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Impact of battery degradation on energy arbitrage revenue of grid-level energy storage

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ABSTRACT

This study investigates the representation of battery degradation in grid level energy storage applications. In particular, we focus on energy arbitrage, as this is a potential future large-scale application of energy storage and there is limited existing research combining the modelling of battery degradation and energy storage arbitrage. We implement two different representations of battery degradation within an energy arbitrage model, and show that degradation has a strong impact on battery energy storage system (BESS) profitability. In a case study using historical electricity market prices from the MISO electricity market in the United States, we find that the achievable net present value (at an interest rate of 10%) for a battery system with a C-rate of 1C dropped from 358 $/kWh in the case considering no degradation to 194–314 $/kWh depending on the battery degradation model and assumptions for end of life (EOL) criteria. This corresponds to a reduction in revenue due to degradation in the 12–46% range. Moreover, we find that reducing the cycling of the battery via introducing a penalty cost in the objective function of the energy arbitrage optimization model can improve the profitability over the life of the BESS.

1. Introduction

Battery energy storage systems (BESSs) are receiving more attention with increasing amounts of electricity produced by variable renewable energy sources like wind and solar, as BESS can address a range of challenges related to the uncertainty and variability in such resources ([1–3]). Therefore, it is important to analyze the profitability and potential for investment in BESSs. The idea behind energy arbitrage is to take advantage of daily energy price differences in order to buy cheap energy available during periods of low demand and store this energy in the battery. This low priced energy can then be sold at higher prices during peak load when prices are high (cf. [4]). Although there are many potential grid-level applications of BESS [5], energy arbitrage represents the largest profit opportunity for BESS in the electric power grid and is therefore an important application. BESS can also provide ancillary services, like spinning reserves and frequency regulation, but the markets for ancillary services are much smaller than the energy market. There are many recent studies on energy arbitrage modeling investigating the most profitable charging and discharging schedule for the storage device based on electricity market prices (e.g. [6–12]). Assumptions about battery lifetime and degradation are crucial to obtain realistic estimates of profitability. However, these issues are typically not addressed in detail in the energy arbitrage literature. One exception is the recent paper by Mohsenian-Rad [13], where a simple representation of lifetime effects on the optimal arbitrage schedule is proposed by introducing a constraint on the number of daily battery cycles. However, the impact on lifetime profitability is not considered. The analysis in Abdulla et al. [14] indicates that degradation has a substantial impact on battery lifetime and economic value for a residential BESS with solar PV under a fixed tariff scheme.

This paper expands on previous literature by proposing a new energy arbitrage model which explicitly represents battery degradation. This enables the investigation of different scenarios for battery degradation and their impact on achievable profit from energy arbitrage, as well as of how battery operation should be

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Nomenclature

Indices

t	Time period (h)

Parameters

$P^{RT}(t)$	Real-time energy price in period t (\$/MWh)
η_{to}	Charging efficiency (including battery and system losses)
η_{from}	Discharging efficiency (including battery and system losses)
η_{ch}	Battery charging efficiency
η_{dis}	Battery discharging efficiency
η_{sys}	Efficiency of power converting system
U_{OCV}	Open circuit voltage (V)
V_{ch}	Charging voltage (V)
V_{dis}	Discharging voltage (V)
I_{ch}	Charging current density (A/cm^2)
I_{dis}	Discharging current density (A/cm^2)
R	Area specific resistance of the battery (Ωcm^2)
l	Loading (Ah/cm^2)
eol	End of life battery (fraction of initial battery capacity)
C^{ch}	Max. rate of charge (1/h)
C^{dis}	Max. rate of discharge (1/h)
SOC_{min}	Min. state of charge
SOC_{max}	Max. state of charge
SOC_0	Initial state of charge
f_B	Battery fade constant (1/MWh)
c_B	Battery penalty cost (\$/MWh)
Q_B	Initial battery capacity (MWh)
i	Interest rate

Variables

$E^P(t)$	Energy purchased in period t (MWh)
$E^S(t)$	Energy sold in period t (MWh)
$E^{to}(t)$	Energy charged to battery in period t (MWh)
$E^{from}(t)$	Energy discharged from battery in period t (MWh)
$SOC(t)$	State of charge, end of period t (MWh)
$ID_{ch}(t)$	Binary battery charging indicator (0,1)
$ID_{dis}(t)$	Binary battery discharging indicator (0,1)
$TE(t)$	Total processed energy (from start to period t) (MWh)
$\Delta D(t)$	Degradation step in period t
$D(t)$	Summation of degradation steps
$DOD(t)$	$Q_{rem}(t)$
$Q_{rem}(t)$	Normalized remaining battery capacity in period t (fraction of Q_B)
$SOC_{max}(t)$	Max. state of charge in period t (MWh)
$\Delta c(t)$	Degradation penalty cost in time period t (\$)
Π_y	Annual net operating revenues in year y
NPV	Net present value of revenue stream over useful lifetime of battery

adjusted to account for these effects. A better understanding of degradation on BESS lifetime and profitability is critical for investors in battery technologies and for improved evaluation of the potential future role for BESS in the electric power grid. Given that the focus of the paper is on battery degradation, we use standard and relatively simple assumptions for other aspects of the energy arbitrage problem, including perfect foresight about electricity market prices and constant battery efficiency. This provides us with a fast analytical tool for energy arbitrage analysis that enables us to analyze the importance of representing battery degradation and aging in such tools.

The rest of the paper has the following structure: Section 2 introduces relevant basic characteristics of Li-ion batteries. Section 3 describes the proposed energy arbitrage model, including two different representations of battery degradation. Section 4 presents a comprehensive case study of BESS profitability with different degradation models, using real-time electricity market prices from a selected location in the Midcontinent Independent System Operator (MISO) market. Conclusions and directions for future work are provided in Section 5.

2. Li-ion batteries: cost and degradation

Li-ion batteries are a relatively mature technology that is promising for grid storage applications due to high power and energy densities in combination with good cycle life and efficiency. However, high system capital costs as well as uncertainty about the lifetime remain important obstacles for a large-scale expansion of this technology in the grid. The capital cost of an energy storage system is composed of the battery cells, the balance of plant to maintain safe operation of the cells, the power conditioning system, and site installation. Operation and maintenance costs add an additional complication to the economics, which are ignored in this first order analysis. For Li-ion, the reported all-in capital costs have ranged from 500 to 1500 \$/kWh ([3,1]). The large range in capital cost reflects the immature market, but also important differences in energy storage system design. Systems designed for longer storage durations (e.g. 5 h vs 1 h) will have a lower normalized capital cost as some components have a set power cost (\$/kW), which appears less significant for longer durations. Longer time duration Li-ion batteries often are less expensive on a per energy basis than their shorter time duration (i.e. higher power density) alternatives. The least expensive Li-ion cells often are challenged from a cycle life perspective. In other words, an energy storage system that undergoes daily or even more frequent cycling will use a cell design and material choice that may have higher initial cost, but result in greater energy throughput over the life of the system. The capital cost of the energy storage systems appears to be on a downward trend owing both to decreasing Li-ion cell costs as well as classical experience curve effects [1] for building energy storage systems.

The lifetime of Li-ion batteries is limited due to unwanted side reactions which lead to a decrease of capacity and an increase in cell impedance [15]. The lifetime is strongly related to the battery chemistry and BESS operation. A major contribution to degradation for batteries with graphite anodes is the decomposition of the electrolyte and the irreversible consummation of lithium during cycling resulting in the growth of the solid-electrolyte interphase [1]. These processes depend on various factors like depth of discharge (DOD), state of charge (SOC), temperature (T), battery application, charging/discharging rate (C-rate), type of battery and manufacturer. It has also been observed that Li-ion battery degradation tends to accelerate at some point [16], and this has implications for its useful life. In this work, two different types of Li-ion batteries are investigated: the cathode of type 1 is $LiFePO_4$ (LFP), type 2 has a $LiNi_{1-x-y}Co_xAl_yO_2$ (NCA) cathode. In both cases, the cells have graphite anodes. The properties of the materials are different. LFP batteries show less dependency of aging on DOD and are considered to have greater abuse tolerance compared to those based on NCA. NCA batteries show a high energy density and better calendar lifetime especially at high temperatures.

As the interplay of the different degradation factors impedes a separation of the individual contributions, a common attempt of describing the degradation of the battery are simplified models