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Economics of centralized and decentralized compressed air energy storage for enhanced grid integration of wind power

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A B S T R A C T

In this paper we model the economic feasibility of compressed air energy storage (CAES) to improve wind power integration by means of a profit-maximizing algorithm. The Base Case is a wind park with 100 MW of installed capacity and no storage facility. In Variant 1 we add a central CAES system with 90 MW of compressor and 180 MW of generation capacity. The compressed air is stored in a cavern. The CAES system is operated independently of the wind park such that profits from peak power sales on the spot market and the reserve power market are maximized. Variant 2 is an integrated, decentralized CAES system, where each wind turbine is equipped with a compressor but no generator. The compressed air is stored in a cavern and converted into electricity by a turbine, again maximizing profit as a peak power plant. Both variants are modeled for conventional diabatic and the more advanced adiabatic systems. We find that the economics of the systems studied depend on how intensively the spot market and the market for minute reserve are used. Unless a minute reserve market exists, where hourly contracts can be traded, none of the CAES power plants studied is economically feasible. CAES plants can be operated economically if combined trade in the spot market and the minute market is enabled, and provided that some support scheme is in place (e.g., such as the German Renewable Energies Act). A centralized CAES plant is found to be more attractive than a wind power plant with integrated CAES, irrespective of whether a feed-in tariff scheme also exists for the integrated plants. Diabatic CAES turns out to be more profitable than adiabatic CAES.

1. Introduction

Increased use of wind energy is a challenge due to the intermittent nature of wind power. For this reason, in countries with fast growth of installed wind capacity, as, e.g., in Germany, there is great attention on how to integrate a high share of wind energy in the grid. This includes strategies to mitigate the impact on the electricity grid by, e.g., geographic distribution of wind capacities or by improving the weather forecasts. Moreover, there are options that potentially help to manage intermittency more economically, e.g., by means of electricity storage [1,2]. For storage applications with low utilization rates, such as emergency power supply units, the investment costs per unit of power are of great interest. In contrast, for applications to balance fluctuations in wind power production at high utilization rates, the relevant parameter is the investment cost per unit of storage capacity. In this respect, compressed air energy storage (CAES) has a high economic potential and can thus play an important role, especially in the light of lacking alternatives and especially in the range of multiple hourly and weekly storage. One such alternative is pumped storage hydro power, which, due to its existing utilization, often has only limited remaining potential for exploitation.[1] It is thus not very surprising that analysis of CAES has received increasing attention in the scientific the community in recent years (e.g., [3–7]).

There is a growing body of literature on various aspects of CAES. Useful overviews of the basics have been provided by Succar and Williams [8] and Succar [9]. The potential of CAES was already being addressed in the 1970s by Glendenning [10], Giramonti et al. [11] and was more recently investigated by Jaber et al. [12], who introduce a simulation model of the behavior of a photovoltaic gas-turbine hybrid system with CAES. Nyamdash et al. [13] investigate the viability of balancing wind power with large energy storage facilities. The integration of higher penetration levels of

[1] Due to the increasingly limited availability of suitable pumped storage hydro power facilities, as well as environmental restrictions and societal concerns about new facilities, the costs of building such plants have increased. In the US, for instance, there is about 20 GW of installed capacity currently operational, and the plants were mainly built a long time ago between the 1960s and 1980s.

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Nomenclature

Abbreviations
AA advanced adiabatic
CAES compressed air energy storage
EEG Erneuerbare Energien Gesetz (Renewable Energies Act)
WPP wind power plant

Symbols
a annuity factor
AN annuity
C cost (general)
c, c_{fix}, c_{var}, $c_{var,o}$, c_{SM}, c_{gas}, c_{PG}, c_t average cost (fixed, variable, other variable, spot market, natural gas, power generation, yearly)
E_0, E_T, E_{in}, E_{out}, E_{max} energy/filling level (beginning, end, feed-in, extraction, and maximum possible)
f_C, f_T, f_{CAES} conversion factor (compressor, turbine, total CAES system)
i discount rate
I_0 initial investment
K accumulated value of the project
NPV_0 net present value
RoI return on investment
p_{SM}, $p_{SM,min}$, $p_{SM,max}$ spot market price (min./max.)
p_{RM}, $p_{RM,pos}$, $p_{RM,neg}$ minute reserve market price (pos./neg.)
P_{Wind}, P_{Tur}, P_{Com} electrical power (wind, turbine, compressor)
r price escalation factor
R, R_{SM}, R_{RM} revenue (spot market, minute reserve market)
RV residual value
T, T_L, TN end of optimization period (modeling time horizon), plant lifetime, time horizon for profit-maximizing payment stream
Z, Z_{TN}, Z_t payment stream (profit-maximizing, yearly)

Indices
j time (years)
t, t_{Com}, t_{Tur} operating time (compressor, turbine) (duration in hours)
τ, τ_{Com}, $\tau_{\overline{Tur}}$, τ, τ_{Comb} hourly time index (compressor, turbine, no turbine, combined turbine/compressor use)

wind power has been tackled, e.g., by Ummels et al. [14], whereas Krajacic et al. [15] present Portugal's energy system planning and technical solutions for achieving 100% RES electricity production, based on hourly energy balancing. Specifically, they study a model-based integration of various types of storage facilities into energy systems, in order to increase the penetration of intermittent renewable energy sources when trying to achieve a 100% renewables-based island, region, or country. Kaldellis et al. [16] present a methodology for the sizing of pumped hydro storage systems that exploit the excess wind energy amounts produced by local wind farms, otherwise rejected due to imposed electrical grid limitations. The integrated computational algorithm developed simulates the operation of the system during an entire year and gives in detail the hourly operational status as well as the various energy losses of the system's main components. Swider [17] studies the operation and economic value of CAES for high levels of wind power generation with a stochastic cost-minimization electricity market model for Germany. Salgi and Lund [18] investigate the energy-balancing effects of adding CAES in Western Denmark for high penetration levels of renewable energy sources and combined heat-and-power (CHP). Several studies have dealt with the cost advantages of CAES versus other energy storage technologies. Still other studies have dealt with specific economic questions, including Sioshansi (role of energy storage to increase the value of wind power in imperfectly competitive markets) [19], Denholm and Sioshansi (benefit of co-location of wind/CAES systems of different size in transmission-constrained electric power systems on transmission utilization and costs) [20], Fertig and Apt (wind/CAES system, economically optimal CAES expander capacity and social welfare analysis) [21], Ibrahim et al. (hybrid wind–diesel–CAES for remote areas) [22], and Hessami and Bowly [23]. The latter simulates the economics of large-scale energy storage to complement a wind farm in a base load-dominated electricity grid. A variety of operating strategies are compared and three different energy storage systems modeled: pumped seawater hydro storage (PSHS), compressed air energy storage (CAES), and thermal energy storage (TES). CAES is found to be the most profitable storage medium, generating a rate of return (ROR) of 15.4% (PSHS: 9.6%, TES 8.0%).

In this paper, which is based on a more detailed study undertaken in Latz [24], we model the economic feasibility of CAES to improve wind power integration for the case of Germany. The Base Case is a wind park with 100 MW of installed capacity and no storage facility. In Variant 1 we add a central CAES system with 90 MW of compressor and 180 MW of generation capacity. The compressed air is stored in a cavern. The CAES system is operated independently of the wind park such that profits from electricity sales on the spot market and the reserve power market are maximized. Variant 2 is an integrated, decentralized CAES system, where each wind turbine is equipped with a compressor but no generator. The compressed air is stored in a cavern and converted into electricity by a turbine, again maximizing profit as a peak power plant. We consider both conventional diabatic (CAES) and the more recently developed advanced adiabatic (AA-CAES) systems [25]. In diabatic CAES, air is cooled before it enters the cavern and preheated (typically with natural gas) before expansion in a (modified) gas turbine. In order to generate 1 kWh of electricity in the adiabatic CAES plant in McIntosh/Alabama, for instance, requires 0.67 kWh of electricity and 1.17 kWh of natural gas [4]. This results in a heat rate of 4.21 MJ/kWh, a total energy conversion efficiency of 54%, and an electrical energy conversion factor of f_{CAES} = 1.49. (el. energy output/el. energy input). The electrical energy conversion factor ratio can be split into the product of the compressor efficiency factor f_{Com} = 0.6 (due to heat losses during compression) and the turbine conversion factor f_{Turb} = 2.49 (higher than 1 due to additional gas-firing). In contrast, adiabatic CAES does not require any cofiring with natural gas. Instead, the heat energy of the air is stored separately and recovered before the compressed air is expanded in an air turbine (cf. [17]). This process achieves a compressor efficiency f_{Com} = 0.81 and a turbine conversion factor f_{Turb} = 0.86, resulting in a total energy conversion efficiency of 70% and an electrical energy ratio of 0.7 [26].

The role of CAES power plants for trading in the spot market and minute reserve market deserves some separate explanation. In principle, CAES systems can help to better accommodate the feed-in of volatile wind power generation into the grid. A profit-maximizing operator of a CAES system will try to fill the storage at minimum cost and to maximize revenues from selling the electricity produced with the storage system to the grid, acting as a trader of electricity. Since CAES systems aim at exploiting the arbitrage opportunities from short-term fluctuations of the electricity price, the spot market (rather than the futures market) is the market of choice. In the spot market, day-ahead and intra-day