Journal of Energy Storage 9 (2017) 25–39

Contents lists available at ScienceDirect

Journal of Energy Storage

journal homepage: www.elsevier.com/locate/est

Wind generation's effect on the *ex post* variable profit of compressed air energy storage: Evidence from Texas

Yun Liu[a,*], Chi-Keung Woo[b], Jay Zarnikau[c,d]

[a] Department of Economics, Hong Kong Baptist University, Hong Kong
[b] Department of Asian and Policy Studies, Education University of Hong Kong, Hong Kong
[c] Frontier Associates LLC, 1515 S. Capital of Texas Highway, Suite 110, Austin, Texas 78746, USA
[d] LBJ School of Public Affairs and Department of Statistics, University of Texas, Austin, TX 78713, USA

ARTICLE INFO

Article history:
Received 23 May 2016
Received in revised form 5 October 2016
Accepted 10 November 2016
Available online 28 November 2016

Keywords:
Investment incentive
Wind generation
Compressed air energy storage (CAES)
Profit effect
Electricity Reliability Council of Texas (ERCOT)

ABSTRACT

We use 1401 daily observations in the 46-month period of 01/01/2011–10/31/2014 to estimate wind generation's effect on the daily per MWH arbitrage profits of compressed air energy storage (CAES) in the four regions of Houston, North, South, and West in the Electricity Reliability Council of Texas (ERCOT). We find an increase in wind generation's MWH output in the discharge hours tends to reduce a CAES system's profits. The same MWH increase in the charge hours, however, tends to increase profits. Hence, a wind generation capacity expansion that increases wind MWH in both discharge and charge hours has offsetting profit effects, implying that a CAES unit's profitability is unlikely affected by wind generation development. Sharply contrasting the "gone with the wind" profitability problem faced by natural-gas-fired generation, our findings lend support to the financial attractiveness of CAES, whose development is useful for integrating a rising share of wind generation capacity into an electric grid.

1. Introduction

Electric energy storage (EES) converts electrical energy input into a storable form for subsequent generation of electrical energy output [1–3]. An example is the Bethel Energy Center compressed energy air storage (CAES) project in Texas, whose 2019 completion will yield 317 MW of fast ramping capacity that helps meet the state's grid operator's need for flexible resources to integrate and manage the intermittent renewable generation [4 and references thereof].[1] This project consumes electricity to compress air for storage and uses natural gas to heat the compressed air to generate electricity.

In a wholesale electricity market such as the Electricity Reliability Council of Texas (ERCOT) with locational marginal pricing (LMP) [5], an installed EES unit can improve economic efficiency by consuming electricity during the low-price hours for later generation during the high-price hours. Since LMP prices track marginal costs, the efficiency gain is the incremental cost saving, which is the positive difference between (a) the unit's incremental revenue from selling the net MWH output (=MWH input − MWH loss due to conversion) and (b) incremental cost of procuring the MWH input and other inputs (e.g., labor and materials for operating and maintaining the unit). As the incremental cost saving is same as the operating profit earned by the unit's owner, construction may occur only when the unit is projected to have sufficiently large operating profits to cover its fixed costs that include the returns on and of investment.

EES is useful for integrating intermittent wind energy into an electric grid because of its operational flexibility in charging and discharging [6–11]. It implements market price arbitrage, offers operation reserve, improves system reliability, defers transmission investment, absorbs wind generation during the low-demand hours, and reduces emissions by displacing thermal generation during the high-price hours [3,8,10,12,13]. Its use in the world will likely expand, thanks to the deep de-carbonization commitments made by the U.S., China and other countries in the 2015 Paris Climate Change Summit [14].

EES has been available since early 20th century. CAES, pumped hydro storage, flow battery, and flywheel are systems that are now commercially available [2,15]. The performance metrics of a typical EES system are MW size, MWH output, and cycle efficiency (=MWH output ÷ MWH input). Similar to hydro pumped storage that requires the locational availability of reservoirs, CAES may be limited by the presence of low-cost storage sites (e.g., caves and

* Corresponding author.
E-mail addresses: 13479261@life.hkbu.edu.hk, LIUY050229@GMAIL.COM (Y. Liu).

[1] See http://www.apexcaes.com/project.

http://dx.doi.org/10.1016/j.est.2016.11.004
2352-152X/

depleted salt mines) [16]. Nevertheless, the commercial viability of CAES is evidenced by the Bethel plant in Texas, as well as the Mclintosh plant in Alabama.[2] When compared to flywheel and flow battery that are relatively costly, CAES is more suitable for large-scale energy management with longer storage duration and life cycle [1–3].

For integrating additional wind energy into the electric grid, CAES can be an attractive alternative to natural-gas-fired generation, whose investment incentive has been found to be "gone with the wind" because of large-scale wind energy development. With zero fuel costs, wind generation displaces thermal generation in a grid operator's economic dispatch to meet electricity demands [17,18], resulting in its extensively documented price-reduction (or merit-order) effect [18,19–21 and references thereof].

The wind-related reduction in electricity prices erodes the per MWH revenue and therefore operating profit of a thermal generation plant typically fueled by coal and natural gas. Hence, a new thermal plant's construction unlikely occurs when the diminished operating profit from market-based energy sales is projected to fall short of the plant's per MWH fixed costs, including the required returns on and of investments [22–26].

To see how wind generation development may affect a CAES system's investment incentive in Texas,[3] this paper uses a regression-based approach to estimate wind generation's effect on the system's daily *ex post* variable profit ("profit" hereafter) per MWH of electricity input under three charge/discharge durations of 1, 2 and 4 h. These chosen durations aim to reflect the technical characteristics of CAES described in [3]. Our focus of *ex post* profits reflects our interest in using recorded data that describe actual market conditions, thereby painting a realistic picture of CAES's profit variations in response to wind generation fluctuations.

We define the profit per MWH of electricity input as the difference between the per MWH revenue from on-peak discharge (=average on-peak price) and the per MWH cost of off-peak charge (=average off-peak price):

π = Cycle efficiency $\times$ Average on-peak price $-$ Average off-peak price.

Hence, π is a variable profit based on the on- and off-peak price differential, without accounting for the system's non-electric variable O&M costs that tend to be relatively small. To the extent that these variable O&M costs are stable, their inclusion has immaterial effects on how π may vary with market price changes caused by wind generation's as-available random output variations.

For empirical illustration, we choose ERCOT because of Texas' salient electricity characteristics [5,27,28]. First, the state is large, with an annual peak demand of 66,454 MW in 2014.[4] Second, the state's installed wind capacity in 2014 is over 12,000 MW, the largest among all the states in the U.S.[5] Third, Texas has highly volatile market prices that can become negative and have large spikes [29]. Finally, Texas faces potential deterioration in its system reliability.[6] It currently sees little construction of new thermal generation plants [30],[7] has experienced substantial plant retirements, encounters delays of newly planned projects [30–32], and likely faces federal environmental regulations that adversely impact the state's large fleet of coal-fired-generation plants.[8]

While wind generation's merit-order effect suppresses the off-peak prices in the charge hours[9] and increases the per MWH profit of an EES like battery and CAES, it also reduces the on-peak prices in the discharge hours and cuts the system's per MWH profit. The profitability of battery EES has been widely investigated, finding that the system's profitability could be greatly improved by implementing a flexible optimal operation within the context of an active-reactive optimal power flow (A-R-OPF) [10,11,33,34].

Turning our attention to CAES with substantial wind penetration, a case study of the 2008 ERCOT zonal market of the Houston region shows that operating a CAES system is unprofitable in a wind-rich state like Texas [16]. Nonetheless, wind generation's profit effect on CAES in the ERCOT market since the adoption of a nodal market structure in 2010 has received little attention in the extant literature, unlike the case of natural-gas-fired generation [22–26].

Using a sample of 1401 daily observations for the 46-month period of 01/01/2011–10/31/2014, we estimate the relationship between a CAES system's per MWH profit and the fundamental drivers of natural gas price, system demands, nuclear generation and wind generation that tend to move ERCOT's market prices [24–26,20,35]. We find that a 1-MWH increase in wind generation in the discharge hours statistically significantly (p-value $<$ 0.01) reduces the per MWH profits.[10] However, the same MWH increase in the charge hours tends to improve the per MWH profits. As the discharge and charge profit effects are offsetting, a wind generation MW capacity expansion's net profit effect is statistically insignificant (p-value $>$ 0.01) at the 1% significance level used throughout this paper, highlighting CAES's natural hedge against the profit risks caused by the wind generation's capacity expansion. This natural hedge characteristic makes CAES attractive in its promotion for integrating wind energy in ERCOT.

Our contributions are as follows. First, our CAES analysis is new. We use historical data to quantify the magnitude and significance of wind generation's effect on investment incentive, thereby complementing the extant studies on the problem of investment incentives of natural-gas-fired generation [22–26].

Second, our regression-based approach uses up-to-date market data to offer an alternative look at EES's financial performance, thus augmenting and complementing the engineering/simulation approaches used in the EES literature [6,10,11,33,34,36–38].

Third, not all generation technologies suffer from the "gone with the wind" problem. Our empirical evidence on the insignificant effect of wind generation development on the investment incentives of CAES sharply differs from the findings for natural-

[2] The 110-MW McIntosh CAES project which has been running for over 20 years, see: http://www.powersouth.com/mcintosh_power_plant.

[3] We do not consider other types of renewable generations (e.g., small hydro, solar, and biomass), which are negligible in ERCOT.

[4] See http://www.ercot.com/news/press_releases/show/51654.

[5] See http://www.ercot.com/content/news/presentations/2015/ERCOT_Quick_-Facts_52215.pdf.

[6] For example, the 2014 planning reserve margin of 9.8% projected by ERCOT is well below the reserve margin target of 13.75% of peak load [30]. A recent forecast depicts an even worse future of the reserve margin, see http://www.ercot.com/content/meetings/lts/keydocs/2011/0405/Generic_Database_Characteristics.xls.

[7] For the latest plant additions, see http://www.ercot.com/content/gridinfo/resource/2015/adequacy/cdr/CapacityDemandandReserveReport-May2015.pdf.

[8] ERCOT at times experienced generation capacity shortfalls amid soaring demand and plant shortages, see http://www.bloomberg.com/news/articles/2015-07-30/texas-power-hits-21-week-high-as-grid-warns-of-reserve-shortage.

[9] Rising wind generation suppresses the off-peak spot market prices through the merit-order effect by displacing the natural-gas-fired generation units with relatively high marginal fuel cost [18,26].

[10] A p-value is the probability used to test the null hypothesis that an estimate is equal to zero. Hence if the p-value $<$ 0.01, the hypothesis is rejected at the 1% significance level. By the same token, if the p-value $>$ 0.01, the null hypothesis cannot be rejected even at the 10% significance level.