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Economic viability of energy storage systems based on price arbitrage potential in real-time U.S. electricity markets

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HIGHLIGHTS

- Estimation of required cost reductions to make ESSs profitable for energy arbitrage.
- Comparison of 14 ESS technologies in 7 regional markets.
- Optimal sizing of ESSs to maximize the IRR for arbitrage in real-time energy markets.
- Pumped hydro, CAES, and ZEBRA ESSs result in the greatest IRR from energy arbitrage.

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ABSTRACT

Energy storage systems (ESSs) can increase power system stability and efficiency, and facilitate integration of intermittent renewable energy, but deployment of ESSs will remain limited until they achieve an attractive internal rate of return (IRR). Linear optimization is used to find the ESS power and energy capacities that maximize the IRR when used to arbitrage 2008 electricity prices (the highest of the past decade) in seven real-time markets in the United States for 14 different ESS technologies. Any reductions in capital costs needed to achieve an IRR of 10% are solved for. Results show that the profit-maximizing size (i.e. hours of energy storage) of an ESS is primarily determined by its technological characteristics (round-trip charge/discharge efficiency and self-discharge) and not market price volatility, which instead increases IRR. Most ESSs examined have an optimal size of 1–4 h of energy storage, though for pumped hydro and compressed air systems this size is 7–8 h. The latter ESSs already achieve IRRs >10%, but could be made even more profitable with minimal cost-reductions by reducing power capacity costs. The opposite holds for Flywheels, electrical ESSs (e.g., capacitors) and a number of chemical ESSs (e.g., lead acid batteries). These could be made more profitable with minimal cost-reductions by reducing energy capacity costs.

1. Introduction

Energy storage systems (ESSs) have the potential to revolutionize the way in which electrical power grids are designed and operated [1]. Presently, power grids require that the generation of electricity continuously balance the demand for it. Significant incorporation of ESSs into the grid would relax this constraint by enabling electrical energy to be withdrawn from the grid when there is excess generation and held in reserve until needed. Such reserve capacity could enable cost and emissions reductions from more efficient dispatch of generators, facilitate the integration of renewable, but intermittent power sources such as wind and solar, and provide numerous services that support grid reliability including frequency regulation, spinning reserve capacity, transmission and distribution support [2], voltage support including VAR compensation [3], and grid stabilization during times of voltage deviation, reverse-power-flow, and over-power in distribution networks [4].

ESSs are already used for some of these purposes, but only to a minor extent [1,3,5–10]. In the United States, the focus of this study, there are 228 GW [2] of installed ESS capacity, which equates to ~20% of the nation's total generating capacity. However, just 2.5% of the total power delivered in the U.S. passes through an ESS [11], and 99% of these are pumped hydro facilities used by utilities for load balancing [2]. Furthermore, the deployment of additional pumped hydro has stalled due to (among other factors) declines in the price of natural gas and stricter environmental regulations for water use in power generation [12].

To date, ESSs other than pumped hydro have rarely been cost effective to install and/or operate. This situation may be changing with increasing capacity of intermittent wind and solar power

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generators, as these generators have fluctuating power outputs capable of increasing market price volatility [13]. This may improve revenue opportunities for ESSs engaging in price arbitrage, i.e. buying and storing energy when electricity prices are low and then selling and discharging the energy back to the grid when prices are high. The arbitrage potential of ESSs has been explored both for generic storage devices [14–16], and for specific ESS technologies in particular markets [11,17–25].

Energy storage systems can be characterized in terms of energy and power capacity, round trip efficiency, and self discharge. Energy capacity is the maximum energy a storage device can hold. Power capacity is the maximum rate at which energy can be transferred into and out of the device. Round trip efficiency is the ratio of output-to-input energy for a storage device throughout the charge and discharge of the device. And self discharge is the loss of energy due to parasitic losses in an energy storage system, where these losses may be due to mechanical friction, chemical reactions, etc., depending on the technology.

Previous studies of ESS arbitrage potential fix both the power and energy capacities, the ratio of which (i.e. energy/power capacity) determines the maximum hours of energy the device can store. However, [26] has shown that this ratio directly affects the arbitrage profitability of an ESS. Thus by arbitrarily fixing power and energy capacity, these studies do not optimally size each ESS, which may prevent the estimation of the highest potential IRR, nor do they quantify the required reduction in power and/or energy capacity capital costs to enable each ESS to yield an acceptable IRR.

Similar to [17,26], a linear optimization model is used, to solve for the maximum possible profit an ESS could achieve through price arbitrage assuming perfect foresight of past price data from a number of major U.S. real-time electric markets. In this analysis, however, the energy and power capacities of the ESS that would yield this maximum profit are also determined. The breadth of currently available storage technologies for use in power grids are evaluated, including: three that store and generate electricity via mechanical energy – pumped hydroelectric (PH), compressed air energy storage (CAES) and flywheels (FW); three devices that store energy electrically – capacitors (CAP), electrochemical double layer capacitors otherwise known as super- or ultra-capacitors (EDLC), and superconducting magnetic energy storage (SMES); and eight batteries that utilize chemical storage – lead acid (LA), nickel–cadmium (NiCd), lithium-ion (Li-ion), sodium-sulfur (NaS), sodium nickel chloride (a.k.a. ZEBRA), zinc-bromine (ZnBr), polysulfide bromide (PSB), and vanadium redox (VR).

The economic viability of using each ESS for price arbitrage based on its modeled internal rate of return in the example markets is assessed. The internal rate of return or IRR is the discount rate that would make the net present value of the investment project equal to zero. It is used here because it is independent of ESS lifetime and power/energy capacity (e.g., the IRR of a 30-year, 1 kW ESS can be directly compared to the IRR of a 5-year, 1 MW ESS). It is arbitrarily assumed that ESSs with an IRR <10% are deemed unprofitable. The minimum changes to current power and energy capacity costs for an ESS that would generate >10% IRR in the most and least profitable of the example markets are then solved for. Consequently, the results of the analysis point to what may be the most cost-effective way to improve the economics of the ESSs for price arbitrage.

Note that while this analysis is limited to the arbitrage potential of ESSs in real-time energy markets, ESSs might also be economically used in the ancillary-service, capacity, and day-ahead energy markets. The ancillary service markets include the reserve capacity market for contingency scenarios, and the frequency regulation market for high-speed, second-to-second power balancing. Both of these sub-markets might yield additional revenue opportunities for ESSs [22], but participation in the reserve capacity market alone has yet to prove profitable [2], and there is uncertainty over how much additional "compensation" ESSs might receive in the frequency regulation market because FERC Order No. 755 (which requires markets to compensate faster-responding units such as ESSs for signal-following accuracy) has yet to be fully implemented. Uncertainty also exists in capacity markets over what payment is appropriate for ESS capacity [26]. And while the day-ahead market is similar to the real-time market, prices in the latter are generally more volatile than in the former [27,28], so if an ESS is unprofitable in the real-time market, the same is likely to be true in the day-ahead market. Hence we do not explore any of these other market options here.

2. Methods

2.1. Price arbitrage optimization model

Fig. 1a depicts our model of the simulated interaction of an ESS and a power grid for the purpose of price arbitrage. The energy E (kW h) stored in the device at time t is given by

$$E(t) = (1-\delta)E(t-\Delta t) + [\eta P_c(t) - P_d(t)]\Delta t \tag{1}$$

where δ is the fractional loss of energy over the interval Δt due to parasitic losses, or self-discharge, η is the roundtrip efficiency of the storage device, $P_c(t)$ (kW) is the charging power from the grid at time t (h), and $P_d(t)$ (kW) is the discharging power from the device at t. Note that $E(t) = 0$ at $t = 0$.

The linear program for maximizing the arbitrage revenue r ($) in a year, assuming time periods of 1 h (i.e. $\Delta t = 1$ h) is expressed as

$$\text{Max } r = \sum_{t=1}^{n=8760} \pi(t)[P_d(t) - P_c(t)]\Delta t \tag{2}$$

subject to the following constraints

$$\begin{aligned} &0 \leqslant P_d(t), P_c(t) \leqslant P_{\max} \forall t \\ &0 \leqslant E(t) \leqslant E_{\max} \forall t \end{aligned} \tag{3}$$

In these Equations, n is the number of 1-h periods (i.e. $n = 8760$ h in a year – the most optimistic estimate for it assumes there will be no maintenance downtime). The price of electricity at hour t is $\pi(t)$ ($/kW h), $P_{\max}$ (kW) is the power capacity of the device (the maximum charge or discharge rate), and $E_{\max}$ (kW h) is the device's energy capacity (the maximum energy the device can store). Fig. 1b shows a sample of the revenue-maximizing operation of the model in which the ESS charges when the price of electricity is low and discharges when it is high.

Eqs. (1)–(3)is solved using as input a yearlong time series of one-hour interval electricity price data to arrive at a representative annual revenue r for the ESS. Then, r is used to calculate the present value (PV) of the total revenue the ESS would generate over its lifetime, R_{PV} ($) as given by

$$R_{PV} = (r - c_{om}) \sum_{i=1}^{L(N_c)} \frac{1}{(1+\rho)^i} \tag{4}$$

Here c_{om} is the annual operations and maintenance (O&M) cost, ρ is the discount rate, and $L(N_c)$ is the lifetime of the storage device, which, for many technologies, depends on the number of times the ESS is cycled per year.

$$L(N_c) = \min\left\{\frac{L_c}{N_c}, L_y\right\} \tag{5}$$

In Eq. (5), L_y is the maximum lifetime of the device in years, L_c is the lifetime of the device in cycles, and N_c is the average number of cycles per year, measured as the total energy charged annually to the device divided by the energy capacity of the device.