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Why market rules matter: Optimizing pumped hydroelectric storage when compensation rules differ

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ABSTRACT

Policies, markets, and technologies interact to create the modern electrical system. Integrating large amounts of electricity generated by variable renewable resources, such as from wind and sunlight, into electricity systems may require energy storage technologies to synchronize electricity production with electricity demand. Electricity markets compensate the performance of these energy storage technologies for the services they provide, and these markets are often operated by regional independent system operators (ISOs) that specify the market rules for this compensation. To examine how different ISO rules can affect the operation and profitability an energy storage technology, we develop a dynamic programming model of pumped hydroelectric storage (PHES) facility operation under the market rules from the Midcontinent ISO and ISO-New England. We present how differences in rules between these ISOs produced different operational strategies and profits, and how important they are for PHES profitability.

1. Introduction

Energy storage could play an important role in the future United States electric system. Numerous federal and state policies have been implemented to stimulate development of low-carbon and renewable technologies. These policies include the wind production tax credit (PTC), a federal tax credit for solar as part of the Emergency Economic Stabilization Act of 2008, and many state Renewable Portfolio Standards (RPSs) (DSIRE, 2014). With over 60,000 MW of installed wind power and 3500 MW of PV solar, these policies have been successful, but managing the variability of wind and solar resources requires new approaches to operate the electric grid and makes storage a critical technology.

Natural variability of electricity flows from wind or solar plants can create grid instabilities that can negatively affect the electrical system's ability to reliably provide electricity when it is needed (Katzenstein and Apt, 2012). In addition, when conventional sources of electricity (e.g., coal or nuclear power plants) cannot be ramped up or down sufficiently to balance variability in wind or solar-generated electricity, wind turbines may have to be curtailed to prevent transmission line congestion and to maintain system balance. One solution to help with grid integration of renewable energy is to store electricity as it is generated (Hall, 2008). Energy storage technologies can help to integrate higher penetrations of low-carbon renewable energy into the electric system and a number of utility-scale energy storage technologies are being developed, including compressed air energy storage, electrochemical batteries and capacitors, and flywheel energy storage (Carnegie et al., 2013).

The need for utility-scale energy storage is also motivating new policy discussions to stimulate development of energy storage technologies—such as the procurement target of 1325 MW of energy storage by 2020 set by the California Public Utilities Commission (CPUC press release, 2013)—and investigations of the reliable energy storage technologies with fast response times ("ramp rates") that can allow electrical grid operators to better accommodate large amounts

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of electricity generated from variable sources (CAISO Strategic Plan, 2013). Fast ramp rates allow electrical grid operators to accommodate large amounts of electricity generated from variable sources.

Among the bulk energy storage options, pumped hydroelectric energy storage (PHES) is the most widely deployed utility-scale energy storage technology (Foley et al., 2013), with over 127,000 MW of capacity installed globally and 40 projects totaling 22,000 MW in the United States alone (Castelvecchi, 2012; EIA, 2012; The Economist, 2012). With PHES, water is stored in an upper water reservoir which is situated at a higher elevation than a lower water reservoir. Energy is stored by pumping water from the lower reservoir into the upper reservoir. The amount of energy that can be stored depends on the elevation difference between the reservoirs, or the “head height,” and the total volume of water that can be moved between the reservoirs. When water flows from the upper to the lower reservoir, it flows through a pump-turbine that generates electricity. The ability to store energy and generate electricity when desired creates a number of opportunities for project developers.

In many parts of the United States, the value of PHES plants will be determined by the revenue the facility could earn in regional energy markets. Independent system operators (ISOs) manage about 70% of the wholesale electric power flows and operate energy markets (EIA, 2011). ISOs use a location marginal pricing (LMP) approach to calculate electricity prices at different market nodes, so the value of a PHES would partially be determined by its location. Historically, prices have generally followed a diurnal pattern; prices are low during off-peak demand periods and higher during peak demand periods. These pricing dynamics create arbitrage opportunities for energy storage because a PHES operator can pump water from the lower reservoir and energy can be stored when prices are low and release water from the upper reservoir to generate electricity when prices are high.

In addition to calculating LMPs, ISOs have also established markets for grid stability services, such as frequency regulation or spinning reserves. The substantial improvement in the pump-turbine technology used in PHES systems can also allow newer PHES turbine technologies to provide regulation services in both pumping and generating modes. So, for PHES facilities located in ISO electricity markets, PHES facility operators can generate revenues both by exploiting arbitrage opportunities and by selling regulation services.

The value of an energy storage project will thus depend on (1) how the electricity market functions; (2) how storage is valued for the sale of electricity; and (3) its ability to provide and earn money from regulation services. But while U.S. electricity markets follow standard market design, the value of an energy storage project depends on the very specific details of how the each ISO's market rules compensate energy storage (Hogan, 2002). There are nine different ISOs in the United States—each of which determines its own rules for compensation in consultation with members and approvals by the Federal Energy Regulatory Commission (FERC).

PHES facility profits are partly determined by the stream of revenues, which depend on the future prices in electricity and regulation service markets, the ISO rules governing those markets, and the operational strategies used by the facility operator. Here, we examine and compare how the rules and markets of the Midcontinent ISO (MISO) and ISO New England (ISO-NE) would affect the optimal strategies employed by PHES operators and thus the total value of providing energy storage. These ISOs were chosen because, until 2011, they had different rules for compensation. In MISO, compensation for frequency regulation only included payments for capacity set aside and payments (charges) for net energy injected into (withdrawn from) the power system. ISO-NE makes capacity payments and “mileage” payments based on the absolute amount of energy injected and withdrawn. The mileage payment is intended to reward the quantity and accuracy of frequency regulation service provided by the participant.

In October 2011, FERC issued Order No. 755 mandating that all ISOs develop a compensation method that provides both a capacity payment and a mileage payment to reward resources with faster ramp rates. We estimate the net profits of a PHES facility under the MISO rules and ISO-New England market rules at the time Order No. 755 was issued to better assess how the rule affects strategy and compensation of storage projects. We estimate the difference in net profits and bidding activity under the different compensation formulas in place prior to the FERC mandate to gain insight into the level of impact that Order No. 755 has on the development and deployment of resources with faster-ramp speeds and to highlight the importance of ISO rules on operator value. In 2012 MISO changed its compensation formula to comply with Order No. 755 (FERC, 2012).

Our model and analysis focus on the perspective of a PHES facility operator, and not on the total system costs examined by other studies (Foley and Lobera, 2013). Previous work has also investigated optimal bidding strategies for PHES facility operators, including approaches that fix the efficiency factor and power generation bid (Lu et al., 2004), model participation in the energy and spinning reserve markets (Kanakasabapathy and Swarup, 2010), and restrict pumping and generation modes to the traditional off-peak and peak periods, respectively, but do not model participation in ancillary services markets (Connolly et al., 2011; Deb, 2000). Kazempour et al. (2009) presents a detailed model that considers uncertainty in price forecasts and allows the PHES plant to participate in the energy, spinning reserve, and frequency regulation services markets, but this approach restricts the flexibility of PHES to set aside different amounts of frequency reserve and fixes the efficiency factor of the plant and of the power generation bid. Algorithms that have been employed require the PHES plant to pump before it generates (Kanakasabapathy and Swarup, 2010), allow pumping to occur either before or after generation (Connolly et al., 2011), or are simple heuristics for dispatch that maximize potential revenues from energy and frequency regulation services for each hour (Deb, 2000).

Our model determines the profit-maximizing behavior of a PHES facility and estimates revenue streams from selling both electricity and grid reliability services into different competitive wholesale electricity markets with different compensation mechanisms. Our model also integrates detailed operational and physical specifications (BARR Engineering Company, 2009) that have previously received scant attention but are crucial for modeling system performance. Operationally, the PHES operator can choose to set aside capacity as frequency regulation reserve. Physically, our model accommodates how pump-turbine efficiencies vary according to head height and flow volume in both pumping and generating modes. Combined, upper and lower bounds are set to provide frequency regulation based on the relationships between head height, flow, and turbine efficiency. Our application determines optimal market bidding strategies for electricity and reliability services that operate under both the MISO and ISO-NE market rules. By comparing the value of PHES systems and the impacts of these different rules on revenue streams, we are able to better understand the value of different policies and how they monetize the benefits provided by PHES.

Section 2 presents a brief discussion of the day-ahead and real-time electricity markets and the market for frequency regulation. Section 3 presents the optimization model and in Section 4 we present the results and provide a discussion of the value of PHES in the MISO and ISO-NE.

2. Materials and methods

The following section details the real time markets and reliability service markets and provides a description of the model.

2.1. Market structure

2.1.1. Day-ahead and real-time markets

The wholesale market for electricity is co-optimized with ancillary services markets to solve for prices for electricity and ancillary services