LTA-CAES
Low-temperature Adiabatic Compressed Air Energy Storage

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Abstract – Current Adiabatic Compressed Air Energy Storage (A-CAES) aim at high temperatures in the Thermal Energy Storage (TES). Such high TES temperatures together with high pressures are not easy to handle. In order to avoiding this technical challenge, we developed a Low-temperature Adiabatic Compressed Air Energy Storage (LTA-CAES) plant based on a two-tank non-thermocline TES. We selected and designed multistage radial compressors and expanders with single stages arranged at the ends of several pinion shafts rotating with different- and for the assembled impellers optimal speeds. The proposed LTA-CAES design shows cycle efficiencies in the range of 58 to 67 %, slightly lower compared to those envisioned for high temperature A-CAES. However, it can be shown that its fast start-up characteristics and wide-ranging part load ability overcompensate the lower cycle efficiencies with regard to plant profitability.

1 Introduction

Compressed Air Energy Storage (CAES) represents a promising storage technology especially at larger scale. It shows a greater siting flexibility compared to pumped hydro plants together with relative low specific investment cost.

The basic functionality of CAES is relatively simple. In order to store electric energy, CAES plants compress ambient air by an electrically driven compressor. The compressed air can be stored in a pressurized containment of any kind. In CAES plants being operated solution mined underground salt caverns are used as pressurized containment. When the stored energy shall be reconverted, the compressed air is released from the containment and will be heated up before being expanded in a turbine. The turbine is connected to an electric generator which supplies electric power back to the grid. For the heating of the compressed air conventional CAES plants require the use of additional energy (natural gas) similar to open gas turbine cycles [1], [2]. In order to avoid the use of additional energy the heat of compression can be stored during charging the contained volume and is later used for heating up the compressed air before its expansion within the turbine. Such a CAES plant incorporates a Thermal Energy Storage (TES) and is therefore called Adiabatic Compressed Air Energy Storage (A-CAES).

2 Current A-CAES design approaches

A-CAES plants have only been realized on laboratory scale [3]. Recently, several design approaches for A-CAES plants on larger scale have been proposed [4], [5]. These approaches are characterized by applying TES at comparably high temperatures of around 600 °C. At such elevated temperatures the TES comprises a pressurized packed bed being operated in thermocline mode. The concrete jacket of the pressurized TES container has to be cooled actively in order to guarantee a safe operation. Main advantage of such a design approach is the usage of relatively inexpensive solid TES material. Furthermore, there is no need for additional heat exchanging devices, since the TES material is in direct contact with the compressed air. Howsoever, this high-temperature TES also leads to some technical challenges such as:

- Currently available turbo compressors are limited to outlet temperatures far below 600 °C. Consequently, new compressors have to be designed and developed with high interstage- and discharge temperatures.
- Due to the coexistence of high temperatures (~600 °C) and pressures (~70 bar) in the TES, a high constructional and maintenance effort has to be accepted.
- Thermal and mechanical stress may lead to attrition of TES material releasing small particles into the air, which could cause damage the inlet blading as well as the expander wheels .
- High temperatures require a rather slow start-up from cold start limiting the A-CAES plant to applications with a required start-up time of 15min and up.

Summarizing current high-temperature TES approaches to A-CAES can be considered as promising but they also involve high development and testing efforts together with considerable challenges. The low-temperature TES design in Adiabatic Compressed Air Energy Storage (LTA-CAES) presented in this paper aims to avoid these challenges of current A-CAES designs and will be described more in detail in the following.

3 Idea behind low-temperature A-CAES

In conventional thermal power plants the urge exists to push maximum process temperatures ever higher in order to increase the plant efficiency. This is especially true for gas turbines, where the temperature of the hot combustion gases determine the magnitude of the thermal efficiency. While in the 1970ies hot gas temperatures below 900 °C were still common, current gas turbines are designed for hot gas temperatures of more than 1400 °C [6].

The direct relation of maximum process temperature and theoretically attainable thermal efficiency of any thermal power cycle can be expressed by the Carnot efficiency η_{Carnot}:

$$\eta_{Carnot} = 1 - \frac{T_{min}}{T_{max}} \tag{1}$$

Herein, the difference of maximum process temperature T_{max} and minimum process temperature T_{min} gives an upper efficiency limit which can be approached but never be achieved by real processes. This relation governs all thermal power cycles, in which heat as only energy source is transformed into work. This includes Joule cycles (gas turbines) and Rankine cycles (steam power plants).

For A-CAES plants the magnitude of interest is the cycle efficiency or round trip efficiency, not the thermal efficiency. The cycle efficiency of an A-CAES is calculated by the difference of the amount of electrical energy fed into the grid while discharging $E_{dch,el}$ and the amount of energy taken from the el. grid to charge the storage $E_{ch,el}$.

$$\eta_{cycle} = \frac{E_{dch,el}}{E_{ch.el}} \tag{2}$$

Therefore, the overall A-CAES cycle efficiency is not governed by the Carnot efficiency [7]. This means that the achievable cycle efficiency is independent of the maximum process temperature and therefore of the storage temperature.

Figure 3-1 shows the Carnot efficiency (light line) according to Eq. (1) assuming 25 °C as lower process temperature. As expected, a drastic decrease towards lower process temperatures can be observed for the Carnot efficiency.

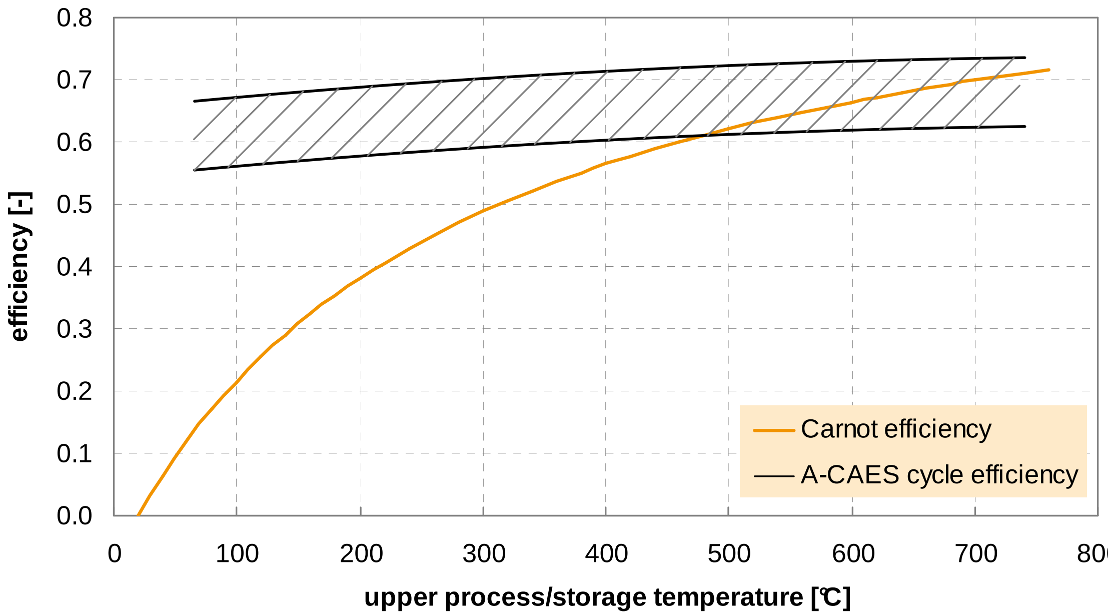

Figure 3-1: Carnot efficiencies (light line) and cycle efficiencies of A-CAES plants (hatched area) plotted over the maximum process or storage temperature respectively

While the Carnot efficiency is a theoretical value, cycle efficiency of A-CAES plants as defined here is not. Consequently, A-CAES cycle efficiency depends on the technical design of the plant, on the electrical- mechanical- and thermodynamical efficiencies of the involved components. That is why for the attainable cycle efficiencies of A-CAES plants a range is shown in Figure 3-1. Depending on the individual plant design a higher or lower value can be attained. Nevertheless, a general trend is visible: There is a slight decrease in cycle efficiency towards lower temperatures. This decrease can be ascribed to enhanced exergy losses due to a higher number of heat exchanging processes necessary for maintaining lower process temperatures. Nevertheless, it is possible to achieve comparatively high cycle efficiencies even for lower storage temperatures, which opens space to apply a substantially different A-CAES plant layout as current high temperature solutions propose.

4 Technical realization of LTA-CAES

In an ongoing research project[1] we developed a LTA-CAES plant layout aiming at TES temperatures from 90 to 200 °C. Based on the general plant layout we also developed a corresponding turbomachinery design. The turbomachinery is designed in detail for two different LTA-CAES plant configurations of 5 MW / 70 bar and 50 MW / 150 bar. The turbomachinery concept chosen for the LTA-CAES is derived from proven technology used for Air Separation Units (ASU), Urea- and other chemical plants. The thermal management comprises a two-tank TES configuration with liquid TES medium as known from Concentrating Solar Power (CSP) plants.

4.1 Plant layout

Figure 4-1 exemplarily shows an LTA-CAES plant layout as developed for the 50 MW/ 150 bar system. The TES material is liquid and stored without thermal stratification in a two-tank system - one tank for the cold, one for the hot TES liquid. As can be seen in Figure 4-1 the compression and expansion processes are desired to consist of several individual stages each comprising aftercooling or preheating, respectively.

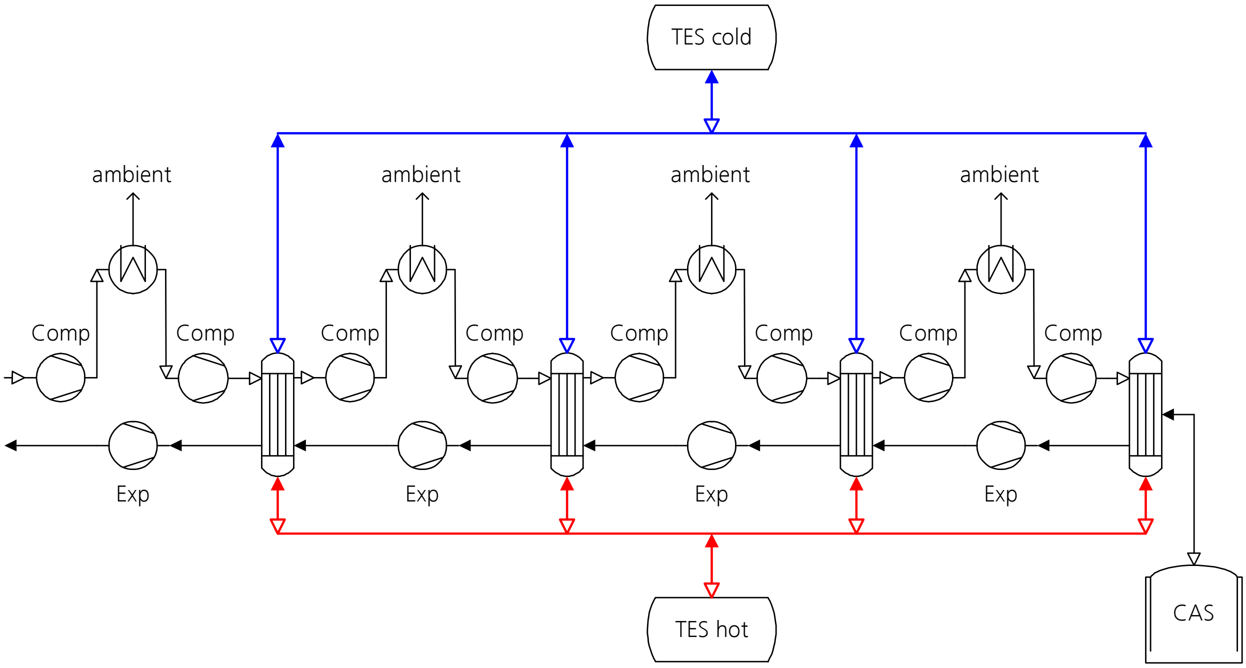

Figure 4-1: Process scheme of a 50 MW / 150 bar LTA-CAES plant

The process scheme of Figure 4-1 essentially shows two different types of heat exchangers being applied in the compression process. One type rejects the absorbed heat to the ambience. The other type dis-

[1] http://forschungsjahrbuch.de/FKZ/0325211/

charges the extracted heat of compression to the hot TES tank, where the heat exchanging liquid is stored as is. The same heat exchangers are applied to preheat the air during expansion process.

4.2 Turbomachinery

The aim of low TES temperatures requires recooling of the air at various points throughout the whole compression process. For this purpose large single-shaft trains with axial blading or radial inline compressors are not appropriate. Axial turbo compressors designed for high pressure ratios consist of many stator and rotor disks, arranged one after the other. Such types of compressors do not allow intermediate recooling of the air, which is a prerequisite for maintaining low TES temperatures. Radial type inline compressors such as MAN Isotherm compressors are intercooled between the stages, but the number of stages is limited to five and very special intercoolers are integrated parts of the compressor. Therefore, the most appropriate compressor types for LTA-CAES-plants are integrally geared or directly driven radial turbocompressors with up to ten intercooled stages. This kind of turbocompressor has a clear advantage when realizing low storage temperatures and is chosen as basic turbomachinery concept for the LTA-CAES plant. With this turbomachinery concept it is possible to recool the air after each stage. Figure 4-2 shows a 3D rendering of an ASU plant integrally geared compressor, demonstrating the possibility for recooling after each stage.

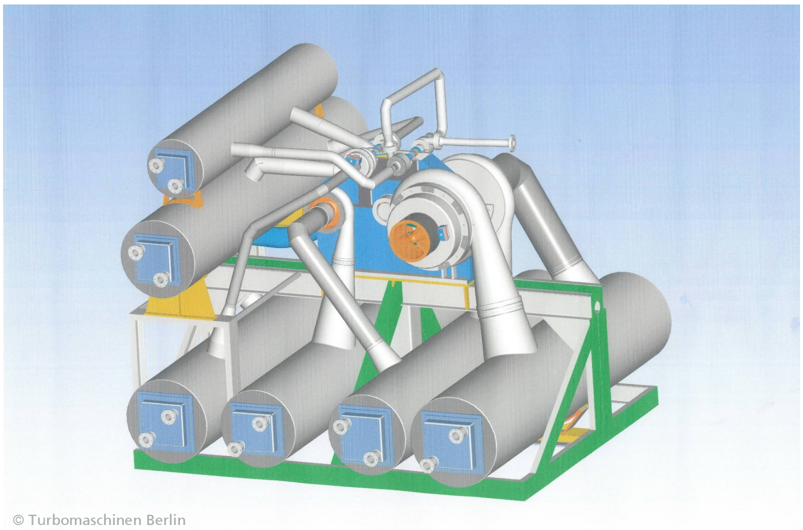

Figure 4-2: 3D rendering of an ASU plant configuration

Moreover, such a concept allows integration of inlet guide vane devices at each radial stage resulting in a wide control range with extensive part load capabilities. In CAES plants a wide control range is of great importance because of two reasons. First, a wide control range offers rather large pressure level variation in an isochoric Compressed Air Storage (CAS). A large allowable pressure level variation increases the overall energy density of the plant. Secondly, in case of a reserve market participation high operational flexibility is required and large part load operating shares are to be expected [8]. Later in this paper it will be shown, how enhanced operational flexibility and part load capabilities significantly increase the revenue of LTA-CAES plants participating in reserve markets.

4.3 Compressor/Expander drive

For the LTA-CAES a single-shaft drive concept as applied for the Huntorf and McIntosh CAES plant would not be appropriate, as already stated earlier. Instead two different drive concepts have been selected for this application.

Integrally geared drive

The first kind is an integrally geared turbomachinery configuration, a reliable well proven type of turbomachinery widely applied in the air separation / urea industry and other common chemical plants.
Such a unit has several rotors with normally two impellers mounted at the ends. The rotors are driven by a central "bullgear". A ten stage machine has five rotors, an eight stage machine four rotors. All rotors run with optimal speed depending on volume flow and pressure ratio. Using the latest "state of the art" gears, speed ratios up to 40 are achievable.
In contrast, the compression train of the Huntorf and McIntosh plant is designed for only two rotational speeds for the used single shaft inline compressors with a transmission ratio of about 2. Furthermore, a very high overall pressure ratio can be realized with such a configuration with feasible final outlet pressures of up to 220 bar and more. Such high outlet pressures again increase storage density. But even more important, high outlet pressures in the three-digit range open up the possibility to use underground cavities at greater depths, too. Being able to set the pressure freely between 70 and 220 bar a far greater range of possible CAS underground formations are made accessible. This way the siting restrictions of the storage plant are reduced considerably.

Direct drive

A second compressor concept developed in the ongoing project aims to substitute the integrally geared turbocompressors by so-called Elcomps. Elcomps are two stage turbocompressors with an integrated, frequency controlled synchronous electric motor in the center. The central electric machine has, similar to a pinion shaft, two mounted impellers at each end. Several two stage Elcomps in series, all with different speeds and stage sizes form a multistage compressor package. The advantage of such a concept is to completely avoid the need for gears. Moreover, the transmission ratios between each shaft are not necessarily fixed any more allowing to adjust rotational speeds individually. This again increases the control range of the storage plant.
This concept offers the possibility to create a high load six-stage air compressor consisting of three Elcomps in series developing a discharge pressure of 150 bar. The modeling of the flow paths allows a reverse flow direction. Therefore, the same unit, but two Elcomps only (four stages) can be used as an expander unit. The electric machines in the center are then used as generators.
We call such turbo stages with reversible flow direction "KompEx". With KompEx stages the whole turbomachinery can be reduced to only one single train. In Pumped Hydro Energy Storage, the combination

of pump and turbine into one single unit has already been realized successfully. This is not the case for gas turbo compressors and expanders, since there was no demand for it yet. However, design principles used for pump-turbines cannot be transferred directly to gas turbomachinery. While water is almost incompressible, gases are compressible demanding a careful design of KompEx-geometry. Within the current project a general and also detailed design of a KompEx-stage has been developed. Building, testing and optimizing of such a device, however, goes beyond the scope of this project and requires further R&D.

4.4 Thermal management

Depending on the system temperature the LTA-CAES plant concept applies up to four additional heat exchangers to recool the compressed air (compare Figure 4-1). These auxiliary heat exchangers use normal cooling water rejecting the heat to the ambience. The heat rejected here comprises only a small portion of the overall heat of compression. The auxiliary heat exchangers are designed as a cross-counter-flow shell-tube configuration and are of well proven design. In contrast, the main heat exchangers required to charge and discharge the TES of the LTA-CAES are components especially designed for this application. However, they do not require significant development efforts or new materials to be applied. The LTA-CAES system as depicted in Figure 4-1 requires four of these pure counter-flow heat exchangers. Because of the need to reach TES temperatures as close as possible to the air temperature at the compressor outlet, the main heat exchangers need a transfer surface up to five times larger than usually. Of course, the required transfer surface depends on the desired terminal temperature difference, which is directly linked to the resulting TES temperature and therefore to the achievable cycle efficiency of the storage. Hence, the heat exchanger dimensioning is carefully optimized in the present project. This optimization is of special importance, since the main heat exchanger components represent a significant part of the investment costs not as high but in the same range as the cost of the turbomachinery itself. Therefore, an economically well balanced plant configuration has to be achieved. Based on first estimations specific initial cost for the 50 MW / 150 bar LTA-CAES plant of below 1,000 €/kW are reachable.

Number, position and design of the main heat exchangers directly determine the TES temperature. Varying these parameters easily leads to higher or lower TES temperatures. By thermodynamic simulations it could be concluded that TES temperatures feasible with the present plant concept range from 90 to 200 °C. Depending on which temperature is aimed at, the TES medium would be water, pressurized water or an organic medium. From a TES point of view using water at temperature below boiling point would be the most favorable solution. This, in turn requires a higher number of main heat exchangers, which is generally not desired. Another factor determining the TES temperature of choice is the achievable start-up time. Higher TES temperatures demand longer start-up times with regard of keeping the thermal stresses to a minimum. Later in this paper it will be shown, that a start-up time below 5min would increase drastically the storage plant revenues. Consequently, a well balanced solution taking into account initial cost against possible plant revenues has to be found. Depending on the chosen thermal solution cycle efficiencies from 0.58 to 0.67 can be achieved.

5 Economic Analysis

5.1 Model and Scenario

The economic performance of the LTA-CAES concept is based on its maximal annual revenue, which is calculated by the generic optimization model GOMES® [9].This model bases on the optimization software GAMS and uses the solver CPLEX. It was developed at Fraunhofer UMSICHT to economically optimize the unit commitment of different storage technologies while operating at several energy markets simultaneously. Because of its modular design GOMES® is able to calculate a wide range of scenarios. Different storage technologies can be considered as well as energy markets or renewable energy producers.

The described short start-up time of LTA-CAES enables its participation in the Secondary Control Reserve (SCR) market. Hence, a new model component was added to GOMES® to take the additional restrictions to the usual mode of operation into account [10]. To ensure the ability of the storage to serve the SCR calls, the provision of sufficient storage capacity is just one demand. The usual permissible range of provided reserve power is restricted as well, and a part of the grid connections capacity is blocked during the bid period. Because of the limited storage capacity, the SCR module assumes a pool to buffer SCR calls, which can not be served by the storage itself. This pool consists of the storage technology, a conventional power plant and an industrial consumer. The use of the pool is severely restricted during the optimization and considered in the economical results by additional costs.

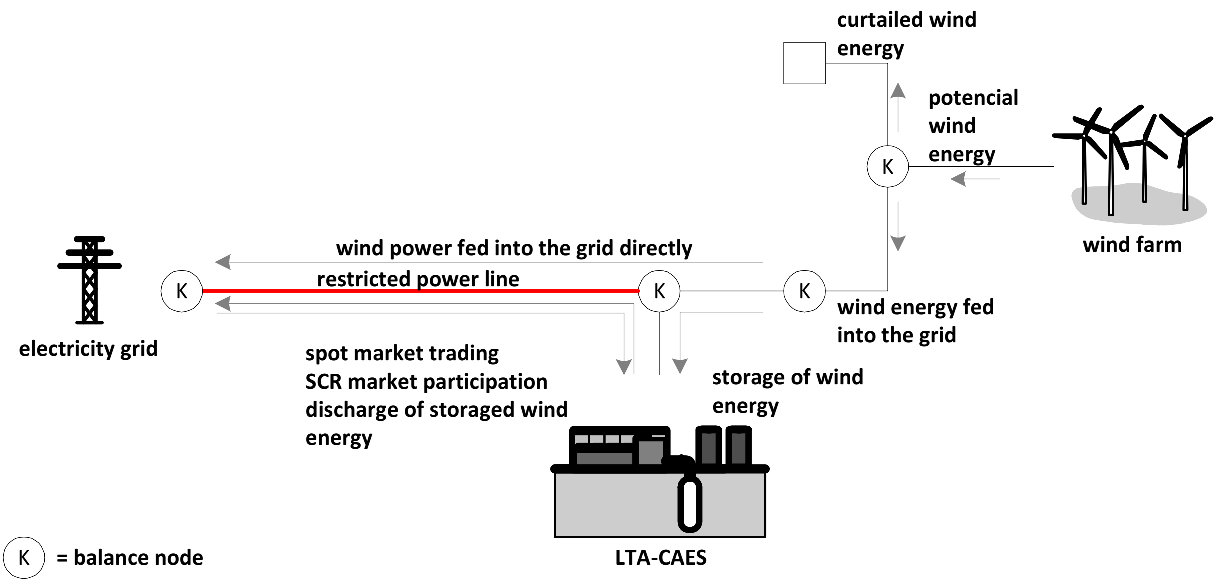

Figure 5-1: Scenario of a LTA-CAES combined with a nearby wind farm and able to trade at different energy markets

Figure 5-1 shows the considered scenario of a LTA-CAES located next to a wind farm and connected to the grid by a restricted power line. The storage is therefore able to minimize the wind energy curtailment and to trade at energy markets at the same time. The assumed scenario parameters are shown in Table 5-1.

Table 5-1: Scenario parameters

Parameters	Value
Representative time series period	2008 and 2009
Inst. compressor power	50 MW
Inst. expander power	35 MW
Part load ability	>30% / >50%
Cycle efficiency	60% / 65%
Storage capacity	8 h of turbine operation at full load
Stand-by storage losses	0.5% per day
Variable operation costs	2 €/MWh
Start-up cost	4 €/MW
Wind farm	350 MW
RES feed-in-tariff	61.9 €/MWh
Transmission line restriction	260 MW
Capacity price (SCR)	monthly average value
Positive and negative energy bid (SCR)	monthly average value

5.2 Results

Mode of operation

Depending on the type and value of the offer at the SCR market, the mode of operation is changed clearly. The unit commitment of LTA-CAES is dominated by the provision restrictions in the bid periods. According to this fact, spot market trade is clearly limited. Because of the restricted purchase in off-peak periods or sale in peak periods there are also effects on periods without any offer.

Use of the pool

As mentioned before, SCR calls not served by the energy storage are summed in a pool. The energy delivered or received by this pool is considered by additional costs and calculated in the annual revenue afterwards. The amount of energy delivered or received by the pool depends on the bid value as well as the absolute number of SCR calls in the considered year. Generally, higher bid values increase the amount of pool energy involved. This leads to additional costs and has a clear effect on the realizable present value of the storage. Design parameters like cycle efficiency or part load ability have a minor effect on the usage of the pool.

Relative present value

For evaluating LTA-CAES profitability it is of interest how much the present value can be increased by providing SCR in addition to spot market trading only. A first answer to that question is given in Figure 5-2. Here, the relative present value of an LTA-CAES (y-axis) plant is shown for different bids into the SCR market (x-axis). A SCR-bid of 0 MW means spot market participation only and is considered as the reference case. The present values are calculated by the optimized annual revenue, discounted over 20 years with an interest rate of 5%.

As can be seen in Figure 5-2, the course of the relative present value can be divided into three sections depending on the value of the SCR market offer. In the first section the present values are not significantly higher and in some cases even lower than that one of pure spot market trading. This effect is based on high operation costs, because of the continuous spinning of the LTA-CAES due to SCR market offer values lower than the part load ability of the turbo machinery. Exceeding this barrier the present value is not reduced by operation costs any longer and therefore pushed up by the additional SCR income. The strong decrease in the third section is the result of the considerable increase in pool usage, because of bid values higher than the maximal expander capacity. The additional costs for its use overweigh the benefits of the SCR market participation.

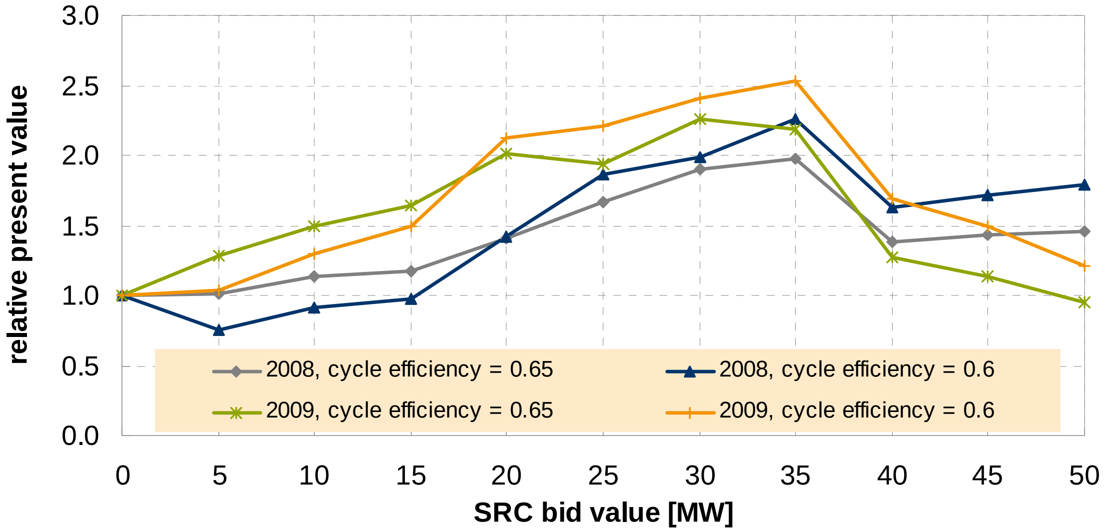

Figure 5-2: Relative present value of a negative SCR bid in the peak period

Absolute present value

Figure 5-3 shows the absolute present values of the analyzed types (negative/positive/peak/off-peak) and values (0-50 MW) of SCR offers in a topographical representation. As can be seen in Figure 5-3, the global maximum is independent of the plant design always located at a negative SCR offer in the off-peak period. The optimal bid value is 25 MW for layouts with a part load ability of 50% and 20 MW at 30%. Another interesting result is that the cycle efficiency has no further effect on the location of the global maximum, but only on the level of the absolute present values.

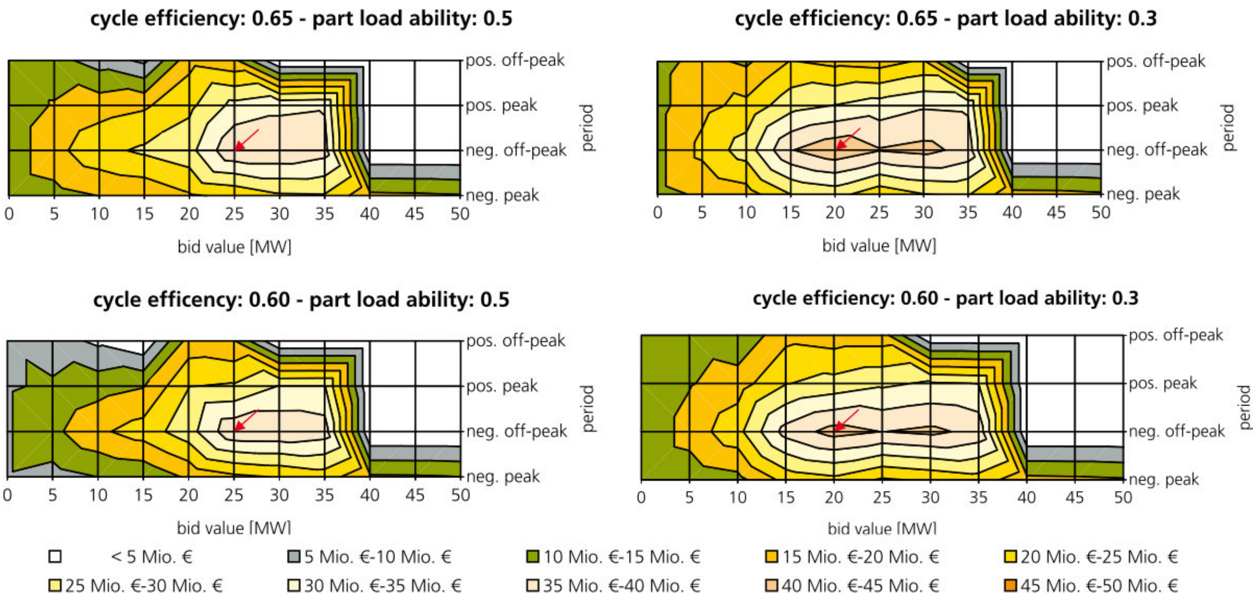

Figure 5-3: Topographical representation of the absolute present values; arrow indicates the point of highest absolute present value

Considering the technical and economical results, the optimal SCR offer is a negative one in the off-peak period. The realizable present values lead to specific break-even initial costs of up to 1,249 € referred to the installed turbine power in kW. Table 5-2 shows the specific results for different plant configurations just trading at the German spot market and for the additional participation in the SCR market with a negative bid in the off-peak period. Here, it can be seen again, that the influence of part load ability on the economical result of a storage offering SCR is as high as that of the cycle efficiency. Compared to usually assumed capital costs of 1,000 €/kW it is obvious, that pure spot market trade is not able to refinance an A-CAES even at higher cycle efficiencies. Therefore, participation in the German SCR market is a clear benefit, allowing for a profitable LTA-CAES plant operation already under today's market conditions.

Table 5-2: Specific break-even costs

Cycle efficiency	Part load ability	Day-ahead spot market trade only		Additional SCR market participation	
[%]	[%]	[€/kWh]	[€/kW$_{Turb}$]	[€/kWh]	[€/kW$_{Turb}$]
60	30	22	290	116	1,197
	50	20	272	108	1,115
65	30	31	387	126	1,249
	50	28	342	113	1,124

6 Conclusion

Low-temperature Adiabatic Compressed Air Energy Storage (LTA-CAES) represents a new approach to realize non-fuel consuming CAES. The approach aims at comparatively low storage temperatures of 90 to 200 °C. The main plant subsystems are derived from already proven technologies guaranteeing minimal development effort on the component level. The Thermal Energy Storage (TES) is designed as a non-thermocline two-tank system similar to those applied in Concentration Solar Power (CSP) plants. The turbomachinery is based on individually cased radial stages as already successfully deployed in air separation and other process industry plants. The radial stages are either integrally geared or directly driven. LTA-CAES as proposed here offers the following advantages:

- Fast plant start-up of < 5min qualifying LTA-CAES plants to provide Secondary Control Reserve (SCR)
- Inexpensive, highly available and environmental friendly TES medium water applicable
- No interaction between air and TES medium keeping the air completely free of particles
- Broad control range and good part load behavior
- High outlet pressures of 150 bar and beyond feasible allowing for higher storage densities und less siting restrictions

A cycle efficiency of 58 to 67 % is to be expected for the LTA-CAES concept. For a system of 8h storage volume the target initial cost are estimated to be below 1,000 €/kW. We finally show that LTA-CAES appears to be profitable in Germany taking 2008 and 2009 market data as a reference. Especially the ability to provide SCR contributes substantially to the overall plant revenue.

7 References

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