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California's renewable generation and pumped hydro storage's profitability☆

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ABSTRACT

An analysis of 860 daily observations finds that rising renewable generation does not significantly diminish a pumped hydro storage system's daily operating profits from energy sales at the day-head and real-time market prices. The system, however, faces severely inadequate investment incentive because its annual operating profit can hardly pay for its annual fixed cost.

1. Introduction

This article is motivated by the two transformative events that have taken place in California's electricity industry. The first is industry reform that has led to competitive wholesale electricity markets with volatile prices. Along with occasional price spikes, this price volatility is attributable to: (a) daily fuel cost variations; (b) weather-dependent hourly demands with diurnal fluctuations; (c) outages of major electrical facilities; (d) intermittent renewable generation; (e) seasonally varying hydro conditions, and (f) frequent transmission constraints (Woo et al., 2016a,b). The state's wholesale electricity is mainly transacted in the day-ahead market (DAM) and real-time market (RTM) operated by the California Independent System Operator (CAISO) based on the theory of locational marginal pricing (Stoft, 2002). Over 95% of the CAISO's energy transactions are settled at the hourly DAM prices and the remainder the 5-min RTM prices (CAISO, 2016).

The second event is California's large-scale renewable generation development, thanks to the state's aggressive renewables portfolio standard (RPS) designed to promote resource diversity and mitigate climate change.[1] Renewable generation reduces the CAISO's market prices via the order-merit effect, exacerbating the inadequate investment incentive for flexible generation units (e.g., combustion turbine (CT) and combined-cycle gas turbine (CCGT)) that are necessary to reliably integrate the an increasing amount of randomly intermittent solar and wind energy into the California grid (Woo et al., 2016a,b).

Electric energy storage (EES) has been widely used since the early 20th century (Chen et al., 2009). It converts electricity as an input into a storable form for later generation (Ibrahim et al., 2008; Ibrahim and Ilinca, 2013). It facilitates market price arbitrage, offers operational reserve, defers transmission investment, and absorbs excess non-dispatchable generation during hours of low system demand.

EES is useful for reliable integration of solar and wind generation into an electric grid (Farret and Simões, 2006). When compared to other EES systems like battery and flywheel, pumped hydro storage (PHS) has a longer storage duration and life cycle, higher cycle efficiency, and lower per MWH capital cost. A real-world case in point is California's 1300-MW Eagle Mountain Pumped Storage Project.

This article addresses the following research question: how may renewable generation development impact a PHS system's profitability in California? Justifying our California focus are the facts listed in Section 2. The empirical evidence reported in Section 3 yields our answer: further expansion of renewable generation is unlikely to have a statistically significant impact on a PHS system's profitability in California. Moreover, changes in the natural gas price, system loads outside where the PHS system resides, available nuclear capacity, and hydro conditions are found not to significantly impact the system's profitability.

Our newly documented findings, however, do not mean that PHS in California is immune to the problem of severely inadequate investment incentive. As shown in the appendix, a PHS system's

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[1] http://www.cpuc.ca.gov/rps_homepage/.

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annual operating profit is woefully insufficient to pay for its annual fixed cost. Hence, California should continue its adopted procurement process for long-term contracts that ensure adequate fixed-cost recovery, so as to promote the use of PHS for reliable integration of renewable generation into the state's electric grid.

2. Why California?

Our California focus reflects the following facts:

- California's size and resource diversity. As the fifth-largest economy of the world, California has the highest state GDP in 2015 of $2.45 trillion in the U.S.[2] The state's vast electric system has an installed generation capacity of ~80,000 MW in 2015,[3] with a diverse fuel mix of natural gas (~59%), large hydro (~16%), renewables (~22%),[4] and nuclear (~3%). Hence, our findings offer insights into PHS's profitability that are of interests to academics, policymakers, and practitioners.
- California's system load profile. Since 2013, California has been seeing a "duck curve" of low mid-day net load due to high solar generation (CAISO, 2014). Leading to relatively low mid-day market prices, this duck-curve will likely persist because of rapid solar development in response to California's aggressive RPS goal of 50% of retail consumption by 2030. As the CAISO mid-day market prices drop, they can adversely affect a PHS system's profitability because of the decline in the system's daytime revenue.
- California's resource adequacy. The state's concerns of resource adequacy stem from (a) the substantial retirements and environmental upgrades of ~16,000 MW generating capacity in the next decade,[5] and (b) the urgent need for flexible generation to achieve the state's ambitious RPS goal. As a result, PHS is potentially a capacity remedy to the state's projected resource inadequacy.
- California's data availability. The state has abundant data suitable for an analysis of PSH's profitability. Specifically, we use the 860 daily observations constructed from the ~21,000 hourly observations described in Woo et al. (2016a,b) for the sample period 12/12/2012 to 04/30/2015. The period's start date is when the CAISO first published its renewable generation's day-ahead forecast. The end date reflects the data available at the time of our analysis. The resulting sample contains sufficient data variations to statistically assess PHS's profitability, as well as its dependence on the fundamental drivers such as the natural gas price, nuclear capacity available, system loads, renewable generation, and hydro conditions.

3. Empirical evidence

Supporting our answer to the research question posed in Section 1 is the empirical evidence based on a regression analysis detailed in the appendix. This analysis suggests that the state's future renewable generation development is unlikely to exacerbate PHS's severely inadequate investment incentive that presently exists, chiefly because renewable generation's merit-order effect tends to simultaneously reduce a PHS system's operating revenue and cost.

The same regression analysis also shows that a PHS system's operating profit only modestly varies with its fundamental drivers. Hence, future changes in these drivers will unlikely remedy the system's currently inadequate investment incentive. This finding sharply contrasts that for natural-gas-fired generation, whose profitability tends to increase with natural-gas price escalation, system load growth and nuclear plant shutdown (Woo et al., 2016a).

4. Conclusion

Our article has good news and bad news. The good news is that renewable generation development is unlikely to worsen PHS's profitability in California. The bad news is that the annual operating profit of a PHS system can hardly pay for the annual fixed cost. Hence, the state should continue its adopted procurement process described in Woo et al. (2016a,b) for PHS and other forms of flexible generation, so as to support the reliable integration of a rising share of renewable energy in the state's resource portfolio.

Appendix A. Regression analysis of a PHS system's per MWH profit

This appendix presents a regression analysis of the per MWH profit of a PHS system. It details the process and data used to develop our answer to the research question posed in Section 1. Thus, it aids readers who wish to conduct a similar analysis for other regional transmission organizations (e.g., ERCOT, ISO-NE, NYISO, or PJM) that have market data similar to the CAISO's.

A.1 Per MWH profit

Let π_{nt} denote a PHS system's daily operating profit per MWH of electricity input on day *t*. This profit is assumed to be the revenue earned in an *n*-hour discharge period, less the 1 MWh cost incurred in a preceding *n*-hour charge period:

$$\pi_{nt} = \frac{[\rho(\sum_h P_{1,ht}) - \sum_h P_{0,ht}]}{n} \quad (1)$$

where ρ = cycle efficiency; $P_{0,ht}$ = energy market price ($/MWH) in charge hour *h* on day *t*; and $P_{1,ht}$ = energy market price ($/MWH) in discharge hour *h* on day *t*.

Eq. (1) ignores the non-electric variable O&M costs that tend to be relatively small. Hence, including the O&M costs is unlikely to substantively change a PHS system's investment incentive. To the extent that the variable O&M costs are stable, their presence does not materially alter the relationship of how π_{nt} may vary with its drivers.

We construct π_{nt} as follows. The DAM-based profit is the daily average of Max (hourly DAM discharge price × cycle efficiency – hourly DAM charge price, 0), reflecting a PHS operator's decision not to operate at a loss under perfect foresight. The RTM-based profit is based on a simple operational rule (Walawalkar et al., 2007), thereby avoiding the need for a complicated algorithm based on stochastic dynamic programming. The RTM-based profit is the daily average of (hourly RTM discharge price × cycle efficiency – hourly RTM charge price).[6] It can be negative, as it does not preempt the possibility of operating losses.

[2] http://fortune.com/2016/06/17/california-france-6th-largest-economy/.
[3] http://energyalmanac.ca.gov/electricity/electric_generation_capacity.html.
[4] The ~22% renewable capacity is the sum of biomass (1.6%), geothermal (3.4%), small hydro (2.1%), solar PV (5.9%), solar thermal (1.6%), and wind (7.5%).
[5] https://www.caiso.com/planning/Pages/ReliabilityRequirements/Default.aspx.
[6] We recognize that PHS may provide ancillary services (AS) (Walawalkar et al., 2007). A PHS operator providing both peak energy and AS may have up to nine operation choices, the product of three operation durations and three operation modes (peak energy only, AS only, and mixed mode). We do not consider PHS's AS revenue, whose calculation is well beyond the scope of our study.