Journal of Energy Storage 16 (2018) 37–45

Contents lists available at ScienceDirect

Journal of Energy Storage

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

What are the tradeoffs between battery energy storage cycle life and calendar life in the energy arbitrage application?

Robert L. Fares[a,b,*], Michael E. Webber[a,b]

[a] Department of Mechanical Engineering, The University of Texas, Austin, TX 78712, United States
[b] Energy Institute, The University of Texas, Austin, TX 78712, United States

ARTICLE INFO

Article history:
Received 7 July 2017
Received in revised form 3 January 2018
Accepted 5 January 2018
Available online xxx

Keywords:
Battery
Energy storage
Electricity markets
Economics

ABSTRACT

This paper develops a method and framework for analyzing the tradeoffs between the calendar life and cycle life of battery energy storage used for energy arbitrage in a wholesale electricity market. We implement a linear program to analyze the revenue potential of a battery system participating in the Electric Reliability Council of Texas (ERCOT) electricity market during 2002–2015, and show how the number of charge-discharge cycles performed in a year affects annual revenue potential. Then, we calculate the potential present worth (or the sum of discounted yearly revenues) of battery systems of various discharge durations and roundtrip efficiencies as a function of their calendar life and cycle life, and show how increasing calendar life and cycle life affects present worth. We show that increasing calendar life provides a greater benefit than increasing cycle life for lithium-ion, sodium-sulfur, and vanadium-redox flow batteries, which counters conventional notions about the importance of battery cycle life. However, we find that increasing the cycle life of lead-acid batteries provides a greater benefit than increasing calendar life, because lead-acid batteries have a lower cycle life than other technologies.

1. Introduction and motivation

In recent years, there has been growing interest in energy storage that operates on the electric grid to store electricity and participate in an electricity market. Energy storage is an appealing technology because it temporally decouples electricity supply from demand, adding new flexibility to grid operations with the potential to reduce grid capital expenditures, integrate intermittent renewable energy, and increase electric reliability. While pumped-hydro energy storage is a common and established form of grid energy storage, there are significant financial and environmental barriers to its further development in the United States [1]. Thus, there has been growing interest in emerging energy storage technologies such as grid-scale batteries. However, there are still a number of questions about the economic viability of battery energy storage in electricity markets given the limited cycle life and calendar life of many battery technologies. While conventional electricity generation and delivery equipment usually lasts for several decades before it has to be replaced [2,3], the lifetime of battery storage is typically just 5–15 years, depending on how it operates and what services it provides to the electric grid [4–7].

The relatively short and uncertain lifetime of battery storage compared with other electricity generation and delivery infrastructure is one of the key factors that affects its economic viability. The question of how long battery storage will last in a given application is compounded by the fact that there are two principal factors that affect battery storage lifetime: its degradation over time (calendar life) and its degradation with repeated charge-discharge cycling (cycle life) [4,7–11]. The lifetime of a battery storage plant that charges and discharges frequently might be determined by its cycle life, while the lifetime of a battery storage plant that charges and discharges infrequently might be determined by its calendar life. Note that both calendar and cycle life are affected by a battery system's operating temperature, depth of discharge, resting state of charge, and charge/discharge rate [8–11].

Despite the fact that the cycle and calendar life of energy storage can strongly impact its value, few previous analyses of the value of energy storage explicitly consider the impacts of cycle and calendar life, and the tradeoffs between the two. As discussed in a major review of energy storage valuation methods by Zucker et al. [12], there are two principal methods used to assess the value of energy storage: (1) "engineering models," which model profit-maximizing operation of energy storage in an electricity market as

* Corresponding author at: Department of Mechanical Engineering, The University of Texas at Austin, 204 E. Dean Keeton Street, Stop C2200, Austin, TX 78712-1591, United States.
E-mail address: robertfares@utexas.edu (R.L. Fares).

https://doi.org/10.1016/j.est.2018.01.002
2352-152X/

a price taker, and (2) "system models," which model storage endogenously within electricity system production cost-minimization models. There are numerous examples of engineering models [13–16] and system models [17–20] in the literature. Engineering models have the advantage that they can reference real, historic electricity prices, but they cannot explicitly model the impact of energy storage operation on electricity market prices. System models can explicitly model the interaction between energy storage and other grid resources and any changes in dispatch, but they can only model the avoided system costs and energy storage profit under an idealized grid system model. For a full comparison of these methods, we refer readers to Zucker et al. [12].

While numerous previous analyses have assessed the potential value of storage in electricity market applications, to our best knowledge no previous analyses have sought to critically analyze the tradeoffs between calendar life and cycle life. One previous paper that we know of by Hittinger et al. [21] assessed the relative impact of storage upfront costs, operating costs, efficiency, and investment duration on storage value, but did not consider how the frequency of storage cycling affects its value and lifetime. Recent work has implemented degradation models within storage control models to dynamically consider the tradeoff between battery degradation and operational value [22,23], but no work that we know of has studied the tradeoffs between calendar life versus cycle life from a technology-neutral perspective for different storage systems using multiple years of historic electricity prices.

This paper aims to fill this knowledge gap by developing an engineering model for analyzing the impact of calendar and cycle life on storage value in the wholesale energy arbitrage application. Understanding this tradeoff is important because it is possible for storage operators to have an explicit influence on the relative calendar life and cycle life of their system. For example, the calendar life of a battery system could be extended by reducing its operating temperature, because calendar degradation follows an Arrhenius rate equation [8,9,24]. However, reducing operating temperature might limit the ability to charge and discharge, effectively reducing cycle life. It is hoped that the analysis conducted in this paper can help to reveal the appropriate balance between calendar life and cycle life, so that storage operators can analyze and adjust their operation strategies to maximize the value of their systems.

To illustrate the proposed method, we analyze the tradeoffs between calendar life and cycle life using historic electricity prices for 2002–2015 from the ERCOT market. The ERCOT market facilitates economic and reliable power trading representing 90% of Texas load, 46,500 miles of transmission lines, and electric delivery to approximately 24 million customers [25]. Detailed background information on the characteristics of the ERCOT market versus other American and international markets is available in the literature [26–28]. We use historic ERCOT pricing data to calculate how much revenue battery storage could earn as a function of the number of cycles it performs in year, and then show how the potential present worth of battery storage is affected by its calendar life and cycle life. Then, the potential net-present value of advanced lead-acid, lithium-ion, sodium-sulfur, and vanadium-redox flow batteries is estimated, and the relative benefit of increasing calendar life versus cycle life is shown.

We focus our analysis on the wholesale energy arbitrage application, where energy storage buys electricity at a low price and sells it at a higher price. While this application is generally less valuable than providing frequency regulation service [16], the market for frequency regulation is relatively small because only a small amount of capacity is required to balance electricity supply with demand over short timescales and maintain grid frequency. The total U.S. market potential for frequency regulation is estimated to be just 1000 MW, whereas the U.S. market for wholesale energy arbitrage is estimated to be over 18,000 MW [29]. Furthermore, storage is already cost competitive or nearly cost competitive in the frequency regulation application [30–32], so it is anticipated that the relatively small market for frequency regulation will become saturated in the near future. Thus, we focus our analysis on critically analyzing how extending storage calendar life and cycle life affect its value for wholesale energy arbitrage, with the hope that our analysis will help inform storage design and operational pathways to achieving cost effectiveness in this significant but untapped market.

The remainder of this paper is organized as follows: Section 2 discusses the linear program used to schedule when battery storage should charge and discharge to maximize its revenue based on the number of cycles it can carry out during the year. Section 3 shows how the number of cycles performed in a year affects annual revenue potential and how the present worth of a battery storage plant varies with its calendar life and cycle life. Finally, Section 4 discusses our results and makes recommendations for future work.

2. Optimization program to schedule battery energy storage operation

Typically, the market price of electricity is lowest when demand for electricity is at a minimum and highest when demand is at a maximum. However, it can sometimes vary unpredictably due to unexpected increases in demand, shortfalls in generation, or other factors. Thus, it is important to dynamically schedule when battery storage charges and discharges to maximize the revenue gained during a given operating day. This section introduces a linear program that reveals when battery storage could charge and discharge in the ERCOT electricity market to maximize its operating revenue given an exogenously determined maximum number of allowable cycles per year.

To make our analysis applicable to a variety of battery storage technologies, we consider a technology-neutral battery storage system defined by its rated power capacity (P_{rated}), energy storage capacity (E_{rated}), and AC-AC roundtrip energy efficiency (η_{rt}). While a real battery system would see decreasing power capabilities, efficiency, and storage capacity over time as a product of calendar and cycle aging, we neglect aging impacts for the purposes of this paper and hold storage parameters fixed so that we can model technology-neutral storage without employing technology-specific aging models.

The optimization program considers a time period of one year, and schedules when the storage charges and discharges to maximize total revenue from the electricity market over the year. Because the ERCOT real-time electricity price is established every 15 minutes, we define the optimization variables over the sets $q:\{1, 2, \ldots, 95, 96\}$, where q represents the numerical index of each of the 96 quarter-hour intervals in a day, and $d:\{1, 2, \ldots, 364, 365\}$, where d represents the day of the year.

The decision variables considered by the optimization program are the discharging power and charging power during each quarter-hour interval of the year. We define the charging power and discharging power during period q on day d using the continuous variables $C(q, d)$ and $D(q, d)$, respectively.

We define the objective function for the optimization program as a function of the charging and discharging power, the real-time electricity price, $\pi(q)$, and the duration of the price interval Δt = 15 min. By maximizing the objective function given in Eq. (1), the optimization program seeks to maximize the total revenue gained from the market over the year.

$$\text{Objective} = \sum_{d}\sum_{q\in d}(D(q,d) - C(q,d))\Delta t\pi(q,d) \quad (1)$$