivered to a radial flow high pressure compressor. Whilst developing new design principles, materials choice, stability, disk-rotor fixing methods, and overall thermal behaviour over a range of operational profiles are currently being considered.

[2] At Huntorf the compressor was made by Sulzer, now part of MAN TURBO AG; the turbine was made by ABB Switzerland, now part of ALSTOM; and the cavern was mined by KBB GmbH, who are now part of DEEP Underground.

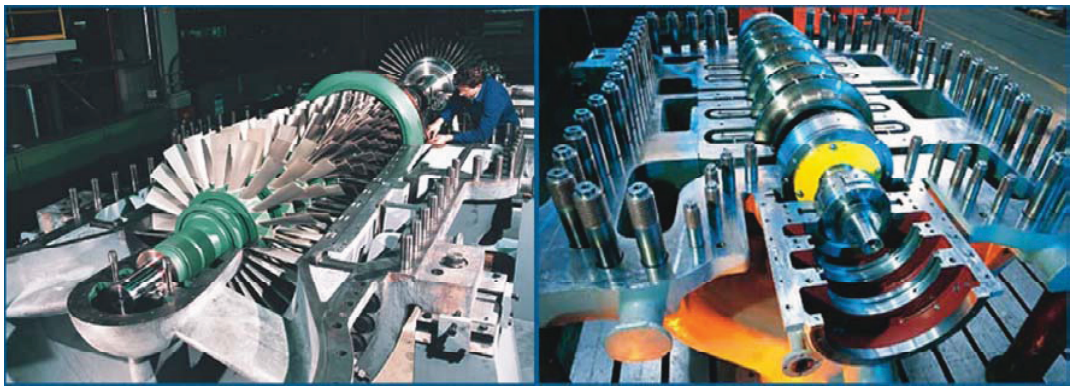

Figure 4: Examples of a current axial compressor (left) and centrifugal compressor (right). (Source: MAN TURBO AG)

Thermal energy store

The thermal energy store (TES) is central to the operation characteristics and overall efficiency of the Adiabatic CAES plant. A thermal storage capacity of 120-1200 MWh(thermal) with high heat extraction rates, and high consistency of the outlet temperature over a generation cycle of 4-12 hours has been considered. A full range of thermal storage devices has been considered (Table 3) , including phase-change, high heat capacity solid and liquid media and hybrid systems. Phase change methods have been discounted since no single system can cover the range of 50 to 650°C.

Of particular relevance to Adiabatic CAES cycle is the need for a pressurised or non-pressurised container for the thermal store. In liquid systems, a heat exchanger can be used, for example obviating the need for a large pressurised container for the liquid but adding cost and complexity through the design and build of the heat exchanger a dual media approach (salt and oil) must be used to cover the temperature range from 50 to 650°C. There is some experience of liquid TES in steam plant (for pre-heating) and solarthermal power stations. Either a "Thermocline" – that is, a single tank with a temperature gradient, or a two tank system with varying liquid levels is used.

Direct contact between the pressurised air and the storage medium in a solid TES has the advantage of a high surface area for heat transfer, and the storage materials are generally cheap, however the pressurised container costs are greater. Present work is considering the characteristics of a range of solid media (natural stone, concrete, fireproof material and metal), and it is notable that "Cowper" heat storage devices are already used widely in the glass and metallurgical industries for preheating temperatures of up to 1,500°C.

Cavern availability

A range of cavern options has been considered for Adiabatic CAES. Indeed, for the smallest plant capacities it may be possible to use pressurised buried pipework, as has already done for pilot plant, and for gas storage. However, for the Central Device, which is considered the most viable, a large underground cavern of 150,000 to 500,000 m^3 is the only option. Often, CAES plant are considered where an existing cavern exists, but solution mining of salt caverns remains an attractive possibility, not least because Palaeozoic salt (Zechstein salt) deposits are found in a broad band

Concept	Solid TES					Liquid TES		
	Rock bed	Cowper-Derivative	Concrete Walls	Cast Iron Slabs	'Hybrid'-PCM	Two Tank	1-Tank Thermo-cline	Air-Liquid
	direct	direct	direct	direct	direct	indirect	indirect	direct
Storage Material(s)	Natural stone	Ceramics	Concrete	Cast Iron	Ceramics, Salt	Nitrate salt, Mineral Oil	Nitrate salt, Mineral Oil	Nitrate salt, Mineral Oil

Table 3. The main thermal energy storage (TES) concepts considered

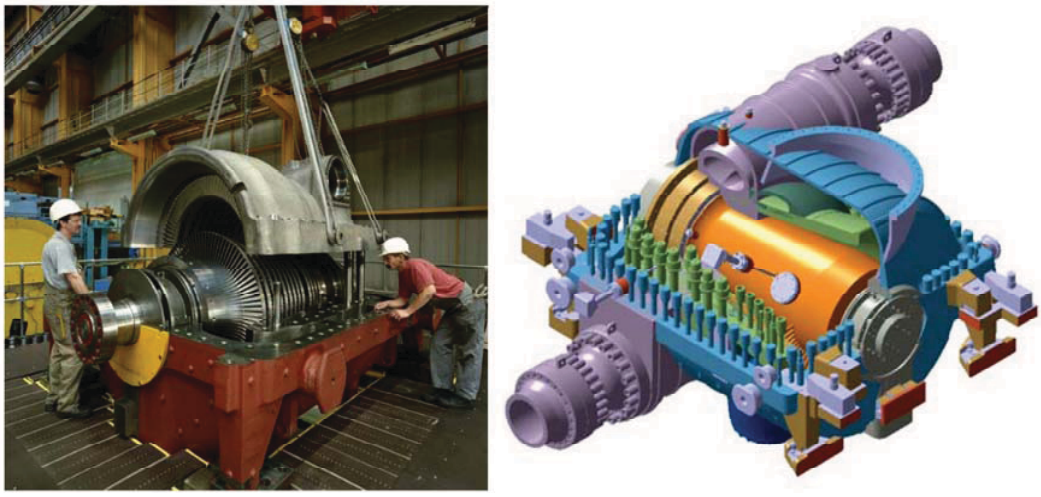

Figure 5 Examples of typical turbine standard modules for low (left) and intermediate (right) flow rates with faster ramp rates than previous designs. (Source: ALSTOM Switzerland).

over much of northern Europe. Elsewhere Triassic salt deposits (such as those at Cheshire, UK) are known. In some areas, salt "domes" or "pillows" form owing to depth variations in the pre-Zechstein crust, or to movements within the salt deposits, and can be particularly attractive sites for salt mines.

Where preparation of a salt cavern is impractical, the use of existing rock caverns, aquifers, depleted gas fields and abandoned mines offer an alternative. For example, the abandoned limestone mine at Norton, Ohio has been considered for a diabatic CAES plant [6]. The AA-CAES Project partner, DEEP Underground, has prepared detailed studies of the geographical and technical constraints for preparing new caverns or utilising existing caverns.

Sliding pressure air 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. Inlet pressures are likely to vary by a factor of x2, 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.

Besides the introduction of adaptive stages, the sliding pressure air turbine is being developed in a modular fashion. This is for two main reasons: firstly, the AA-CAES Project has yet to finalise the optimum parameters for the overall cycle; and secondly, local constraints (size of compressor/cavern, role of the storage device etc.) demand flexibility. Examples of a small steam turbine, and a modular medium sized air turbine are shown in Figure 5. Further design work is in progress to ensure that the turbine meets the requirements identified from the economic research, for example ramp rate. Special consideration is being given to pre-heating of the turbine using excess heat from the compression cycle so that a fast start-up can be achieved.

Summary and Conclusions

The overall goal of the AA-CAES Project is to identify and develop the technology and plant concepts relevant to present and future market conditions. The project is on target to allow the design and building of a demonstrator plant shortly after the project completes. The current achievements have been to demonstrate the economic incentives for mass storage of electricity, and to identify the characteristics of storage plant that can operate within the deregulated markets that dominate within the industrialised nations. We have characterised the type of plant that may be suitable for centralised storage (300MW generating capacity), storage adjacent to windfarms (150MW), and on isolated grids (30MW).

Regarding the design of Adiabatic CAES plant, concepts for the compressor, thermal energy store, cavern, and turbine are now available. The thermodynamic and technical constraints indicate pressure and temperature limits of

approximately 200 bar and/or 620°C limits. The next stage in the development of Adiabatic CAES is to optimise the overall system. Attention is also now turning to detailed costing of the plant, and its viability in particular markets.

Our work has led to the following conclusions:

1. Adiabatic CAES is an electricity mass-storage technology, with high efficiencies, zero CO_2 emissions, and less geographical restrictions, and that offers an attractive alternative to diabatic CAES and pumped hydro storage.
2. Wind power and electricity storage are natural partners; Adiabatic CAES plant will permit better integration of wind power into national grids, primarily by providing balancing and peak load power.
3. Adiabatic CAES plants increase wind power utilisation, thereby potentially allowing countries to meet their CO_2 targets more easily.
4. As the penetration of wind-power increases, the economic arguments for Adiabatic CAES increase significantly. The strongest market for Adiabatic CAES is the Netherlands, but Germany, Belgium, Spain and Great Britain are also favourable markets.
5. The technology developments required to build a viable demonstrator plant are well within the grasp of the AA-CAES Project partners.

Acknowledgements

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References

[1] European Union Energy Outlook to 2020. The European Communities, Luxembourg 1999.
[2] EREC: Renewable Energy Target for Europe: 20% by 2020. European Renewable Energy Council Report, January 2004, (downloadable from www.erec-renewables.org , accessed November 2004)
[3] Crotogino F, Mohmeyer K-U, and Scharf R. Huntorf CAES: More than 20 Years of Successful Operation. Proc of SMRI Spring Meeting, Orlando, Florida, USA, 15-18 April 2001.
[4] Alabama Electric Cooperative, CAES McIntosh Alabama, further details from http://www.caes.net/mcintosh.html (accessed November 2004)
[5] AA-CAES: "Advanced Adiabatic Compressed air Energy Storage" contract ENK6-CT-2002-000611, Framework 5 programme of the European Commission. Further information can be found at: www.cordis.lu
[6] Gatzen C. Modellgestützte Wirtschaftlichkeitsanalyse innovativer Speichertechnologien am Beispiel einesadiabaten Druckluftspeichers. Proc Symposium Energieinnovation "Erfolgreiche Energieinnovationsprozesse", February 2004, Graz, Austria