Sensitivity Analysis of Adiabatic Compressed Air Energy Storage

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***Abstract*—The increasing use of fluctuating renewable energy represents a challenge for the German electricity market. Electricity storage plants can provide flexibility to the energy system and the development of new, efficient and economical energy storage technologies is of great importance. In this paper, the use of compressed air energy storage plants in the German electricity market is simulated and a sensitivity analysis is carried out. The optimization of the system is done to minimize at each time step the total system costs. The analysis shows the influence of storage plant parameters such as efficiency, storage capacity and natural gas usage on the dispatch and operation hours. It is performed over one year and for three different future scenarios. The results indicate that utilization of storage plants will increase in each scenario considered from 2025 to 2035 but remains in most cases significantly below the maximum capacity of 3000 h/a power generation. While the operation of storage plants lowers the total electricity cost, earnings per plant and profits are not necessarily positive: the wholesale price signals do not create enough revenues to justify the investment in CAES plants.**

***Index Terms*—Energy management, energy storage, optimization, sensitivity analysis.**

I. INTRODUCTION

The target of the German "Energiewende" is 80 % electricity generation from renewables by 2050 [1]. Most of the renewable energy comes from wind and sunlight, both fluctuating sources. More flexibility will be required of the generation assets in the electric grid to ensure the balance between production and consumption, system stability and security of supply. In order to achieve such flexibility in an efficient and sustainable way, energy storage is a widely acknowledged option.

The ADELE program is part of the "Energy Storage Funding Initiative" of the German Federal Government and is supported by the German Federal Ministry for Economic Affairs and Energy. The focus of ADELE ("**A**diabater **D**ruckluftspeicher für die **Ele**ktrizitätsversorgung" - adiabatic compressed air energy storage for electricity supply) is the study and development of adiabatic compressed air energy storage (CAES) plants that can store electricity efficiently and in 100 MW scale over multiple hours similar to pumped hydro. The work includes system design of various concepts, specification and layout of the core components cavern, thermal storage system and turbomachinery as well as studying the grid and market integration [2]. The program consortium consists of German Aerospace Center e.V. (DLR) as the consortium leader, RWE Group Business Services GmbH, GE Global Research, Ed. Züblin AG, Otto-von-Guericke-Universität Magdeburg and Fraunhofer IOSB-AST.

The current work of Fraunhofer IOSB-AST and GE is a techno-economic consideration of profitability for different ACAES systems when the total system costs are minimized.

II. OPTIMIZATION MODEL

Fraunhofer IOSB-AST has developed a fundamental optimization model of the German electricity market. The objective is to find the optimum operation of the German power plant park including storage assets by minimizing the total system costs subject while meeting the demand. The total system costs include the costs of electricity production of the power plants and the costs of natural gas for the fired CAES variants. The model is based on mixed integer linear programming. Below is a simplified specification form of the used optimization problem:

$$\min\left\{\sum_{t=0}^{T}\left(\sum_{i=1}^{S} c_i^S(t)x_i(t) + \sum_{i=S+1}^{P+S} c_i(t)e_i(t)\right)\right\} \quad (1)$$

$$s.t. \qquad \ell(t) \le \sum_{i=1}^{P+S} e_i(t)x_i(t) + e_R(t), \quad (2)$$

$$0 \le l_i(t) = \sum_{j=0}^{t} e_i^S(j)x_i^S(j) - e_i(j)x_i(j) \le v_i, 1 \le i \le S, \quad (3)$$

$$0 \le e_i^{min} \le e_i(t) \le e_i^{max}x_i(t), \quad 1 \le i \le P+S, \quad (4)$$

$$0 \le e_i^{S,min} \le e_i^S(t) \le e_i^{S,max}x_i^S(t), \quad 1 \le i \le S, \quad (5)$$

$$0 \le x_i(t) + x_i^S(t) \le 1, \quad i = 1, \dots, S, \quad (6)$$

$$x_i(t), x_i^S(t) \in \{0,1\}, \quad (7)$$

$$t \in \{0,1,\dots,T\}. \quad (8)$$

Here we denote by

- P, S, T the number of power plant cluster, storages and time steps respectively,
- $c_i(t), c_i^S(t)$ the marginal costs of element $i = S + 1, \dots, P + S$ and the costs for natural gas of element $i = 1, \dots, S$ at time t,

- $e_i(t), e_i^S(t)$ the discharged (charged) energy from unit i at time t,
- $e_R(t)$ the energy from renewable sources at time t,
- $\ell(t)$ the energy load at time t including the trade,
- $x_i(t), x_i^S(t)$ the indicators for discharge (charge) of element i at time t,
- e_i^{min}, e_i^{max} the minimum and maximum discharge power depends on monthly availabilities, reserves of element $i = S + 1, \ldots, P + S$ and efficiency of element $i = 1, \ldots, P + S$,
- $e_i^{S,min}, e_i^{S,max}$ the minimum and maximum charge power depends on minimum and maximum capacity of element $i = 1, \ldots, S$,
- $l_i(t)$ the storage level of $i = 1, \ldots, S$ at time t and
- v_i the volume of the storage i.

In the optimization problem, the variables $x_i(t)$ are restricted by additional constraints. These constraints are used to describe the required minimum operation time and minimum downtime of each power plant cluster. In our model, one time step $t \rightarrow t + 1$ represents one hour. Since the optimization runs over an entire year this yields $T = 8759$ time steps. Due to complexity issues the optimization was automatically executed on a rolling eight-day basis with the next optimization always starting after the preceding optimizations' seventh day.

The modeling was done with the optimization tool of the software solution EMS-EDM PROPHET®. The General Algebraic Modeling System (GAMS) was used for the mathematical formulation of the optimization problem and the calculations were performed with the solver CPLEX. The model is described in detail in [3].

All power plants in Germany are included in the optimization model in clusters containing the individual plants with averaged characteristics. This clustering method significantly reduces the amount of data to ease the adjustment to future scenarios. The four clustering criteria are:

- Energy source
- Age
- Capacity
- Combined heat and power (CHP) capability.

The storage plants, CAES and pumped hydro, were integrated into the model. Depending on the future scenario, the model contains 54 to 69 power plant clusters and 30 to 36 pumped hydro power plants. Each storage plant is modelled separately to make sure the storage capacity is not exceeded. For the CAES study, three types of compressed air storage plants with different technology are integrated into the fundamental optimization model for the scenario calculations.

The model does explicitly not aim at maximizing the profit of each individual plant. The profitability of the individual plants is not checked at the end of the simulation year. Just as all other plants in the model, the storage plants are dispatched in a way to minimize the total system costs for generating the required amount of electricity to satisfy the demand. As a result of the optimization, energy prices are calculated based on the power plants marginal costs according to the merit order principle. Constraints for the optimization model result from scenario definitions and include energy load conditions, feed-in from renewable energy sources and restrictions of power plants and storage systems.

III. Configurations

A. CAES Power Plants

Two gas turbine power plants using compressed air storage have been providing peak load generation and ancillary services since 1978 in Huntorf (Niedersachsen), Germany, and since 1991 in McIntosh (Alabama), USA. In these plants, known as CAES, the air is compressed in an intercooled compression train before being stored in an underground cavern. The heat of compression is discharged by the intercoolers at low temperature to the environment. For power generation, the air is heated through combustion of natural gas prior to expansion in the turbines. A considerable fraction of the electric energy driving the compressors is dissipated as intercooler heat and lost in the process, while natural gas is used later for reheating the air.

With a renewed focus on storing electricity with high efficiency, like in pumped hydro power plants, adiabatic CAES concepts were developed. These plants store the heat of compression while cooling the air in a heat storage system and use this heat during the generation phase for the expansion without the need for natural gas. Adiabatic CAES use relatively more electricity for compression but save natural gas, which can be used for electricity generation more efficiently in gas turbine combined cycle plant. Concepts for adiabatic CAES plants promise to generate almost 70 % of the electricity in the turbines that has been used in the compressors for storage, while CAES plants only generate about 50 % ... 54 % of the combined electricity and fuel input. Adiabatic CAES plant concepts have been developed by the German ADELE consortium [2], [7], [8] amongst many others, but not yet been built.

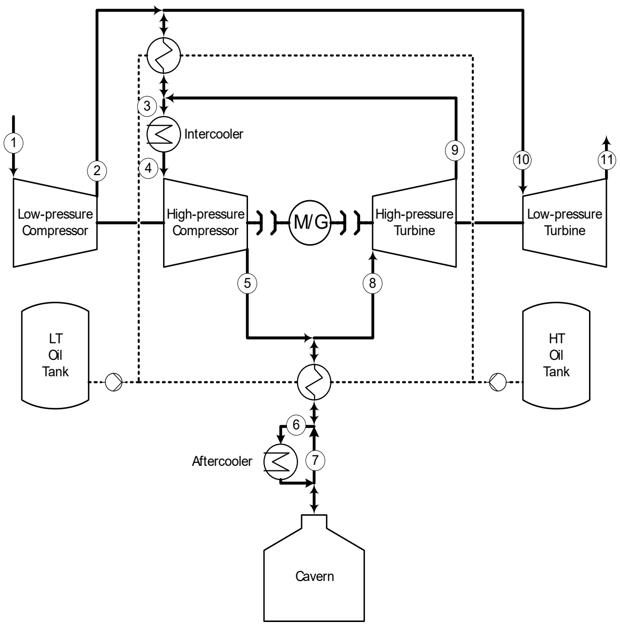

FIGURE 1: FLOW DIAGRAM OF AN ACAES PLANT

Between CAES plants that generate higher power with lower efficiency using high-temperature firing, and adiabatic CAES plants, which store more electricity and re-use compression heat, hybrid solutions can be found that increase the expansion power of an efficient adiabatic CAES plant by raising the turbine inlet temperature through natural gas combustion. Though overall efficiency suffers, it is still higher than in a CAES plant without heat storage and the amount of natural gas usage is smaller, potentially improving profitability.

Another type of CAES plant considered in this analysis uses the exhaust gas waste heat of a neighboring open gas turbine for heating the air prior to expansion, replacing most if not all natural gas use in the CAES system. The operation of gas turbines tends to coincide in time with the generation phase of storage plants as both sell their electricity only when demand is high. CAES using exhaust gas heat matches well with gas turbine plants when natural gas prices are sufficiently low to operate simple-cycle gas turbines during peak demand. A concept of such a plant with the designation "CAES-GT" that uses the heat of two GE LM6000 gas turbines is included in this study.

A modern combined cycle gas turbine plant with an efficiency of 60 % and a power rating upwards of 500 MW is often considered the benchmark for power generation. Conceivably, such a plant could be turned into a giant CAES plant and several authors have in past provided concept studies [9]. There are engineering challenges to be surmounted: huge low-loss heat storage, large cavern added to the plant and split of the gas turbine into two separate compressor and expander units. If such a power plant could be built, it would outperforms any current CAES concept in terms of power, efficiency and operation hours. This concept is included as "CAES-CC" in this study although it has not been further developed in the ADELE program.

The key performance parameters of the three types of CAES plants described above are shown in TABLE I. These are the baseline configurations based on feasibility analysis or conceptual plant layouts and specifications from the on-going ADELE program. Power plant design and specification constantly requires trade-off choices between lower cost or larger components and higher efficiency. Information for deciding reasonable equipment specifications comes from assessing the market value resulting from any performance trades. In order to analyze the sensitivity of the dispatch hours, revenue and profitability in the market relative to these plant parameters, the simulations include not only the CAES plants with baseline specifications in the table, but also plants with modified efficiency and storage capacity.

B. *Future scenarios for the years 2025 and 2035*

The three different future scenarios differ in terms of the electric capacities installed for each energy source, the amount of electricity traded with other European countries and the electric consumption and prices for fossil fuels.

The power plant park for the three scenarios is based on the list of power plants of Bundesnetzagentur [4] and has been adjusted with respect to the installed capacities for each scenario. The installed capacities for the three scenarios are shown in Table II. The category "Renewables" includes hydropower, wind, solar photovoltaic and biomass. Other remaining conventional and renewable energy sources are summarized in the category "Other". 2012 was selected as reference year, on which the times series for fluctuating renewables, demand and

TABLE I CAES POWER PLANT DATA

Plant Type Name	Operation Mode	Power [MW]	Duration [h]	Efficiency [%]	Combustor [MW]
Adiabatic / Hybrid with add'l firing „ACAES"	Charge	64.0	7.1	-	-
	Discharge adiabatic	78.0	4.0	68	-
	Discharge fired	96.0	5.3	56	86
Diabatic 2xLM6000„CAES-GT"	Charge	73.4	5.7	-	-
	Discharge	77.0	4.0	74	-
Combined cycle split-GT "CAES-CC"	Charge	445	6.0	-	-
	Discharge fired	897	6.0	70	833
	GuD	500	-	60	833

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cross-border trade are based. These time series were then scaled to match the required capacity depending on the scenario.

The three future scenarios are characterized by the specifications and assumptions summarized in the following paragraphs.

TABLE II CHARACTERISTICS OF THE BASE SCENARIO

Characteristics of the Base Scenario	Values		
	Unit	***2025***	***2035***
natural gas price	€cent/kWh	3.1	3.2
oil price	€/t	737	807
hard coal price	€/t	114	123
CO_2 certificate costs	€/t	25	52
gross electricity consumption	TWh	564	552

1) Base Scenario: This scenario is constructed from the Trend Scenario of the EWI-Prognos study [5]. Although renewables rise further and nuclear is phased out, the fossil fired installed capacity is higher than in the alternative scenarios. At the same time, the proportion of feed-in by windand photovoltaics increases. Rising commodity prices for natural gas, oil and hard coal as well as rising CO2 certificate costs are assumed. Compared to the reference year 2012, a lower electricity consumption is assumed.

2) Alternative Scenario 1: This is based on the Target Scenario of the EWI-Prognos study [5]. This scenario describes the framework to achieve the target of the German government with respect to the „Energiewende." An increase in renewable capacities is assumed while hard coal- and lignite-based power generation is reduced and natural gas becomes the most important fossil energy source. This scenario is characterized by very high commodity prices for natural gas, oil and hard coal and CO_2 certificate costs. This scenario accepts the highest natural gas prices compared to the other two future scenarios. In the Alternative Scenario 1 a lower gross electricity consumption is assumed in the years 2025 and 2035 compared to the Base Scenario.

3) Alternative Scenario 2: This scenario is based on Scenario B2 of the NEP 2015 [6]. It is characterized by a large newly installed capacity of renewable energy sources and the reduction of lignite and hard coal power plants. The significant reduction of coal power plants is compensated here by an increased newly installed capacity of gas-fired power plants. Contrary to the other two scenarios, wind power plants dominate the renewable energy sources. The net electricity consumption is assumed for both years constant at 543.6 TWh. Compared with the other two scenarios, the CO_2 certificate costs and the price for oil and hard coal are expected to be lower. This scenario assumes the highest expansion of renewable energy sources.

C. Sensitivity of the CAES plant market performance to storage capacity and efficiency

The sensitivity analysis was performed to find the change in operation hours, revenues and profitability of the CAES plants with respect to their discharge time and thermal efficiency. In the basic configuration, all the CAES variants have a discharge time of 4 hours, except for CAES-CC, which has 6 hours. For the sensitivity analysis, calculations were performed for each variant with discharge times of 2 hours more or less than the baseline and all other parameters remaining the same. To adjust the efficiency by plus/minus 5 %, the quantity of compressed air required for the given discharge duration decreases and increases by 5 %, respectively, which leads to shorter/longer charge duration while the compressor and expander power remain constant.

TABLE III INSTALLED CAPACITIES OF FUTURE SCENARIOS

Capacity of Energy Sources in GW	Base Scenario		Alternative Scenario 1		Alternative Scenario 2	
	2025	***2035***	***2025***	***2035***	***2025***	***2035***
Lignite	19.0	17.5	17.0	16.5	12.6	9.1
Hard coal	23.0	22.5	23.0	18.5	21.8	11.0
Natural gas	31.0	33.0	28.0	25.5	29.9	40.7
Oil	2.0	1.5	2.0	1.5	1.1	0.8
Other	2.0	3.0	2.0	3.0	3.9	4.3
Renewables	124.0	142.0	132.0	152.5	140.6	179.8
Total	**201.0**	**219.5**	**204.0**	**217.5**	**209.9**	**245.7**

IV. RESULTS

Table IV presents the results for the basic configurations for every scenario in 2025 and 2035. The results of the sensitivity analysis are also shown in this table, indicating for each concept the improvement to be expected from an increase in efficiency or in discharge capacity. The results show the full load hours and the earnings per MW, whereby earnings is the difference between the cost for buying energy and the revenue from selling electricity for the hourly market prices resulting from the optimization model. No further operating costs, financing and depreciation etc. are considered.

The results for the discharge full load hours appear low compared to the maximum of app. 3000 h/year, i.e. storage plants tend to be frequently idle or in low part load. However, full load hours generally increase from the Base Scenario to the Alternative Scenarios and from 2025 to 2035. As already discussed, the Alternative Scenario 1 is characterized by a higher PV production that leads to a storage supportive residual load. In Alternative Scenario 2 production from wind is dominant, which leads to fewer full load hours for the considered CAES plants that provide short-term storage only. PV deployment is more favorable to CAES systems than wind deployment. In all cases, an increase of storage capacity by 2 h increases the number of full load hours.

Before discussing the specific earnings, it should be stressed that the objective function of the model is minimization of total system costs. For this reason, the model dispatches the storage plants irrespective of individual plant profits or losses. The earnings increase from the Base Scenario to the Alternative Scenarios although the full load hours are decreasing in Alternative Scenario 2. Reasons are higher electricity prices resulting from increased marginal costs of the power plants. Both Alternative Scenarios show less capacity of thermal power plants, whereby the remaining flexible power plants that set the prices tend to be costly gas turbine plants.

The sensitivity analysis shows how an increase of 2 h storage capacity leads to an increase in operating hours and in

TABLE IV RESULTS OF THE SCENARIO CALCULATION

Scenarios	**Results of Scenario Calculations (base configuration)**				**Results of Sensitivity Calculations (best variant)**		
	Year	***CAES concept***	***Earnings € per MW***	***full load hours in h***	***CAES concept***	***Earnings € per MW***	***full load hours in h***
Base Scenario	2025	ACAES unfired	1,092	684	ACAES unfired	1,092	684
		ACAES fired	58	131	ACAES fired (+2 h)	280	151
		CAES-GT	653	93	CAES-GT	653	93
		CAES-CC	-28	152	CAES-CC (-5 %)	16	155
	2035	ACAES unfired	-863	825	ACAES unfired (+2 h)	-625	851
		ACAES fired	-1,208	461	ACAES fired (+5 %)	-641	444
		CAES-GT	2,488	248	CAES-GT (+5 %)	4,585	297
		CAES-CC	-1,344	451	CAES-CC (+2 h)	-607	463
Alternative Scenario 1	2025	ACAES unfired	9,625	1,873	ACAES unfired (+5 %)	10,172	1,913
		ACAES fired	925	1,093	ACAES fired (+2 h)	2,515	1,173
		CAES-GT	9,244	653	CAES-GT (+5 %)	11,214	669
		CAES-CC	-498	1,051	CAES-CC (+2 h)	861	1,107
	2035	ACAES unfired	21,360	2,991	ACAES unfired (+2 h)	26,113	3,212
		ACAES fired	1,159	2,311	ACAES fired (+2 h)	5,627	2,461
		CAES-GT	14,218	2,258	CAES-GT (+5 %)	25,425	1,349
		CAES-CC	-2,384	2,208	CAES-CC (+2 h)	2,735	2,343
Alternative Scenario 2	2025	ACAES unfired	14,237	1,265	ACAES unfired (+2 h)	19,332	1,580
		ACAES fired	3,721	429	ACAES fired (+2 h)	5,726	593
		CAES-GT	10,857	435	CAES-GT (+2 h)	15,869	606
		CAES-CC	4,751	480	CAES-CC (+2 h)	6,088	594
	2035	ACAES unfired	8,888	1,099	ACAES unfired (+2 h)	12,531	1,443
		ACAES fired	1,732	478	ACAES fired (+2 h)	2,494	609
		CAES-GT	7,500	349	CAES-GT (+5 %)	11,203	441
		CAES-CC	1,642	482	CAES-CC (+2 h)	3,235	595

earnings. An increase of 5 % in efficiency shows an improvement mostly in earnings but to some extent also in operating hours. These increases in earnings and operating hour as a function of incremental capacity and efficiency can be used for plant optimization when traded against the associated increase in capex.

In all three future scenarios, the unfired ACAES configuration achieves significantly higher specific earnings and higher full load hours than the fired ACAES. Apparently, it is often not economical to generate additional power through natural gas. The fewer hours of the fired variant are also due to the assumption that the fired configuration always burns natural gas when in operation, rather than optionally only in case it is economical to generate extra power at the expense of burning gas. The unfired ACAES variant shows an increase of full load hours in every scenario compared to 2025 base except for the Base Scenario in 2035, where ACAES unfired has negative earnings.

For the ACAES plant, an increase of the storage capacity rather than of the efficiency leads to an improvement in full load hours. For the CAES-GT variant, a better efficiency has more effect on the earnings than higher capacity.

V. CONCLUSION

The operation of compressed air energy storage plants within the German electricity market has been analyzed in this paper using the clustered fundamental model. Studies were performed for three future scenarios for the years 2025 and 2035. The calculations were carried out exclusively under techno-economic considerations for minimizing the total system costs. A strategic market behavior for profit maximization is not used in the optimization model.

The sensitivity analysis shows that an increase in the discharge time of a storage plant from 4 h to 6 h increases full load hours and revenues for all variants, just as an efficiency increase. Taking into account full investment calculations, profitable concepts will be selected in further work packages of the ADELE project. Simulations will be carried out with a more detailed model of a CAES plant including the individual components compressor, expander, heat storage and cavern, aiming at an optimized use of the CAES plant in a (real) power plant portfolio with profit maximization. For a detailed economic evaluation, the capex and opex costs of the CAES plant variants must be considered in addition to the revenues, but the current results indicate which variants are promising. Discharge time and efficiency of the plant can be optimized when their relative capex is considered.

It is often stated that storage plants are essential for the successful implementation of the German “Energiewende”. In addition to the undisputed economic value for the energy system as a whole, business value for the operators of storage plants must be realized under market conditions. The results presented here show that profitable operation of storage plants will be challenging with the market prices in any of the scenarios. This is also true for the “peaker” plants, which have a very low number of full load hours: the plants are assumed to be part of the power plant park in the scenarios considered, but their economic viability from the point of view of the plant operator is not given.

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