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Opportunities for Energy Storage in CAISO

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***Abstract*—Energy storage is a unique grid asset in that it is capable of providing a number of grid services. In market areas, these grid services are only as valuable as the market prices for the services provided. This paper formulates the optimization problem for maximizing energy storage revenue from arbitrage and frequency regulation in the CAISO market. The optimization algorithm was then applied to three years of historical market data (2014-2016) at 2200 nodes to quantify the locational and time-varying nature of potential revenue. The optimization assumed perfect foresight, so it provides an upper bound on the maximum expected revenue. Since California is starting to experience negative locational marginal prices (LMPs) because of increased renewable generation, the optimization includes a duty cycle constraint to handle negative LMPs. The results show that participating in frequency regulation provides approximately 3.4 times the revenue of arbitrage. In addition, arbitrage potential revenue is highly location-specific. Since there are only a handful of zones for frequency regulation, the distribution of potential revenue from frequency regulation is much tighter.**

I. Introduction

Energy storage is a unique grid asset in that it is capable of providing a number of grid services. These services can be broken into two categories based on the characteristics of the charge/discharge profile required to provide the service. Energy applications typically transpire over long periods of time, often up to several hours. On the other hand, power applications happen on a much quicker time scale, seconds to minutes, and are often aimed at maintaining grid stability. A summary of energy and power applications appears in Table I. A detailed description of potential benefits from energy storage is found in [1].

TABLE I
Summary of energy storage applications.

Energy Applications	Power Applications
Arbitrage	Frequency regulation
Renewable energy time shift	Voltage support
Demand charge reduction	Small signal stability
Time-of-use charge reduction	Frequency droop
T&D upgrade deferral	Synthetic inertia
Grid resiliency	Renewable capacity firming

In market areas, energy storage is only remunerated for activities associated with market products. The common services include energy arbitrage and providing ancillary services. Arbitrage refers to purchasing energy (charging) when prices are low, and then selling (discharging) energy when prices are high. An early study identifying the potential arbitrage benefit is presented in [2]. While arbitrage is the most well known service that can be provided by energy storage, it rarely offers the most potential revenue [3], [4], [5], [6], [7], [8].

The most common ancillary service is frequency regulation, which is the second by second adjustment of output power to maintain system frequency. In some market areas like PJM, there is a single product for frequency regulation and the device must have a bidirectional capability. In other markets like CAISO and ERCOT, there are separate products for regulation up (inject power to the grid) and regulation down (pull power from the grid). Pay-for-performance was mandated by FERC Order 755 [9], [10], so all Independent System Operators (ISOs) in North America, with the exception of ERCOT, have adopted pay-for-performance mechanisms. Typically, this includes some type of mileage measurement combined with a performance score. The remuneration is a function of the capacity and mileage price, as well as the performance score.

A framework is outlined in this paper for calculating the maximum revenue from an electricity storage system that participates in the CAISO day-ahead market for energy arbitrage and frequency regulation. The approach is designed to calculate the best-case scenario using historical data to simulate operation with perfect day-ahead energy and reserve price forecasts. This best-case scenario calculation is critical because it provides an upper bound on the revenue that can be collected by a storage facility and can be used to score other trading strategies. Hence, it is useful in estimating an upper bound for the value of a storage facility. Cost data is required to perform a cost-benefit analysis for a particular system and location. Information on the capital and operational costs of different energy storage technologies may be found in [11]. It should also be noted that this approach is only valid for scenarios where the size of the storage is such that it does not impact market prices. For large systems that might impact the market, a production cost modeling approach must be implemented.

The approach in this paper formulates the revenue maximization problem as a linear program. The energy storage model and optimization formulation builds on the results in [12], where the authors present a stochastic framework for the valuation of electricity storage. Previous results using a similar approach (without pay-for-performance) were presented in [3], [4], [5]. The algorithm, results for CAISO data (including a

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sensitivity analysis for each parameter), and results for several implementable trading algorithms appear in [3]. ERCOT results for a single node, two years of data, and implementable trading algorithms are presented in [4]. All nodes in ERCOT were analyzed over a three year period to look at the impact of location and to identify longer term trends in [5]. The pay-for-performance optimization for PJM, along with results for a representative flywheel plant are found in [5]. The pay-for-performance optimization for MISO is presented in [8]. The optimization formulation for the ISO-NE market along with expected results for a 2 MW, 3.9 MWh system deployed by the Sterling Municipal Light Department (SMLD) are found in [6]. This paper extends the optimization approach to include pay-for-performance as implemented by CAISO, and presents results for three years of historical data at 2200 nodes to provide insight into the impact of location on potential revenue.

This report is organized as follows: Section II provides an overview of the CAISO pay-for-performance implementation. Section III presents the energy storage model that is used throughout this paper as well as the revenue maximization problem formulation. Section IV presents results for 2200 CAISO nodes for the 2014-2016 period. Concluding remarks are found in Section V.

II. CAISO Market

Prior to FERC Order 755, CAISO provided a capacity payment based on the energy opportunity cost of the marginal unit, and also provided payment of net energy from providing frequency regulation based on the real-time market energy price [13]. Effective May 12, 2013, CAISO added a market-based mileage payment as well as an accuracy adjustment for the mileage payment. In addition, inter-temporal opportunity costs were included with the bid [13]. Regulation resources receive a new Automatic Generation Control (AGC) setpoint every 4 seconds.

Energy storage is treated as a Non-generating Resource (NGR), along with dispatchable demand response [14]. There are two options for participating in the day ahead frequency regulation market: a Regulation Energy Management (REM) resource and a traditional (non-REM) resource. A traditional (non-REM) resource is required to maintain the dispatched power level for 1 hour. Therefore, a 20 MW, 5 MWh system would be limited to bidding 5 MW into the frequency regulation market. In contrast, a REM resource is only required to maintain the dispatched power level for 15 minutes. Thus, a a 20 MW, 5 MWh system could bid the full rating of 20 MW into the frequency regulation market. Both REM and non-REM systems must meet he 10-minute ramping requirement (the same as a generator). Additionally, each resource must meet a minimum performance threshold of 25 % accuracy over a calendar month. If a resource fails to meet this minimum requirement, the resource must recertify to provide regulation services within 90 days.

The remuneration for providing frequency regulation in CAISO is given by

$$\begin{aligned} \text{Regulation Payment} \;=\; & \text{Capacity Payment}+ \\ & \text{Performance Payment}+ \\ & \text{Net Energy Settlement} \end{aligned} \tag{1}$$

The capacity payment is simply the market price for the period times the capacity accepted. The performance payment is the instructed mileage times the mileage price, multiplied by an accuracy adjustment β. The accuracy adjustment is based on the following calculations for every 15-minute period:

$$M_{AGC} = \sum_{i=0}^{225} |AGC_i - AGC_{i-1}| \tag{2}$$

$$M_{deviation} = \sum_{i=1}^{225} |P_i - AGC_i| \tag{3}$$

$$\beta = \frac{M_{AGC} - M_{deviation}}{M_{AGC}} \tag{4}$$

where AGC_i is the 4-second AGC command signal at time i and P_i is the metered output power at time i. The accuracy adjustment is the sum of commanded mileage minus the sum of absolute errors divided by the commanded mileage. If the sum of the absolute error is always zero, the accuracy adjustment will be 1.0. For the day ahead market, the accuracy adjustment is the average of the four 15-minute period calculations. The net energy settlement is based on the real-time market price for energy.

III. Energy Storage Model

The key parameters that characterize a storage device are [15]:

- Power Rating [MW]: the maximum rated power of the storage device (charge and discharge). It is possible to have a different power rating for charging and discharging.
- Energy Capacity [MWh]: the amount of energy that can be stored.
- Efficiency [percent]: the ratio of the energy discharged by the storage system divided by the energy input into the storage system. Efficiency can be broken down into two components: conversion efficiency and storage efficiency. Conversion efficiency describes the losses encountered when input energy is stored in the system. Storage efficiency describes the time-based losses in a storage system.
- Ramp Rate [MW/min or percent nameplate power/min]: the ramp rate describes how quickly a storage system can change its input/output power level.

An energy flow model is often employed to model market interactions. The simplest formulation is a discrete linear time invariant model given by [12]:

$$S_t = S_{t-1}\gamma_s + q_t^R \gamma_c - q_t^D \tag{5}$$

where S_t is the state of charge at time t, γ_s is the storage efficiency over one time period, γ_c is the conversion efficiency, q_t^R is the quantity of energy charged over one period, and q_t^D is the quantity of energy discharged over one period. This model assumes constant storage and conversion efficiencies.

For the analysis in this paper, we are concerned with the quantity of energy charged or discharged during each time period for each potential activity (e.g. arbitrage and frequency regulation). For regulation, it is assumed that the device is capable of tracking the regulation signal.

The following parameters capture the storage system constraints:

t	time period (e.g. one hour)
$\bar{q}$	maximum discharged/recharged energy in one period (MWh)
$\bar{S}$	maximum storage capacity (MWh)
$\underline{S}$	minimum storage capacity (MWh)

For a storage device that provides only one service, e.g. arbitrage, there are two decision variables: q_t^D and q_t^R. The decision variables are assumed to be non-negative quantities. Additional constraints include:

$$\underline{S} \leq S_t \leq \bar{S}, \forall t \tag{6}$$

$$0 \leq q_t^D + q_t^R \leq \bar{q}, \forall t \tag{7}$$

Note that the constraint in Equation (7) is required if negative LMPs are present to guarantee that simultaneous charging/discharging is within the constraints of the system. For a device that is participating in arbitrage and the regulation market, a few additional quantities must be incorporated into the storage device model. Assuming a separate market for regulation up and regulation down, the additional decision variables are:

q_t^{RU}	energy offered into the regulation up market at time t (MWh)
q_t^{RD}	energy offered into the regulation up market at time t (MWh)

Once again, the decision variables are assumed to be nonnegative quantities. For energy arbitrage, the scheduled and actual quantities are equal. For the regulation market, a resource usually offers a capacity and there is no guarantee that all of the offer will be accepted. Fortunately, since frequency regulation is concerned with the short-term balance of load and generation to maintain system frequency, regulation signals are usually zero mean over longer time periods.

In order to quantify the change in state of charge from participation in the regulation market, it is useful to define the regulation up efficiency γ_{ru} as the fraction of the regulation up reserve capacity that is actually employed in real-time (on average). Similarly, the regulation down efficiency γ_{rd} is the fraction of the regulation down reserve capacity that is actually employed in real-time (on average). For some markets where historical regulation data is available, it is possible to calculate γ_{ru} and γ_{rd} at each time step.

The state of charge at time t for a device participating in arbitrage and regulation with a separate market for regulation up and regulation down is given by

$$S_t = \gamma_s S_{t-1} + \gamma_c q_t^R - q_t^D + \gamma_c \gamma_{rd} q_t^{RD} - \gamma_{ru} q_t^{RU} \tag{8}$$

subject to the following constraints:

$$\begin{aligned} \underline{S} &\leq S_t \leq \bar{S},\ \forall t \\ 0 &\leq q_t^R + q_t^{RD} \leq \bar{q},\ \forall t \\ 0 &\leq q_t^D + q_t^{RU} \leq \bar{q},\ \forall t \end{aligned} \tag{9}$$

Participating in regulation down provides the opportunity to increase the state of charge subject to the regulation down efficiency and the conversion efficiency. Participation in regulation up provides the opportunity to decrease the state of charge subject to the regulation up efficiency. The quantities allocated to regulation up and regulation down reduce the maximum potential quantities allocated to arbitrage subject to the charge/discharge constraints of the device.

For CAISO, the objective function that maximizes potential revenue from particpating in the day-ahead energy and regulation markets is given by

$$\begin{aligned} &\max \textstyle\sum_{t=1}^{T} \big[(P_t - C_d)(q_t^D + \gamma_{ru} q_t^{RU}) - \\ &(P_t + C_r)(q_t^R + \gamma_{rd} q_t^{RD}) + q_t^{RU} P_t^{RU} + q_t^{RD} P_t^{RD} \\ &\beta_t^{RU} M_t^{AGC} PM_t^{RU} + \beta_t^{RD} M_t^{AGC} PM_t^{RD}\big] \, e^{-rt} \end{aligned} \tag{10}$$

IV. CAISO Results

For this analysis, three years (2014-2016) of CAISO market data for day ahead energy and frequency regulation was analyzed for 2200 node locations. The arbitrage results are summarized in Figure 1. The distribution of potential arbitrage revenue is shown in Figure 2. The monthly revenue profile for the minimum node, the median node, and the maximum node are found in Figure 3. The highest/lowest ten revenue nodes are listed in Table II. The maximum potential 3-year total arbitrage revenue ranges from \$53.87K to \$145.87K, with an average of \$81.05K. There are relatively few "high revenue" nodes, as noted in the distribution and heat map. The majority of the difference between the maximum node and the median node can be attributed to a few months with extremely high potential revenue opportunities.

TABLE II
HIGHEST AND LOWEST POTENTIAL ARBITRAGE REVENUE NODES.

Node	**Revenue**	**Node**	**Revenue**
SYLMARDC_2_N501	\$53.87K	ELNIDO_1_N004	\$155.05K
JBBLACK1_7_B1	\$54.42K	ELNIDO_1_N001	\$155.05K
JBBLACK2_7_B1	\$54.65K	CRESSEY_1_N003	\$147.44K
PIT3_7_N001	\$55.83K	CRESSEY_1_N001	\$147.44K
PIT6U2_7_B1	\$56.02K	LIVNGSTN_1_N001	\$146.52K
PIT5_7_N001	\$56.22K	ELCAPTN_1_N004	\$146.38K
PIT5_7_B1	\$56.22K	ATWATER_1_N001	\$146.28K
PIT6U1_7_B1	\$56.34K	ATWATER_1_B2	\$146.28K
PIT3_2_B1	\$56.41K	MERCED_1_N001	\$146.12K
PIT1U1_7_B2	\$56.65K	ELCAPTN_1_N001	\$145.87K

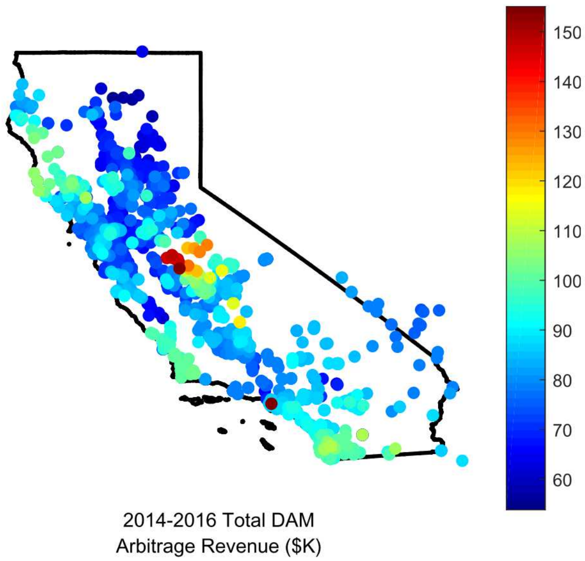

Fig. 1. Maximum potential arbitrage revenue 2014-2016 ($K).

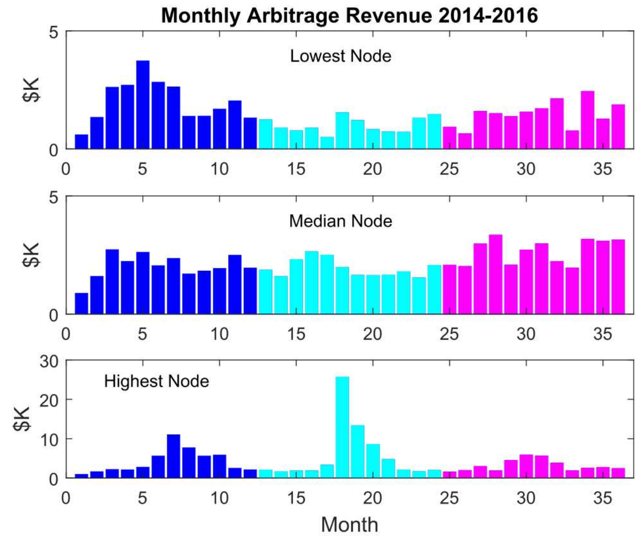

Fig. 3. Monthly arbitrage revenue profile for the minimum node, the median node, and the maximum node (2014-2016).

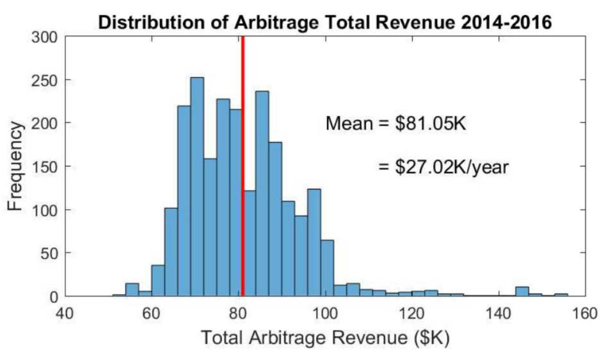

Fig. 2. Distribution of maximum potential arbitrage revenue 2014-2016 ($K).

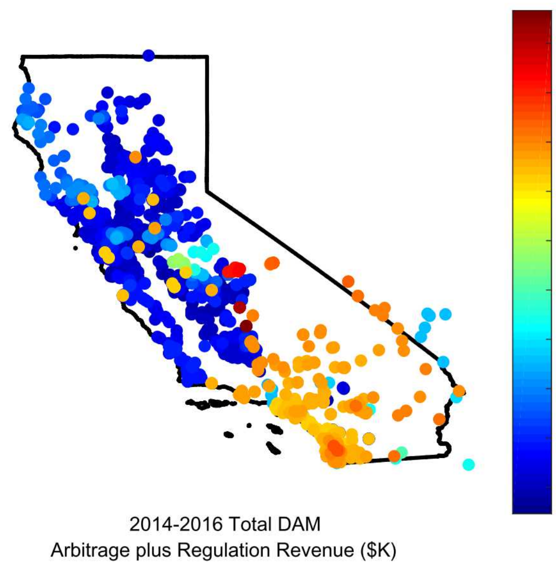

Fig. 4. Maximum potential arbitrage plus regulation revenue 2014-2016 ($K).

The arbitrage and regulation results are summarized in Figure 4. The distribution of potential arbitrage and regulation revenue is shown in Figure 5. The monthly revenue profile for the minimum node, the median node, and the maximum node are found in Figure 6. The highest/lowest ten revenue nodes are listed in Table III. The maximum potential 3-year total arbitrage revenue ranges from $244.64K to $346.68K, with an average of $273.33K. Most of the spread in potential revenue can be attribited to the ancillary service zone, with the SP15 zone exhibiting slightly higher potential revenue.

TABLE III
HIGHEST AND LOWEST POTENTIAL ARBITRAGE PLUS REGULATION REVENUE NODES.

Node	Revenue	Node	Revenue
CHICOB_1_N002	$244.64K	LBEACH2G_7_N002	$346.68K
TJI-230_2_N101	$244.78K	LBEACH2G_7_N001	$346.68K
FULTON_2_N049	$244.79K	LBEACH1G_7_N001	$346.68K
TLRELKE_6_N001	$244.79K	HINSON_6_N001	$346.68K
KANAKA_1_N001	$244.97K	JRWDGEN_1_N001	$340.56K
KANAKA_1_N003	$245.02K	JRWOOD_1_N001	$340.56K
BUTTE_1_N101	$245.05K	CRESSEY_1_N003	$340.56K
HYATT5_7_B1	$245.60K	CRESSEY_1_N001	$340.56K
PIT6U1_7_B1	$246.70K	RECTOR_6_N009	$340.56K
COVERD_7_B1	$246.70K	BIGCRK1_2_B1	$333.00K

V. CONCLUSION

This paper formulates the revenue maximization problem for energy storage participating in the CAISO day-ahead energy and regulation markets, including pay-for-performance. Then, three years of historical market data for 2200 nodes

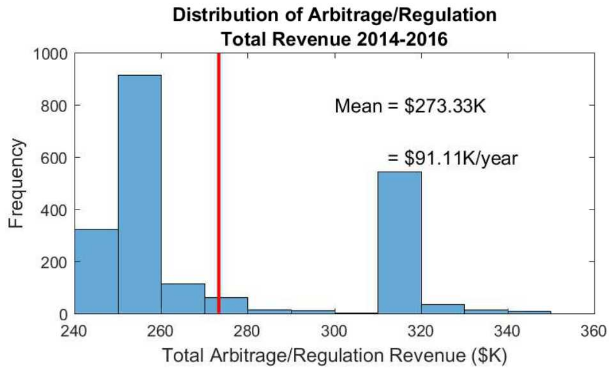

Fig. 5. Distribution of maximum potential arbitrage plus regulation revenue 2014-2016 ($K).

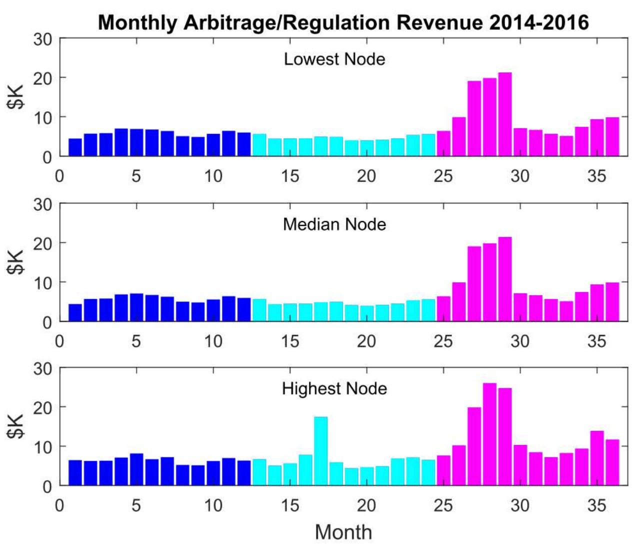

Fig. 6. Monthly arbitrage plus regulation revenue profile for the minimum node, the median node, and the maximum node (2014-2016).

was analyzed to identify the impact of location on potential revenue. The analysis considered arbitrage alone, and then arbitrage combined with frequency regulation. When arbitrage was combined with frequency regulation, the optimum policy was to participate in frequency regulation the majority of the time. In addition, the potential revenue from frequency regulation was approximately 3.4 times the arbitrage potential revenue. This is consistent with results from other ISOs. There was also much more variability in potential arbitrage revenue based on location. Since there are only a couple frequency regulation zones, the impact of location was diminished for the arbitrage plus frequency regulation case. Future research will focus on including arbitrage opportunities between the day-ahead and real-time markets, as well as providing the newly introduced flexible ramping product.

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