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Energy storage systems in energy and ancillary markets: A backwards induction approach

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HIGHLIGHTS

- Battery ESS is assumed to be used for both energy and reserve markets.
- Battery ESS is considered to be an exhaustible resource due to fixed life cycles.
- Backward induction is applied to capture the opportunity cost when it is used.
- The battery ESS generates insufficient profits to cover up the investment cost.
- The result implies that bids would be made rarely into the energy market.

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ABSTRACT

Battery storage technologies have developed to the point that some are mature enough to serve as a generation resource. However, whether a battery can generate profits by interacting solely in energy markets is unclear. Meanwhile, FERC order 784 requires electricity exchange markets in the U.S. to install the necessary technical equipment for batteries to supply ancillary services [12]. We suggest that current economic studies on the battery energy storage system (ESS) are limited because they do not explore possibilities to use battery storage in ancillary (reserve) markets. Applying battery ESS to ancillary service could be profitable enough to cover investment costs.

In this study, we consider a battery storage operator's best strategy each day, using backwards induction. We analyze the storage device as an exhaustible resource with a limited number of charging cycles and operating years. Based on this approach, we build a revenue model to maximized the net present value of the battery energy storage system revenues by applying the three-staged-method employed by Shcherbakova et al. [14]. We found that the battery in unable to cover its costs, and it does not use all the cycles available in its lifetime. This result, however, may be a function of the limits of our analytical approach.

1. Introduction

Electricity is one of the essential energy resources in our daily lives. However, it offers a critical challenge: it cannot be stored without a special device. Battery ESS (Energy Storage System) potentially solve this problem by storing electricity energy when demand is low (prices are lower) and offering stored energy when demand is high. As a result, battery ESS may be considered a generation resource for a variety of reasons, such as for use in energy arbitrage, self-generation resource for Demand Response, and ancillary service [1,2,3].

Empirical studies, however, offer mixed results on the profitability of battery ESS, depending on types of battery and markets. Some have found that the technology is able to generate enough revenues to pay off the capital cost depending on technological attributes [4,5,6,7], while others found that the technology is not profitable [8,9,10,11]. These studies, however, were limited because they did not consider using the battery ESS to ancillary service, so that they would be paid by both reserve and energy service payments.

In a deregulated electricity market, two types of services are provided; energy service and ancillary service. Energy service pays generators energy payments for the amount of electricity they provide. On the other hand, ancillary services give two types of payments: reserve and energy payments, so reserved capacity to ancillary service gets paid regardless energy is supplied for service

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or not. To date, this additional profit opportunity from reserve payment has not been studied. FERC Order 784 enables third parties to provide ancillary services to markets. Previously, companies that bid for energy service were not allowed to purchase ancillary services from third parties. The order requires deregulated markets to open markets for ancillary services, so that third party suppliers can provide it through newly established channels. As battery ESSs' has faster ramping up speed than conventional fossil fuel turbines, the new order is designed promote investment on battery ESSs [12].

In this study, an economic analysis is presented on the profitability of the battery ESS operator taking part in both energy and ancillary markets. Assuming a single discharge opportunity in a day, backward induction is employed to calculate revenues from bidding for an ancillary service by incorporating potential profits, so that the optimal bidding strategy is determined for every day. Here, the shadow value offering ESS services, derived from Hotelling's [13] work is applied modeling the battery as an exhaustible resource with limited life cycles. As charging and discharging the battery once sacrifices a life cycle in the future, profit making activity at present is potentially made at the expense of an opportunity cost. Thus, our analysis requires a threshold which will equate the present and opportunity cost. The shadow value equates profit of using the battery at the present time and the lost potential profit because of the use. Based on this approach, we build a revenue model to maximize net present value of revenues while using up given lifecycles over operating years by applying the three-staged-method by Shcherbakova et al. [14].

This paper is structured as follows. Section 2 offers a brief introduction to attributes and relevant economic analyses of ESS, focusing on battery ESS Section 3 provides a research statement and objectives, clarifying the scope and goal of this study. Section 4 introduces the revenue maximization model, with backward induction and the three stages analysis approach. In Section 5, an economic analysis of an ESS battery in the Electricity Reliability Council of Texas (ERCOT) market is presented. Finally, Section 6 offers proposals for future work extending the present model to one with multiple discharging opportunities.

2. Literature review

A battery consists of an electrochemical cell, which is made up of a cathode, an anode, and an electrolyte which connects the two electrodes. The battery produces electric energy when the two electrodes react with the electrolyte: oxidation at the anode and reduction at the cathode. This process results in the discharge of energy from the battery. Electric energy can be stored by reversing the process by providing electric energy from the outside [15]. An electro-chemical battery has a finite useful cycling capability or lifecycles. Generally, chemical storage devices have far fewer available lifecycles than mechanically-based storage (i.e., pumped hydro and compressed air energy storage), due to accumulated chemical by-products during each cycling [15,16].

Non-electro-chemical storage technologies, Compressed Air Energy Storage (CAES) and pumped hydro storage, have the largest module size and longer duration for supplying energy at rated power. Some battery ESSs, including some flow batteries, sodium-sulfur (NaS) and advanced lead-acid battery, are suitable for supplying energy for periods from minutes to hours, with rated power ranging from 0.1 MW to more than 10 MW. This range makes the battery able to supply ancillary services, which is reserved for deploying electricity to recover and maintain the reliability of the grid for short (seconds to minutes) and long periods of time [1,2,3].

Technical reports have reviewed projects applying battery ESSs to grid for several purposes. Price et al. [17] examined projects in Europe and the U.S., where ESSs were used with renewable resources or smart grid systems. In these projects, battery ESSs were charged from the resources then discharged stored electricity to energy markets when prices are high.

Studies by Eyer [18] and Akhil et al. [19] discussed currently operating battery ESSs in the U.S. These reports focused on technical maturity, eligible service types, and operation costs. Finally, Ellison et al. [6] and Denholm et al. [11] analyzed economic benefit of currently operating or planned operating battery ESSs in state of Colorado and Nevada respectively: They analyzed the saved depreciation and fuel costs if batteries can be used as an ancillary service resources.

Empirical studies on battery ESS offer inconsistent results on the profitability of the technology. Zafirakis et al. [20] examined storing surplus energy from wind power into an battery ESS for deployment in energy markets during peak demand hours. Results showed that a subsidy is needed for battery ESS even at the lower capital costs used in this scenario. Similar results have been shown in other studies on other regions in Europe, such as with compressed air energy storage in Germany [8], and in Denmark using battery ESSs for arbitrage not attached to renewable generation [9].

Similar results have also been found in an analysis of the U.S. electricity markets. Bradbury et al. [7] used ESSs for arbitrage opportunities in several U.S. markets (California ISO, New York ISO, Midwest ISO, and PJM) to measure their economic viability. Non-electro-chemical technologies, pumped hydro and CAES were found to be more profitable than battery-based ESSs. Furthermore, comparing results throughout the market, technical specifications (round-trip efficiencies, as well as rates of charging and discharging) are seen to have a great influence on financial performance.

Walawalkar et al. [4] conducted an empirical study in NYISO that involved operating a NaS battery for energy arbitrage and flywheel storage for an ancillary service. They concluded that in general it would not be profitable to run the given ESSs. However, the exception was in New York City—there battery ESSs may be profitably operated for arbitrage due to high prices during peak hours. Peterson et al. [10] also studied arbitrage opportunities in NYISO, using a Li-ion battery from Plug-in Hybrid Electric Vehicles. Based on five-year operating revenues, results showed that insufficient revenue would be generated to cover the battery cost.

One study measured change in welfare as a result of more ESSs supplying electricity to the PJM market in the U.S. [5]. The study measured how greater penetration of the storage would affect the profitability of the battery ESSs in PJM. As more ESSs enter market, off-peak hour prices increase while on-peak prices decrease, lowering the number of opportunities for arbitrage.

Hotelling [13] provides an important direction in dealing with the value of postponing battery usage to a later time in order to save cycles. Hotelling's work on the optimal extraction schedule for exhaustible goods is a cornerstone principle in dealing with non-renewable energy. That study found that the profit-maximizing resource extraction schedule for an exhaustible resource is one in which the resource's marginal return grows at the interest rate. Below we apply this result to the deferral value of using the energy storage device at later times and changes in this value over time.

Shcherbakova et al. [14] applied Hotelling's approach in introducing a new framework that considers battery storage as a non-renewable energy resource with limited life cycles. The study introduced the concept of the discharging premium, the shadow cost of using the battery now and not at later times, increased by the interest rate each year following Hotelling's rule. Following this idea, they studied the profitability of an electric storage system in the South Korea, using it for arbitrage in the energy service market. To estimate the life-long revenues from the battery storage device, a three-stage analysis was developed: in the first stage, simulations measured the