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Energy Procedia 105 (2017) 3798 – 3805

Energy Procedia

The 8th International Conference on Applied Energy – ICAE2016

Economic feasibility of a Compressed Air Energy Storage system under market uncertainty: a real options approach

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Abstract

Since the liberalization of electricity markets power prices are considered as highly volatile. Thus investment in new power plants is exposed to higher risks. Traditional capital budgeting methods lack the integration of flexibility. This can be overcome by applying real options analysis. In the context of an increasing electricity production by highly volatile renewable power plants, new solutions need to be found to ensure security of supply and to accommodate intermittent generation. Energy storage is seen as a possible solution. The Compressed Air Energy Storage (CAES) technology provides many key features that are relevant to deal with arising problems by renewables. Lately an advanced adiabatic version with higher roundtrip efficiencies has been discussed. However, high capital expenditures limit the economically viable implementation. As conventional CAES uses natural gas for production, it is exposed to price fluctuations on two markets. Depending on the configuration of component sizes, CAES storage units can be used for different purposes. A price model is set up to produce, in combination with the application of a Monte Carlo simulation, possible future price paths for power, natural gas and demand rate for minute reserve. Based on these price paths costs and revenues for different CAES applications are calculated. For the economic evaluation three different configurations are considered for both diabatic and adiabatic CAES. Investment in a diabatic CAES used for load-leveling purposes is found to be the most economical option.

Peer-review under responsibility of the scientific committee of the 8th International Conference on Applied Energy.

Keywords: CAES, Real option, Minute reserve

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Peer-review under responsibility of the scientific committee of the 8th International Conference on Applied Energy.
doi:10.1016/j.egypro.2017.03.888

1. Introduction

Since the introduction of the Renewable Energies Act in Germany (the EEG), power generation from renewable energy sources (RES) has grown enormously. However, electricity production from RES is driven by volatile weather conditions rather than actual energy demand. Energy storage, besides alternative options such as grid expansion, more flexible power plants or demand response, is discussed as one possible solution to maintain the balancing of electricity demand and supply at any point in time [1].

Nomenclature

DR	Demand rate (positive/negative)
HR	Heat rate
κ	Rate of adjustment (back to the mean value of the price)
L	Mean value of the simulated price
P	Price of electricity/natural gas
PR_{com}	Power rating compressor
PR_{tur}	Power rating turbine
OC_{spot}	Operating cost spot market
OR_{res}	Operating revenue reserve market
OR_{spot}	Operating revenue spot market
σ	Volatility of simulated prices
t	Charging/discharging time of the storage unit
dZ	Wiener process

In this context, despite its rather low roundtrip efficiency of only 54%, Compressed Air Energy Storage (CAES) is a mature storage technology that is able to cope with that challenge [2]. The adiabatic CAES does not rely on adding natural gas during the generation stage, but instead uses the heat that arises during the compression phase. With no other fuel input adiabatic CAES achieves roundtrip efficiencies of up to 70% [3]. However, apart from attractive technical features the deployment of the CAES technology also depends on its economic viability. The price spread between low-cost off-peak hours and high-priced on peak hours can be used for gaining profits from temporal arbitrage. In general, a CAES system is composed of three major elements: (1) a compressor unit, (2) a generation unit, and (3) a storage unit. These units can be dimensioned as needed, and thus the power output per unit of time as well as the duration of a full cycle can be designed flexibly [4]. This allows for different operational purposes. The so-called load-leveling operation shifts demand from daytime to nighttime. Thereby the storage is charged at night and discharged during the day. In contrast, in peak-shaving mode only the highest daily price spreads between single hours that occur are utilized, enabling to exploit the maximal arbitrage potential.

Since the liberalization of electricity markets and the privatization of production utilities, the power markets are opened to competition on both the producer and the consumer side. The installation of energy exchanges brought significant changes to the formation of electricity prices. Today, electricity is traded on the spot market, where demand and supply determine the price for each hour. Hourly prices became highly volatile and the future price development is hard to predict. Investment decisions in the energy sector thus have to be undertaken under uncertain electricity price development, thus exposing irreversible, capital-intensive investments in a CAES power plant to risk [5]. Since an investment in energy storage is not an obligation but an option to an investor, value arises from the possibility to gain information on market development by postponing investment. The investment decision is subject to opportunity costs regarding the deferral of it. Therefore, the investment in a CAES is undertaken only if the current value exceeds the value of postponing [6]. In order to estimate an investment decision under market uncertainty correctly, a method has to be applied that is able to appropriately capture the (value of) managerial flexibility to postpone the project and thus to enable further information gathering. Real options analysis seems to be an adequate approach in this respect.

The main focus of our study is on the identification of the most feasible CAES technology and furthermore on the identification of the optimal operational strategy. Specifically, we compare the diabatic and the adiabatic CAES technology variants for both load-leveling as well as peak-shaving purposes.

2. Methodology

Three investment cases are defined for both diabatic as well as adiabatic CAES. For each case the sizing of components is differentiated by altering the possible operating mode as well as the initial investment costs. In the *Base Case* the power plant endows a 300 MW generation unit. It is operated on the spot market as a peak shaver. The commitment of power is possible for the four highest-priced peak hours. The storage is fully charged for a duration of eight hours, mainly during low-cost off-peak times; therefore, it is operated in a 2:1 manner regarding charging and discharging operation. In *Variant 1*, the CAES power plant's storage capacity and compressor power are increased. It is designed for a daily discharge of eight hours by a 300 MW generation unit. The storage unit is again charged eight hours during low-cost off-peak times, thus charging and discharging operating times are of equal duration (1:1). In *Variant 2*, the CAES power plant is operated in the same way as the *Base Case* (2:1), but turbine power is set to 402 MW. Therefore, more power can be provided during the 4-hour discharge operation, and influencing the optimal sizing of the storage capacity and compressor unit as well.

2.1. Price model

For evaluating the feasibility of the different cases, a dynamic price model was developed for an hourly time resolution based on 10 years of perennial price data. The following mean-reversion process is applied to the data for simulating electricity and natural gas spot prices:

$$\frac{dP}{P} = \kappa\,(L - \ln P)\,P\,dt + \sigma\,PdZ. \tag{1}$$

where κ is the rate of adjustment, L is the mean value of the price simulated, P is the price simulated, dt is a time increment, σ is the price volatility, and dZ is a Wiener process.

The demand rate for minute reserve is modeled as a stochastic process that is based on the probability of occurrence. The price model combines the created paths of electricity, natural gas and minute reserve for an entire year. A single simulated price path is equivalent to a single realization of the probability distribution of the incorporated price data. In order to consider a broad spectrum of the probability distribution of the prices, a Monte Carlo simulation is applied to generate 1000 possible price paths for each year of the power plant's lifetime. A simple algorithm executes the daily unit commitment for each simulated price path in every year. Under perfect price foresight the CAES power plant operator aims at fulfilling a full operation cycle on the spot market on a daily basis. If revenues exceed costs for a specific day, operation is executed based on the following eqs. (2)-(4):

$$OR_{spot} = PR_{tur} * t_{dis} * P_{el} \tag{2}$$

$$OC_{spot} = HR * PR_{tur} * t_{dis} * P_{gas} + PR_{com} * t_{ch} * P_{el} \tag{3}$$

$$OR_{spot} > OC_{spot} \tag{4}$$

where OR_{spot} denotes operating revenues from the spot market, PR_{tur} the power rating of the turbine, t_{dis} the time of discharging the storage unit, P_{el} the price of electricity, OC_{spot} the cost of operating in the spot market, HR the heat rate, P_{gas} the price of natural gas, and t_{ch} the time of charging the storage unit.

Turbine capacity and compressor capacity are additionally offered on the minute reserve market, if an operation on the spot market is not feasible. Due to reasons of simplicity the incorporation of the energy rate is neglected in (5).

$$OR_{res} = PR_{tur} * DR_{pos} * PR_{com} * DR_{neg} \tag{5}$$

where OR_{res} denotes operating revenues from the reserve energy market, PR_{tur} the power rating of the turbine, DR_{pos} the positive demand rate, PR_{com} the power rating of the compressor, and DR_{neg} the negative demand rate.

The respective contribution margin is determined for the single simulated price path and then aggregated to an expected yearly contribution margin by averaging. This is done for each year of the power plant's lifetime.

2.2. Economic evaluation

The averaged margins computed with the price model serve as the foundation for the investment appraisal. It is carried out using the Net Present Value (NPV) method and Real Options (RO) analysis. All cases are assessed over a project lifetime of 55 years, which includes a construction time of five years. The project's implementation can be postponed in annual steps for up of 10 years. The real option to defer the project is evaluated with the binominal lattice model of Cox, Ross and Rubinstein (CRR) [7]. In a sensitivity analysis, input parameter values are varied in order to determine the individual impact on the economic performance of the CAES system. Parameters such as investment costs, tax rate, interest rate, as well as technical parameters such as heat rate and roundtrip efficiency are altered in steps of 10%.

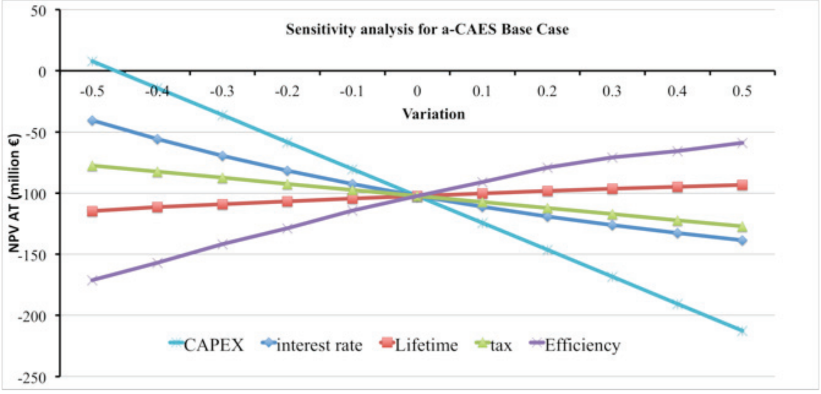
3. Results and discussion

The results show that the diabatic CAES is more economical than the adiabatic CAES in all three cases investigated and with regard to their project value and NPV. More specifically, the diabatic CAES shows higher values for the NPV BT (before tax) and NPV AT (after tax) and features a higher overall project value. However, the option value is higher for adiabatic CAES, being almost twice as high in all three cases. The same applies for the average annual revenues, which are generally higher for adiabatic CAES. Since adiabatic CAES does not rely on natural gas but only on electricity for operation, the independence from natural gas and its volatile prices is an important advantage of adiabatic CAES. In the sensitivity analysis, natural gas-related parameters prove to be the most sensitive parameters for diabatic CAES (Figure 1(a)). Therefore, the economic superiority of diabatic CAES does not rely on higher revenues but merely on the fact that initial investment costs are much lower compared to those of adiabatic CAES. In the *Base Case*, the costs of adiabatic CAES are almost €70 million higher. In *Variant 1*, capital expenditures for adiabatic CAES are more than €100 million larger. Distinct higher investment costs for adiabatic CAES also occur in *Variant 2*. Therefore, the most sensitive parameter for the economic viability of adiabatic CAES is the initial capital outlays arising because of the larger storage unit, compressor power and the additional heat storage unit to store the heat generated from the compression stage. The stored heat is needed during the generation stage in order to avoid the freezing of the generation unit by the expanding air. The sensitivity analysis for the adiabatic CAES is shown in Figure 1(b).

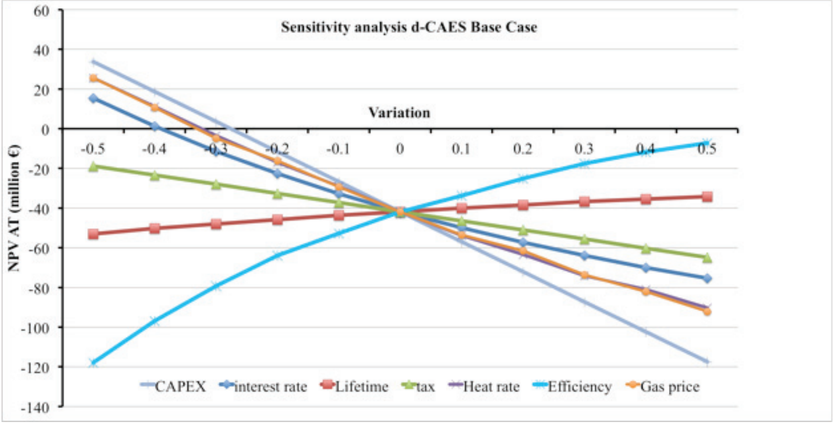
The load-leveling operation, which allows for more full-load hours of discharge, yields a better economic performance compared to the peak-shaving operation. Applying the NPV AT, *Variant 1* is favored (since it is the only result with a positive economic outcome). Based on the positive NPV AT, an instant investment would be reasonable. However, considering the result from the RO analysis, the investment decision needs to be postponed. The option value exceeds the NPV AT; therefore, postponing the decision to invest is more valuable than to invest immediately. Figure 2 presents the annual decisions regarding the investment and the probability of occurrence. With a probability of more than 53% the diabatic CAES with the assembly of *Variant 1* is implemented after one year. At the option's maturity date the probability of project implementation lies at almost 70%. The diabatic CAES, with an operation mode as a peak shaver and a component assembly as in the *Base Case*, is implemented only with a probability of ca. 24% at the maturity date of the real option. A diabatic CAES project with a configuration as in *Variant 2* is implemented with almost 45% at the option's maturity date. Probabilities for the investment in an adiabatic CAES are rather low. An adiabatic CAES with an assembly as in the *Base Case* is implemented only with a probability of about 8% in period 10, the same applies for *Variant 2*. The load-leveling operation proves to be superior economically for the adiabatic CAES as well, as an investment in an adiabatic CAES power plant with the assembly of *Variant 1* is realized with a probability of 46% at the maturity date of the real option (Figure 3).

Table 1: Results of the economic analysis for all three cases investigated, for both diabatic and adiabatic CAES (million €).

Case	CAES technology	NPV BT	NPV AT	Option Value	Project Value	Investment costs	Avg. annual income
Base Case	diabatic	4,196.1	- 41,834.9	57,336.8	15,501.9	151.313.9	7,646.1
	adiabatic	- 52,699.3	- 102,322.9	108,719.4	6,396.5	220,346.5	8,284.5
Variant 1	diabatic	116,364.4	30,304.3	44,237.7	74,542	174,379.2	14,427.9
	adiabatic	33,443.9	- 57,729.7	96,262.8	38,533	274,575	15,198,6
Variant 2	diabatic	9,086.5	- 52,521.9	76,155.3	23,633.4	199,050	10,259.3
	adiabatic	- 66,747.5	- 133,291.5	142,265.5	8,974	291,588.3	11,102.4

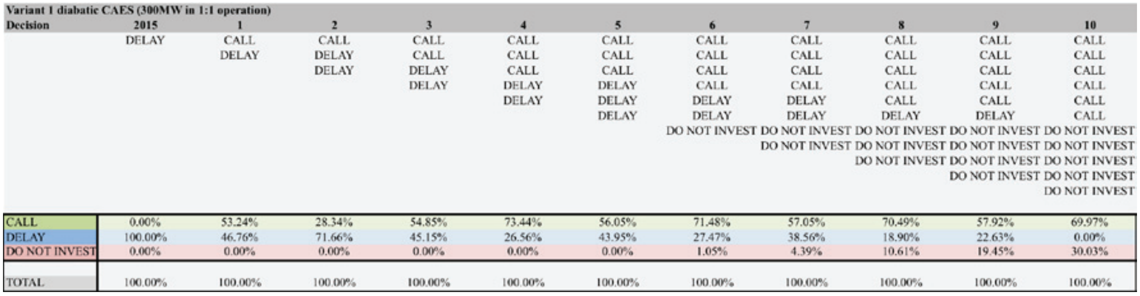


(a) Adiabatic CAES



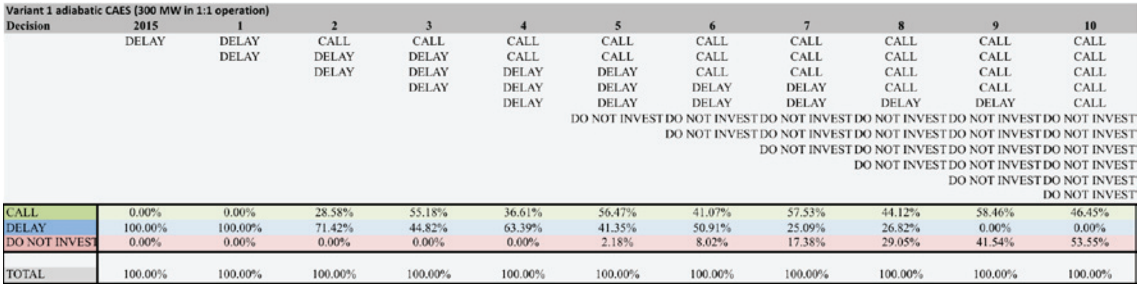
(b) Diabatic CAES

Figure 1: Sensitivity analysis for several input parameters of both adiabatic (upper plot) and adiabatic (lower plot) CAES with regard to the NPV AT, Base Case (parameter value variation of ± 50%).



Variant 1 diabatic CAES (300MW in 1:1 operation)											
Decision	**2015**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
	DELAY	CALL DELAY	CALL DELAY DELAY	CALL CALL DELAY DELAY	CALL CALL CALL DELAY DELAY	CALL CALL CALL DELAY DELAY DELAY	CALL CALL CALL CALL DELAY DELAY DO NOT INVEST	CALL CALL CALL CALL DELAY DELAY DO NOT INVEST DO NOT INVEST	CALL CALL CALL CALL CALL DELAY DO NOT INVEST DO NOT INVEST DO NOT INVEST	CALL CALL CALL CALL CALL DELAY DO NOT INVEST DO NOT INVEST DO NOT INVEST DO NOT INVEST	CALL CALL CALL CALL CALL CALL DO NOT INVEST DO NOT INVEST DO NOT INVEST DO NOT INVEST DO NOT INVEST
CALL	0.00%	53.24%	28.34%	54.85%	73.44%	56.05%	71.48%	57.05%	70.49%	57.92%	69.97%
DELAY	100.00%	46.76%	71.66%	45.15%	26.56%	43.95%	27.47%	38.56%	18.90%	22.63%	0.00%
DO NOT INVEST	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	1.05%	4.39%	10.61%	19.45%	30.03%
TOTAL	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%

Figure 2: Annual investment decisions for the diabatic CAES, Variant 1, and probabilities of occurrence over a time horizon of 10 years.



Variant 1 adiabatic CAES (300 MW in 1:1 operation)											
Decision	**2015**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
	DELAY	DELAY DELAY	CALL DELAY DELAY	CALL DELAY DELAY DELAY	CALL CALL DELAY DELAY DELAY	CALL CALL DELAY DELAY DELAY DO NOT INVEST	CALL CALL CALL DELAY DELAY DO NOT INVEST DO NOT INVEST	CALL CALL CALL DELAY DELAY DO NOT INVEST DO NOT INVEST DO NOT INVEST	CALL CALL CALL CALL DELAY DO NOT INVEST DO NOT INVEST DO NOT INVEST DO NOT INVEST	CALL CALL CALL CALL DELAY DO NOT INVEST DO NOT INVEST DO NOT INVEST DO NOT INVEST DO NOT INVEST	CALL CALL CALL CALL CALL DO NOT INVEST DO NOT INVEST DO NOT INVEST DO NOT INVEST DO NOT INVEST DO NOT INVEST
CALL	0.00%	0.00%	28.58%	55.18%	36.61%	56.47%	41.07%	57.53%	44.12%	58.46%	46.45%
DELAY	100.00%	100.00%	71.42%	44.82%	63.39%	41.35%	50.91%	25.09%	26.82%	0.00%	0.00%
DO NOT INVEST	0.00%	0.00%	0.00%	0.00%	0.00%	2.18%	8.02%	17.38%	29.05%	41.54%	53.55%
TOTAL	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%

Figure 3: Annual investment decisions for adiabatic CAES, Variant 1, and probabilities of occurrence over a time horizon of 10 years.

4. Conclusion

From an investor's point of view, the investment in a diabatic CAES with an assembly for load-leveling purposes as in *Variant 1* turns out to be the most economical option. Still, the investment might not be implemented immediately, but postponed by one year in order to gain additional information about the market development. The adiabatic CAES technology is found to bear great potential. The results from our analysis show that revenues generated by adiabatic CAES are higher on average than for diabatic CAES. The great potential is reflected by its high option value, whereas the project value is rather low. High initial capital expenditures for a larger compressor, storage equipment and for the additional heat storage unit required represent the main obstacle. Therefore, cost reductions can help fostering the adoption and diffusion of adibatic CAES in future applications. The study conducted shows that the Net Present Value method is inadequate when evaluating power plant investment decisions in a market environment that is characterized by high degrees of uncertainty. The NPV method underestimates the project value because it ignores the value of managerial flexibility. Real Options Analysis is a much more powerful and adequate approach in this respect. Although the NPV AT was negative for almost all of the cases considered, the projects nevertheless possess economic value, which is ignored by the simple static Net Present Value calculation. Furthermore, Real Options Analysis is able to provide some guidance on the optimal time for the investment.

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Biographies

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