Compressed Air Energy Storage Fits Today's Market Requirements

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The demand for electricity undergoes considerable daily, weekly and seasonal fluctuations. The periods with high system demand usually last only a few hours per day. Electricity as such cannot be stored in the system and has to be generated just in time with the demand. As a result, huge power generation capacities have been installed to follow the demand curve. The power plants could very well be operated at their nominal capacity for at least 90% of the time, but due to the aforementioned approach of sizing the generation capacity the power plants are operated in part load most of the time. In many cases the plants are even subjected to daily or weekly cycling. To operate such plants only few hours each day or each week at their nominal capacity and the rest of the time at less efficient part load conditions or even to start and shut them down in short intervals with increased costs for fuel and maintenance results in high costs for electricity.

Such uneconomic investment for the power plant capacity can be avoided by complementing the base load power plant fleet with large scale energy storage facilities. For this bulk storage, two technologies are available, namely the pumped hydro technology, which has been used for roughly a century and Compressed Air Energy Storage (CAES), which has been in commercial use in Huntorf (Germany) for 25 years and in Alabama (USA) for 10 years. Pumped hydro plants are in wide use where the geographic characteristics made them possible, but new projects are becoming increasingly difficult to realize due to the required size of the water reservoir and environmental considerations. Here CAES is the answer to complement the electricity supply systems with the necessary storage capacity.

A typical CAES power plant train consists of the following elements:

- A cavern, serving as compressed air reservoir.
- Motor driven compressors, which store the energy by charging the cavern with air during periods of low electricity demand.
- An expansion turbine, consisting of high pressure turbine, combustion chamber and low pressure turbine including a generator.
- A recuperator, preheating the cavern air with the turbine exhaust gases before it enters the high pressure turbine for highest efficiency of the cycle.

Figure [1]: CAES power plant cycle.

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The heat from the inter-coolers after the air compressors can be extracted and used for district heating purposes, in desalination plants or in other chemical processes. (see Fig. 1)

An interesting alternative of the CAES cycle above is the ‘CAES Booster’, complementing a standard gas turbine in open or combined cycle operation with a compressed air storage, which can feed pressurized air into the gas turbine between compressor and combustion chamber. This reduces the amount of air needed from the gas turbine’s compressor and allows partial closing of its inlet guide vanes and thus reduces the mechanical power needed to drive the compressor. As a result the output of the gas turbine can be increased up to 170% of its nominal output. The necessary compressed air storage volume is smaller than for a standard CAES power plant, making it possible to use pressure vessels for this purpose. However if colder air, coming from the cavern, is added to the gas turbine just before the combustion chamber, the specific fuel consumption of the gas turbine increases. Preheating the compressed air by means of a recuperator can compensate this effect at least partially.

![Figure 2: CAES Booster](image)

The following discussion focuses on the most efficient standard CAES cycle with a heat rate of approximately 4000 Btu/kWh as depicted in Fig. 1, whilst the heat extraction or the CAES Booster represent attractive project specific options.

In a typical weekly utilization pattern, the CAES plant charges the cavern mostly during the weekend and also for some 6 to 10 hours each weekday night. These are the times when the cost of taking electricity from the grid is lowest and when the advantage of not having to shut down or throttle other power plants can be utilized fully. Emission free electricity from wind farms is also available for the CAES plant’s storage operation as wind energy is stochastic and often not in line with the demand.

During the daily medium to peak load hours, when the electricity price is at its highest value, the cavern is discharged and electricity is supplied into the grid. A specific feature of the CAES plant is its ability to support the grid quickly, in case sudden extra high demands, unscheduled outages of other power plants or grid disturbances occur. This flexibility enables the CAES plant to contribute more than other power plants to regulation service, frequency support and voltage control.

Considering the load span from compression (200 MW consumption) to full load (300 MW generation), the CAES plant has a regulation leverage of 170% of its generation capacity. This enables an extraordinary contribution to keeping the other power plants at base load, whilst the CAES plant absorbs the major part of the daily and weekly load cycling. Figure [3] shows how these considerations transfer into the overall power plant portfolio planning of a large utility. At present the installed capacity of 9000MW is just able to cover the peak demand, but the existing plants, mostly coal, are operated at deplorably low part load almost half the time each weekday and at even lower part loads during the weekend. In Figure [3] the assumption is that the system needs a capacity increase of 1500 MW. This load increase can be covered by adding a 1500MW CAES power plant to the portfolio. The CAES power plant then not only provides for the extra output during the periods of high demand each weekday, it also enables the coal fleet to run throughout the week at nearly full load.
In economic terms, the benefits of adding the CAES plant to the existing power plant fleet are manifold. The Independent System Operators (ISOs) have begun to reimburse the market participants for several of these benefits as shown in the following list, based on data obtained from PJM grid operator. These are the electricity price elements, and thus revenue earning opportunities dedicated for CAES plants in today's market environment:

- The Locational Marginal Price (LMP) for the kWhs generated. This represents still the largest revenue flow.
- The capacity price based on the installed capacity.
- The regulation price based on the ability of the CAES plant to participate in the frequency support and voltage control.
- The price for the spinning reserve to support emergency demand.
- The premium for grid regulation on the demand control side, where the CAES plant participates with its compressors.

Over and above what is paid for by the ISO, having a CAES plant in the portfolio the following cost savings can additionally be materialized as:

- The efficiency increase of the existing fleet of coal fired power plants.
- The reduction in O&M costs of the coal fleet thanks to reduced or eliminated load cycling.
- The extension of the lifetime of key components in the coal fleet thanks to the reduced load cycling.

The revenues of the CAES plant vary depending how many hours of generation can be achieved per year. Whilst the revenues generally increase with increasing operating time per year, operation much above 4000 hours per year would be difficult to achieve considering the time requirement for charging the cavern and furthermore there are usually less than 4000 hours of good electricity price per year anyway. Figure [4] shows the elements of revenue of a CAES plant over the number of operating hours per year.
On the cost side, there are the following elements to be considered in the economical evaluation:

- Fuel costs for the CAES operation.
- Electricity costs for charging the cavern.
- Capital costs for the CAES plant investment.
- Fixed operation and maintenance cost.
- Variable operation and maintenance costs, increasing with the operating hours per year.

Figure [5]: Fixed and variable costs of a CAES plant versus the number of operating hours per year.
The income before taxes is obtained by subtracting the costs from the revenues as shown in Figure [6]. As can be seen, there is a wide range of profitable operation for CAES, with an optimum around 4000 hours per year.

Besides these day in day out commercial considerations, there are benefits from the CAES plant with positive implications on the long term economy, the ecology of our planet. These benefits stem from several factors:

- The gas consumption of the CAES plant is significantly lower than that of the most important other peaker, the open cycle gas turbine.
- The base load arbitrage achieved by the CAES plant enables the remaining plants to run at or near their nominal capacity, with highest efficiency and lowest emissions.
- The emission free power from renewable sources such as wind and solar can be stored in the CAES plant and fed into the grid at times of high demand. This enables the economic use of renewable energies, which would otherwise contribute to considerable unbalances in the grid, as can be seen from the typical wind power characteristics versus load characteristics in Figure [7].
Besides the already mentioned electricity generation versus electricity demand considerations and their ups and downs during the day, bottlenecks in the electricity distribution grids have more and more shifted into focus. In many areas the distribution systems have not fully kept pace with the rapid increase of electricity demand over the past decades. During periods of high demand, there is not much of a margin available as contingency for disturbances of any kind. Unfortunately the extension of the distribution systems is a very time consuming, costly process and it would again not be economical to upgrade a costly system based on the peak demand and then have that system only used at part of its capacity during most of the time. This effect is even more apparent where renewable energy sources are added to the system, since these are often located near the boundaries of the grid, where the adequately sized transmission lines are rare. Strategically located CAES plants can help avoiding overload in the existing grid and to defer upgrades of the transmission system.

Another challenge is the need to provide sufficient reactive power to the grid. Particularly where large contributions of wind farm or other mostly active power generating plants (cos φ near 1.0) are present, this can pose a serious threat to grid stability. Here the CAES plant with its generously sized generator and compressor motors can supply the needed reactive power not only during periods of high demand, but also during low demand periods by running the compressor motors, equipped with couplings, as synchronous condensers.

Summary: The CAES concept helps all partner in the complex power generation business to achieve low electricity prices while integrating renewable resources and maintaining energy security:

- The low heat rate of about 4000 Btu/kWh for the CAES technology represents a perfect hedging tool against high fuel price volatility
- The combination of CAES with a base load fleet operating nearly at full load improves substantially the value of the generation portfolio and the income of the power generation utility.
- The combination of the wind energy with CAES increases considerably the value of the renewable resources since the stochastic portion is balanced by CAES and additional standby capacity can be avoided
- To store energy leads to a higher utilisation and a more balanced grid operation resulting in less grid congestions