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Compressed air energy storage power plants

- **Implementation of wind energy for peak load is becoming possible**
- **Necessary balancing energy, reserve capacity, and network expansion are being reduced**
- **Favourable geological conditions in many high wind areas**
- **Synergy effect upon utilisation of low BTU- gases**

Fig. 1

30 years in operation - and still ahead of its time? Compressed air energy storage power plant in Huntorf, Germany

In Germany, wind energy utilisation is growing dynamically. There is potential for further expansion on land, and offshore, and the technology for realisation is mature. Already 5 % of the electricity generated in Germany comes from wind energy. According to the plans of the European Union, renewable energy sources as a whole should reach 20 % Europe-wide by 2020. This requires adjustments to electricity grids, the power plant mix, and energy management, as wind turbines do not produce in a demand-oriented manner, but in a weather-dependent manner. The short-term fluctuations in the electricity feed volume can indeed be predicted quite well, however inexactness remains in the forecasts. Added to this, wind turbines are mostly installed in weak grid areas in coastal regions, and far from large consumption centres. Already today, it does happen that wind turbines in the North are prohibited from feeding electricity into the grid for some periods, due to grid overloading.

According to the so-called dena grid study, the demand for balancing energy, i.e. energy to balance supply and demand, will increase to more than double by 2015. Simultaneously, 400 kilometres of power routes must be enhanced, and 850 kilometres must be newly built. Many experts doubt that this is possible in the short amount of time available.

Alleviation could be provided by large energy storage systems, which allow the energy supply from wind parks to be planned and controlled similarly to the energy supply from conventional power plants. The established pumped storage power plants, however, with their space requirements and their special site-related needs, are not suitable for broad implementation, especially as wind turbines' peak outputs are concentrated in the flat Northern regions. A more promising solution is buried deep underground: Northern Germany's widespread salt domes offer ideal conditions for the construction of the large caverns which are the central component of compressed air energy storage power plants. Worldwide, there are as yet only two of these so-called CAES (compressed air energy storage) power plants, which store excess energy as compressed air, and when required, convert it, together with natural gas, back into electricity.

Research into whether and how wind energy can be better integrated into the German and European electricity supply by means of CAES power plants, is being conducted in various studies, sponsored by the German Federal Ministry for the Environment. The technological prerequisites, opportunities and costs are being examined in comparison to other solutions. Meanwhile, surprising possibilities for utilisation of natural gas deposits which were previously thought to be no longer usable have also become apparent.

▸ Storage power plants – enabling wind energy to be planned

Due to many years of experience, and refined forecasting methods, grid operators can make good predictions as to the consumption fluctuations in the grid. With the feeding of wind energy into the grid, another factor of uncertainty is added on the generator side. Here, newly developed processes (Projekt-Info brochure 14/03) now allow a forecast of the expected wind energy grid-feed, with a mean square error of 10 % for the following day, and 6 % for short-term forecasts of 3 to 6 hours, in relation to the installed rated capacity.
Flexible and fast storage power plants can balance out these deviations. Instead of reducing the output from thermal power plants, the excess energy is transferred to storage, and is then available for short-term additional demand, thus replacing expensive power from the spot market. This could result in thermal power plants being able to constantly operate in an optimised manner, thus achieving higher efficiency and lower wastage. Simultaneously, the additional reserve capacity of storage power plants increases the operational reliability in the public grid, due to their voltage-frequency regulation and power-frequency regulation capabilities. Operators of wind turbines also benefit if systems no longer need to stand idle as a result of grid overloading.

▸ How compressed air energy storage power plants work

Normal compressed air energy storage power plants function in a similar manner to conventional gas turbine peak-load power plants, with one decisive difference: the gas turbines in conventional power plants require up to two thirds of the mechanical energy which they generate, to drive their compressors. Only about one third is available as operating power for the electricity generators. This is not the case in compressed air energy storage power plants: here, the pre-compressed air and combustion gas are channelled directly to the combustion chamber. Correspondingly higher turbine outputs can be transferred to the generator shafts.
At the core of a CAES power plant, is a large compressed air store, which is charged by means of electrically driven compressors during low load periods when wind availability is high. As well as aquifers and porous rock formations, large caverns in underground salt domes (which can be created by solution mining) are most suitable. The technology is proven and tested. It has long been practice to use salt domes for stockpiling of natural gas reserves. And there are also two instances where these domes are used in CAES power plants.
In the future, 'adiabatic' storage power plants (AA-CAES) should be able to operate without any fossil fuels, and require about 1.4 kWh of low-load electricity to generate 1 kWh of peak-load electricity.

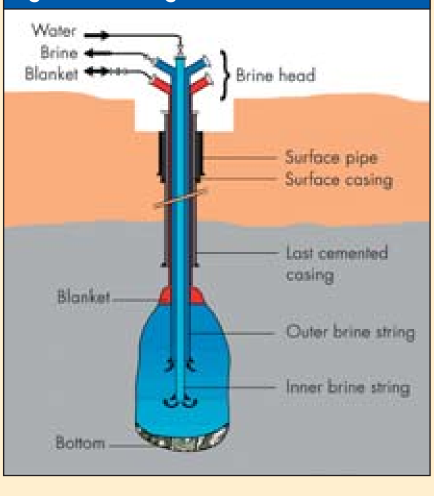
▸ CAES power plants in existence today

Fig. 2: CAES power plants in existence today

Location	Huntorf, Germany	McIntosh, USA
Commissioned	1978	1991
Store	Two cylindrical salt caverns, each with 150,000 m³ at a depth of 600 m – 800 m (height 200 m, diameter: 30 m)	Salt cavern, 538,000 m³ at a depth of 450 m – 750 m
Output	290 MW over 2 hours	110 MW over 26 hours
Energy required for 1 kWh el	0.8 kWh electricity	0.69 kWh electricity
	1.6 kWh gas	1.17 kWh gas
Pressure tolerance	50 – 70 bar	45 – 76 bar
Remark	World's first CAES plant	First CAES plant with recuperator

Already 30 years ago, in Lower Saxony, a 290 MW CAES power plant was connected to the grid, in order to refine base-load electricity from the Unterweser nuclear power plant, producing peak-load electricity. This power plant has been working as minutes reserve to this day, with high availability, although with relatively low overall efficiency. About 1.6 kWh of gas, and 0.8 kWh of base-load electricity are required in order to generate 1 kWh of peak-load electricity. This is essentially due to the fact that the air which is heated upon compression must be cooled down before it is stored in the cavern. Conversely, the cooling which occurs upon expansion in the turbine must be compensated for by use of natural gas.
A power plant in McIntosh, USA, utilises heat from turbine exhaust gases, via a heat exchanger, to preheat the compressed air. Thus, this power plant, which was commissioned in 1991, achieves a somewhat higher efficiency. In the future, 'adiabatic storage power plants' (AA-CAES) should be able to operate without any fossil fuels, and require about 1.4 kWh of low-load electricity to generate 1 kWh of peak-load electricity.

Fig. 3: Leaching

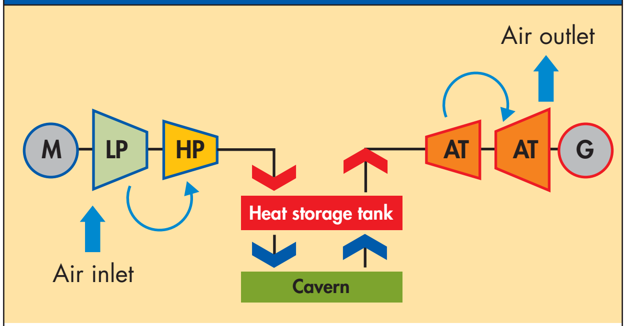


Cavern stores

Storage caverns with a volume of far more than 500,000 m³ have already long been used to store natural gas. Salt domes at depths of less than 800 m, and over 300 m thick, are most suitable for construction of these caverns. Many such domes are available in Schleswig-Holstein and Lower Saxony, whereas the coastal region in the North-East of Germany has only a few individual salt domes in South-Western Mecklenburg. As well as geological suitability, there are other site factors to consider: close proximity to existing wind parks in Northern Germany, to future offshore wind parks in German coastal waters, and to the existing power grid, sufficient fresh water supply for solution mining, and possibilities for disposal of the brine which this produces (close to the sea), unless this brine can be used as an industrial raw material.
Storage caverns are created in solution mining by means of boreholes in which a number of pipes are installed (fig. 5). With brine pipe sections which can slide with respect to each other, water is added to dissolve the rock salt mass, and the brine which this creates is conveyed to the surface. During this process, the roof of the cavern is protected from uncontrolled dissolving by means of a blanket of air, natural gas, or oil.
The main factors relevant to the environment are the fresh water required when creating the salt cavern, and the brine which is produced. In the area of the North Sea coast, sea water is available for the leaching process. The brine produced can be channelled into the lower course of strong currents, and into the North Sea. As the salt content of the Baltic Sea is lower, higher costs can be expected in order to achieve acceptable dilution of the cavern brine in the immediate vicinity of disposal installations.

AA-CAES – research objectives

Fig. 4: Adiabatic storage power plants



LP Low pressure compressor
HP High pressure compressor
AT Air turbine
G Generator
M Motor

Fig. 5: Axial-radial compressor, suitable for the low pressure component (LP in fig. 4)

'Adiabatic storage power plants' (AA-CAES) store not only the compressed air, but also the heat (in a separate heat storage tank) which is released upon compression of the air (fig. 3). For generation of electricity, the heat is returned to the compressed air which flows to the turbine. This renders the use of natural gas unnecessary. Operated with only regenerative electricity, AA-CAES should achieve efficiency of up to 70 %. The development of such plants is supported by the European Union, but is still in its infancy. Almost all components must be newly developed. The researchers are correspondingly cautious with predictions as to when the technology will be ready for implementation. A demonstration power plant could be built in five to ten years. Until then, there are still numerous challenges to overcome:

Heat storage tanks with a storage capacity of up to 1,200 MWth at temperatures of over 600 °C are required. Two lines of development are being investigated:

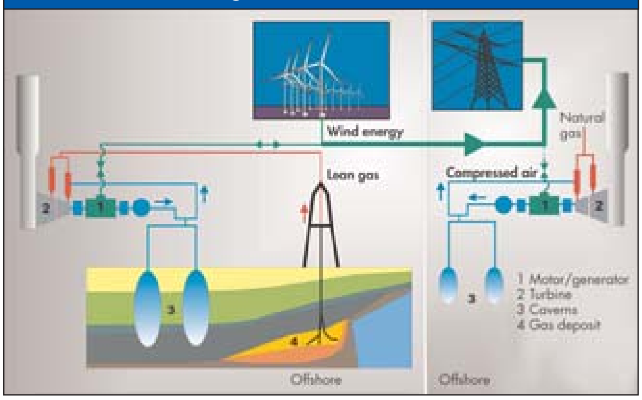
- Solid stores made of ceramic, natural stones, concrete, or cast iron, could be directly charged and discharged. They have proven themselves in industry, are simple in structure, and have a large heat transfer surface. However, solid stores require a pressure-resistant shell.
- Another technology, also proven many times over in industry, uses commercially available fluids. Charging and discharging occur via heat exchangers, so corresponding temperature losses and pressure losses are incurred. But on the other hand, low-cost containers can be used.

Compressors for charging the store should cope with temperatures of up to 600 °C, and generate pressures of up to 160 bar. Other requirements are: high efficiency, a variable flow rate, and rapid availability with a start-up time of a few minutes. Design studies for appropriate radial compressors are encouraging.

Air turbines must be newly developed, to achieve capacities of up to 300 MW by expansion of the compressed hot air to atmospheric pressure. Here, the challenges include: high power density, high entry temperatures, large volume flows, and changes in volume flow. Simultaneously, high efficiency should be achieved across the entire load range, with low specific costs.

Base-load electricity from the North Sea

Fig. 6: Shared grid connection of wind turbines and low BTU- gas turbines



In the German North Sea, there are known gas deposits, exploitation of which was no longer profitable, due to high nitrogen content. The Association of German Oil and Gas Producers (WEG) estimates the exploration potential to be up to 230 billion m³.

In the project 'Grid integration of large offshore wind plants – Base load from the North Sea', sponsored by the German Federal Ministry for the Environment, researchers at the Clausthal University of Technology are investigating whether the infrastructure required for future offshore wind parks in the North Sea can also be utilised for this resource. An integrated implementation of wind power, compressed air stores, gas deposits, electricity generation from low BTU-gas, and gas power plants, would entail considerable synergy benefits.

When the load is small, excess energy is stored in a compressed air store, and is converted to electricity when needed, together with the lean gas, in a special gas turbine. It would be possible to plan the offshore supply of electricity, up to the level of base load supply from the North Sea. Simultaneously, the electrical transmission lines to the offshore wind parks are used optimally. This shared utilisation of the infrastructure reduces the proportional costs.

The North Sea and Germany's northern coastal region provide ideal geological conditions for the construction of compressed air energy storage gas turbine power plants. A working group at the Clausthal University of Technology are investigating the extent to which the envisaged concept can actually be implemented. The researchers are also investigating whether, and to what extent, the additional power plants with gas turbines on the coast would be necessary and cost-effective, upon implementation of such a concept. Preliminary investigations of the 'Clausthal concept' have drawn the following conclusions:

- Gas turbines for generation of electricity from natural gas with nitrogen content of up to 70 % are available.
- Financially, the utilisation of natural gas deposits in conjunction with wind parks (with up to 3500 hours of full wind load p.a.) is comparable to development of the natural gas deposits alone.
- Development of wind parks is more economical with utilisation of natural gas than without.
- oint operation only makes financial sense with large capacities (200 MW and above).

Conclusion

The geological conditions are favourable for the construction of CAES power plants in Northern Germany, and also in many areas in Europe, for instance in the Netherlands, Great Britain, and Spain. Suitable salt domes are situated in many coastal and mountain regions where the winds are high. It is advantageous for Germany, that these locations are where there is potential for future expansion of wind energy: at sea, i.e. off Germany's shores. With their underground caverns, the plants require little space, and their influence on the environment is only slight.
The flexibility of CAES power plants is similar to that of pumped storage power plants. Full capacity is available just a few minutes after start-up. For limited periods, the compressed air stores cover the short-term reserve requirement, the minutes reserve, and the balancing capacity, which are needed due to the inexactness of forecasts regarding wind power grid-feed. This reduces the need for fossil reserve power plants and additional grid capacity. Wind turbines do not need to deactivate in the event of a grid overload, and if there is excess supply of electrical energy, the storage technology refines base-load electricity, converting it to peak-load electricity. Thus, the fluctuating electricity prices on the liberalised electricity market can be used to yield profits.
Storage power plants cannot replace the entire requirement for reserve power plants. Within an overall concept, they reduce the amount of grid expansion needed, and share the task of supplying peak load power with gas power plants, which can be regulated quickly. Grid optimisation is complemented to no small extent by more effective consumption management, with which load fluctuations are regulated not only on the supply side, but also on the demand side.
Storage technology can also be combined with offshore wind farms. The idea of utilising low BTU-gas deposits under the North Sea with a shared infrastructure is fascinating. The extent to which this is technically and economically feasible has not yet been conclusively determined.
There are currently CAES power plants in the design phase all around the world; 10 plants are being planned in the USA alone. A CAES power plant belonging to the energy supplier EnBW should also be commissioned on the German North Sea coast by 2011. This will initially still be fired conventionally with gas, and will serve as a research project for more efficient storage technology with heat storage tanks, which is to be realised in a second phase. About 20 companies and institutes are working on this AA-CAES technology in the EU-sponsored project 'Advanced Adiabatic Compressed Air Energy Storage'. It is expected that there will be systems ready for industrial implementation by around 2015.

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ADDITIONAL INFORMATION

Literature

- Verbesserte Integration großer Windstrommengen durch Zwischenspeicherung mittels CAES. Wissenschaftliche Studie, gefördert durch das Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit, Berlin. Endbericht. FKZ 0327558. Alstom Power Generation AG, Baden; Ecofys GmbH, Berlin; E.On Energie AG, München; KBB Underground Technologies GmbH, Hannover; REpower Systems AG, Hamburg; Vattenfall Europe Powerconsult GmbH, Vetschau (Hrsg.). 2006. 46 S. + 17 Anlagen; 29 S.; 39 S.

Service

- Additional information such as literature, addresses and internet links are available online from BINE at www.bine.info (Service/InfoPlus) in German.

Images

- Fig. 1: E.ON Kraftwerke GmbH, Wilhelmshaven
  Fig. 3: KBB Underground Technologies GmbH, Hannover
  Fig. 5: MAN TURBO AG, Oberhausen
  Fig. 6: Technische Universität Clausthal, Clausthal

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