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Revenue Opportunities for Electric Storage Resources in the Southwest Power Pool Integrated Marketplace

Ricky J. Concepcion, Felipe Wilches-Bernal, Raymond H. Byrne
Sandia National Laboratories, Albuquerque, NM
{rconcep, fwilche, rhbyrne}@sandia.gov

***Abstract*—This paper explores the revenue potential for electric storage resources (ESRs), also referred to as electrical energy storage, in the Southwest Power Pool Integrated Marketplace. In particular, opportunities in the day-ahead market with the energy and frequency regulation products are considered. The revenue maximization problem is formulated as a linear program model, where an ESR seeks to maximize its revenue through the available revenue streams. The ESR has perfect foresight of historical prices and determines the optimal policy accordingly. A case study using FY2018 data shows that frequency regulation services are the most lucrative for revenue potential. This paper also explores different methods of using area control error data to infer the regulation control signal and the consequent effect on the optimization. Finally, the paper conducts a sensitivity analysis of ESR energy capacity and power rating, showing that revenue potential is dominated by the power rating given perfect foresight.**

***Index Terms*—Electricity market; ancillary services; energy storage; linear programming; optimization; arbitrage; frequency regulation market**

I. Introduction

Electric storage resources (ESRs), occupies a unique niche in the electrical energy space. Traditional generation assets are tied to fuel and restrictions such as minimum uptime. Variable resources such as photovoltaic and wind power are temporally and locationally limited. Energy storage, on the other hand, has the unique capability of being able to store energy in the present for use in the future, when it may be better utilized. This ability is attractive in the context of electricity markets, considering energy arbitrage or renewable energy time-shifting. Additionally, ESRs connected to the grid through fast, power electronics-interfaced technologies can serve a valuable role in providing services such as frequency regulation, contributing to grid reliability.

Energy storage systems such as battery or flywheel technologies open the possibilities of fast-responding and flexible resources that can be immensely value to the grid. To date, however, the costs of these technologies have challenged their economically feasibility. Strides in manufacturing or changes in business models or tariff structures for energy storage projects may improve this outlook. Regulatory actions such as FERC (Federal Energy Regulatory Commission) Orders 755 [1] and 841 [1] create the prospect of increased viability for ESRs, but, especially for Order 841, the effects are heretofore yet to fully manifest.

The value of energy storage systems is an active area of research, motivated by encouraging adaption of these technologies. Previous work by the authors has estimated potential revenue of ESRs in the ERCOT [2], [3], PJM [4], MISO [5], and CAISO [6] energy and frequency regulation markets. Value stacking, one of the often cited advantages of energy storage systems, is explored in [7]. In addition to energy arbitrage and frequency regulation services, the authors examine the additional benefit of outage mitigation. In [8], a similar optimization approach for energy arbitrage revenue estimation is applied to PJM data showing that expected revenue can be predicted by clustering historical prices. This paper continues previous energy storage valuation work done in other market areas in the Southwest Power Pool (SPP) Integrated Marketplace. Using a linear programming (LP) approach, the optimization solves for the maximum amount of revenue generated in the energy arbitrage and frequency regulation markets by a given ESR. Historical data such as prices is used and the ESR model determines the optimal policy of market participation, given perfect foresight of data. The resulting revenue generated is taken as an upper bound on revenue potential. This paper also examines several methods for inferring the frequency regulation control signal based on area control error (ACE) data as well as its effect on optimal policy. Finally, this paper presents a sensitivity analysis of estimated revenue to ESR energy capacity and power rating.

II. The Southwest Power Pool Integrated Marketplace

Southwest Power Pool was founded in 1941 for the purpose of ensuring that a national security asset in Arkansas remained powered at all times. A collaboration of eleven regional power companies, it originally encompassed portions of the central United States in the vicinity of Oklahoma. In 2004, the Federal Energy Regulatory Commission (FERC) approved SPP as a Regional Transmission Organization (RTO) [9]. Its footprint expanded over the years, and currently provides services in fourteen states with plans to expand further west.

The Southwest Power Pool Integrated Marketplace (IM) opened in 2014. In this market, participants buy and sell

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wholesale electricity in the day-ahead market (DAM) and real-time balancing market (RTBM). There is also a transmission congestion rights market. On the DAM and RTBM, the products that are traded are energy and operating reserve. Operating reserve consists of four products: (frequency) regulation up, regulation down, spinning reserve, and supplemental reserve. In the DAM, market participants submit offers and bids to buy and/or sell energy and operating reserve products. In the RTBM, differences as a result of real-time operation and reliability commitment processes are settled on a five-minute basis, resulting in variable dispatch instructions. Following the operating day, the financial settlement of all market activities occurs. In 2017, the DAM accounted for 98% of the energy consumed in the SPP IM [10].

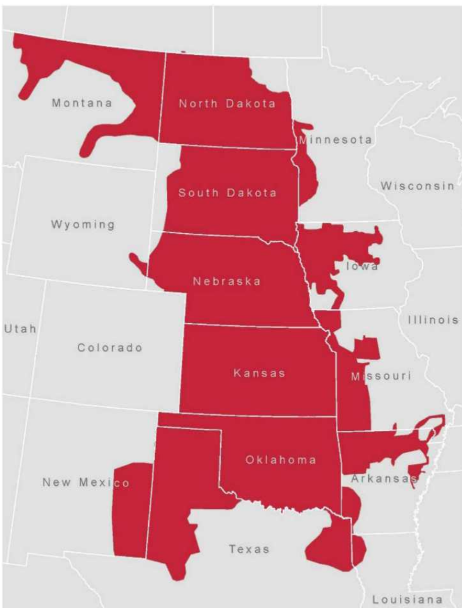

Fig. 1: SPP market footprint (from [10]).

A. Mileage compensation and pay-for-performance

In 2011, FERC issued Order 755, decreeing new rules for compensating frequency regulation resources, colloquially referred to as *pay-for-performance* [1]. For compliance, independent system operators (ISOs) and RTOs such as SPP were required to pay frequency regulation resources based on the actual amount of regulation service provided rather than just the capacity offered. As SPP was not an RTO at the time of the order, it was allowed additional to design a compliant implementation. In March 2015, SPP introduced a new set of products in the operating reserve space, paying regulation resources for mileage costs based on mileage, the movement between instructed setpoints. Mileage for both regulation up and regulation down services is accounted for with different product prices. Additionally, *mileage factors* for each product are computed monthly, representing the percentage of mileage the frequency regulation resource is expected to deploy versus what it actually cleared. Resources that deploy more than what they are expected to are compensated for the excess amount while those that deploy less are expected to buy back the difference [10]. It is through these mileage-based products that higher performing regulation resources may be more fairly compensated.

B. Electric storage resource participation

In early 2018, FERC issued Order 841, aimed at removing "barriers to the participation of electric storage resources (ESRs) in the capacity, energy, and ancillary service markets operated by [RTOs and ISOs]" [11]. Specifically, each RTO/ISO is required to revise its tariff to facilitate the participation of ESRs. Each resource must be eligible to provide all of the services it is "technically capable of providing" to the market and have its physical and operational characteristics taken into consideration. Additionally, the sale of electric energy from the RTO/ISO markets to ESRs that the ESR resells back to the market must be at the wholesale locational marginal price (LMP). SPP recognized the need for the market rules enhancements enacted by Order 841 [10] and recently submitted tariff revisions in response with a requested effective date in December 2018.

C. Integrated Marketplace protocols

This paper focuses on an ESR participating in the DAM of the SPP IM. Settlements for the DAM are performed hourly, based on the DAM clearing for the corresponding operating day. Each market participant with cleared offers is paid for each settlement location for [12]:

- The amount of physical energy sold at the LMP
- The amount of virtual energy sold at the LMP
- The amount of regulation-up service sold at the regulation-up service market clearing price (MCP)
- The amount of regulation-down service sold at the regulation-down service MCP
- The amount of spinning reserve sold at the spinning reserve MCP
- The amount of supplemental reserve sold at the supplemental reserve MCP

Each market participant with cleared bids are charged for each settlement location for:

- The amount of physical energy purchased at the LMP
- The amount of virtual energy purchased at the LMP

Actual charges for operating reserve procurement in the DAM are based on *reserve zones*, which are regularly computed and assigned. *Make whole payments* are available to recoup the costs of resources' offers if insufficient revenue is generated from energy and operating reserve sales in the DAM. Other processes, such as congestion management and demand reduction, are also settled in the DAM but are not considered in this paper.

III. Energy Storage Participation in the SPP Day-Ahead Market

This paper focuses on an ESR participating in the SPP's DAM, buying and selling energy and operating reserve products. Specifically, the ESR is eligible to engage in energy arbitrage and offer regulation up and down services. While spinning reserve and supplemental reserve services are available, SPP's IM offers *product substitution* which ensures that the regulation up MCP are no less than those of the spinning and supplemental reserve products [12]. Because mileage-related settlements are based in the RTBM, they are not considered in this paper. As a result, pay-for-performance is not explicitly considered.

The problem of revenue maximization over a given month is considered. This problem is formulated as a linear program in which an ESR makes bids in the SPP DAM at each hour. Each bid is assumed to be cleared and financially settled accordingly. The ESR is assumed to have perfect foresight of the historical data (e.g., prices) populating the mathematical program model. Therefore, the optimal policy solved for is considered a best-case scenario and the corresponding objective function value, the gross revenue over the time horizon, is taken as an upper bound on the ESR's revenue generation. This type of retrospective analysis for energy storage valuation can be used to infer value from future cash flows.

TABLE I: Nomenclature

	Decision Variables	**Units**
q_i^{r}	Energy recharged in period i	MWh
q_i^{d}	Energy discharged in period i	MWh
q_i^{ru}	Energy capacity bid for reg. up in period i	MWh
q_i^{rd}	Energy capacity bid for reg. down in period i	MWh
S_i	State of charge in period i	MWh
	Storage Parameters	**Units**
$\overline{S}$	Energy capacity	MWh
$\overline{Q}$	Power rating	MW
$\underline{S}$	Minimum state of charge	MWh
η_{s}	Self-discharge efficiency	%/h
η_{c}	Round-trip efficiency	%
	Market Parameters	**Units**
λ_i	Locational marginal price in period i	\$/MWh
$\lambda_i^{\mathrm{c,ru}}$	Reg. up market clearing price in period i	\$/MWh
$\lambda_i^{\mathrm{c,rd}}$	Reg. down market clearing price in period i	\$/MWh
δ_i^{ru}	Fraction of reg. up bid deployed in period i	-
δ_i^{rd}	Fraction of reg. down bid deployed in period i	-
R	Interest/discount rate	-
$\mathcal{T}$	The set of all hours in a given month	-

The nomenclature used in this paper is shown in Table I. This paper uses an energy-based, discrete-time model for the ESR. Decisions for bidding are done at each hourly timestep, affecting the state of charge (SOC) for the subsequent timestep. The decision variables are nonnegative. The SOC at each timestep is governed by the following difference equation:

$$S_{i+1} = \eta_s S_i + \eta_c q_i^{\mathrm{r}} - q_i^{\mathrm{d}} + \eta_c \delta_i^{\mathrm{rd}} q_i^{\mathrm{rd}} - \delta_i^{\mathrm{ru}} q_i^{\mathrm{ru}} \quad \forall i \in \mathcal{T} \quad (1)$$

with $S_0 = S_{|\mathcal{T}|} = \underline{S}$. The objective function to be maximized is given by:

$$J(q^d, q^r, q^{\mathrm{ru}}, q^{\mathrm{rd}}) = \sum_{i \in \mathcal{T}} [\lambda_i (q_i^{\mathrm{d}} + \delta_i^{\mathrm{ru}} q_i^{\mathrm{ru}}) - \lambda_i (q_i^{\mathrm{c}} + \delta_i^{\mathrm{rd}} q_i^{\mathrm{rd}}) + \lambda_i^{\mathrm{c,ru}} q_i^{\mathrm{ru}} + \lambda_i^{\mathrm{c,rd}} q_i^{\mathrm{rd}}] e^{-Ri} \quad (2)$$

The constraints of the LP describe the physical limitations of the ESR, namely its energy capacity and power rating. At each timestep, the ESR may not go below its minimum SOC or exceed its energy capacity. Additionally, the sum of its energy and operating reserve product bids is limited by its power rating. This constraint is formulated to prevent simultaneous charging and discharging in the same time period allowing the ESR to exceed its power rating. Note that since the discrete timestep is one hour, power and energy are used interchangeably. These families of constraints are given by:

$$\underline{S} \leq S_i \leq \overline{S} \qquad \forall i \in \mathcal{T} \quad (3)$$

$$q_i^{\mathrm{r}} + q_i^{\mathrm{d}} + q_i^{\mathrm{rd}} + q_i^{\mathrm{ru}} \leq \overline{Q} \qquad \forall i \in \mathcal{T} \quad (4)$$

It is assumed that, on the timescale considered, the ESR can ramp sufficiently fast enough to meet its obligations such that ramp rate can be neglected. Additionally, since this is a retrospective analysis, it is assumed that the ESR is a price taker and its activities have no influence on the market.

IV. Results

This paper uses data available on SPP's marketplace portal.

A. Using ACE signal to estimate regulation deployment

Southwest Power Pool also posts the current and previous years' area control error signal in one- and ten-minute averages. This paper uses this data to generate values for the δ^{ru} and δ^{rd} series, the fraction of each regulation up/down bid that is actually called upon, under the following assumptions:

- The signal is characteristically representative of the frequency regulation control signal.
- The signal is proportionally applied to the particular ESR's regulation capacity bid.

The δ^{ru} and δ^{rd} series are derived in one of two manners, using the one-minute averaged data:

1) Binary: The ACE signal x^{ACE} for the month is averaged for each hour and then normalized to the range $[-1, 1]$ to obtain $\widetilde{x}^{\mathrm{ACE}}$. For each hour i where $\widetilde{x}_i^{\mathrm{ACE}} > 0$, set $\delta_i^{\mathrm{rd}} = \widetilde{x}_i^{\mathrm{ACE}}$ and $\delta_i^{\mathrm{ru}} = 0$. Similarly, for each hour i where $\widetilde{x}_i^{\mathrm{ACE}} < 0$, set $\delta_i^{\mathrm{ru}} = \left|\widetilde{x}_i^{\mathrm{ACE}}\right|$ and $\delta_i^{\mathrm{rd}} = 0$. This implies that δ_i^{rd} and δ_i^{ru} may not simultaneously be nonzero in any period i.

2) Independent: The ACE signal x^{ACE} for the month is first split into two signals. $x^{\mathrm{ACE,rd}}$ is equal to x^{ACE}, except negative values are clipped to zero. Likewise, $x^{\mathrm{ACE,ru}}$ is the analog with positive values clipped to zero instead. Each component is then independently hourly averaged and normalized into the range $[0, 1]$, resulting in the series for δ^{ru} and δ^{rd}. Through this method, each series *may* be simultaneously nonzero.

B. Case study: Flywheel plant in central Oklahoma in FY2018

The type of ESR studied is a flywheel plant with storage parameters shown in Table II. While consecutive months of results are shown, each month is considered independently from the others. The period of study is fiscal year 2018 (FY2018). The settlement location for pricing is SPPSOUTH_H, a hub in

TABLE II: Case Study Parameters

Parameter	Value
$\overline{S}$	5 MWh
S_0	0
$\overline{Q}$	20 MW
η_s	99%
η_c	80%
R	0
Pricing node	SPPSOUTH_H
Time period	FY2018
Time horizon	One month

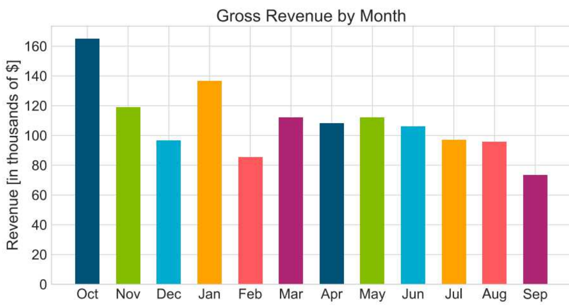

Fig. 2: Gross revenue by month totaling all revenue streams.

central Oklahoma. The independent method is used to derive δ^{ru} and δ^{rd} values from ACE data.

Fig. 2 shows the gross revenue for each month simulated. The gross annual revenue for the time period simulated is $1,307,442.27. The breakdown of revenue between energy arbitrage and regulation up/down is shown in Fig. 3. The majority of revenue was generated through offering capacity for regulation; the ESR took significant losses through arbitrage transactions, presumably to increase its SOC for lucrative regulation up bids. This observation is reflected in the chart in Fig. 4, which shows proportion of bid events corresponding to each decision variable over the entire time period. In this particular case, less than 10% of the ESR's activity was for selling energy for arbitrage. This is likely due to receiving additional credits by offering regulation services to offset the cost of energy purchases or augment the sales of energy.

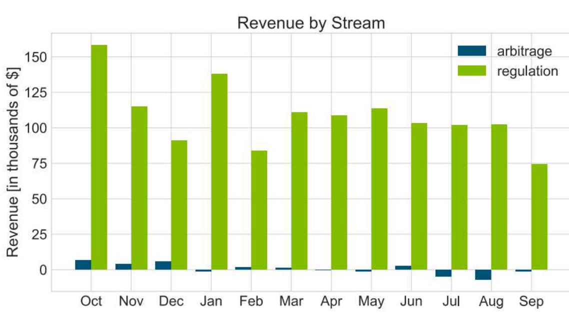

Fig. 3: Gross revenue by month separated by revenue stream.

For ESRs that can follow regulation command signals accurately, they can generate a significant amount of revenue, especially considering the operating reserve products that account for mileage. Although not explicitly accounted for in

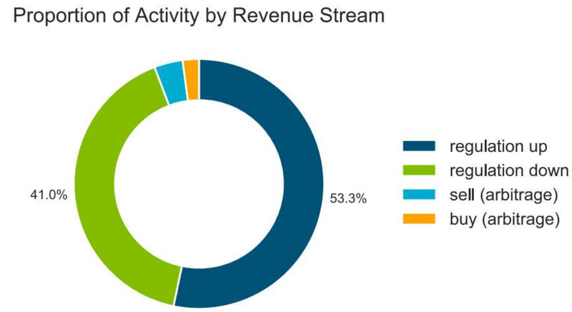

Fig. 4: The percentage (by event) of total offers/bids for each bid type, for the year.

the model in this paper, higher performing ESRs will likely clear even more revenue in mileage credits and not have to "buy back" their positions if not meeting their performance expectations, according to assigned mileage factors [12].

C. Effect of how much regulation capacity offered is deployed

The portion of regulation capacity bids that are actually called upon has a considerable effect on how much energy is purchased or sold and, consequently, the SOC. Section IV-A described the process for approximating the regulation control signal from ACE data. This section explores the effect of δ^{ru} and δ^{rd} on the optimization solution. The same simulation parameters as described in Table II are used but with different values for the regulation fractions. The estimated revenue generated is shown in Fig. 5 and the corresponding annual revenue is shown in Fig. 6. The results labeled *binary* and *independent* use the ACE data as previously described. The other results use fixed values for the entire time horizon.

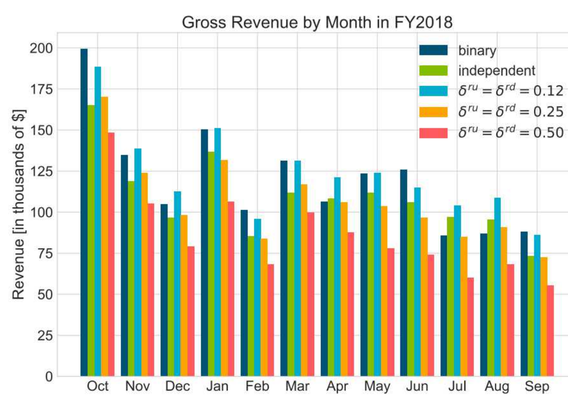

Fig. 5: Gross revenue by month for different regulation deployment fraction signals. For labels with values of δ^{ru} and δ^{rd}, the fractions of the regulation capacity bid actually deployed are fixed for all time at the indicated value.

The revenue generated when the binary method of processing the ACE data was occasionally the greatest. This is likely due to the possibility of δ^{ru} or δ^{rd} being equal to 0. A value of zero implies that the ESR can offer capacity for regulation without being required to purchase energy or change its SOC, effectively getting something for nothing. This type of no-risk

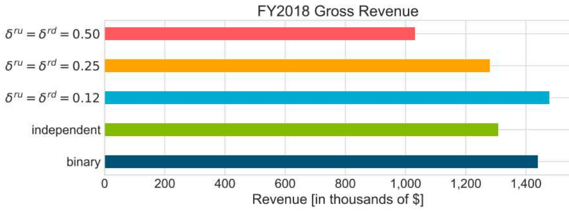

Fig. 6: The gross annual revenue computed from Fig. 5.

bid is an anomaly resulting from the model formulation that would be corrected through the mileage factor mechanism.

Using the independent method for the ACE data, the results are comparable to a fixed value for $\delta^{\text{ru}} = \delta^{\text{rd}} = 25\%$. This matches a priori expectations used in other analyses when no data is available otherwise to estimate those fraction values. Larger values of δ^{ru} and δ^{rd} further decrease potential revenue due to the increased use of storage capacity when making regulation bids, while smaller values increase it. However, it should be noted that in 2017, the RU mileage factor averaged 18% while the RD mileage factor averaged 24% [10].

D. Sensitivity of energy capacity and power rating

Based on results from Section IV-B, significant revenue potential comes from operating reserve products such as regulation. This favors ESRs with high power ratings, with energy capacity having less of an effect unless it bottlenecks the power rating. In Fig. 7, the same simulations as before are performed but with varying power rating and energy capacity values. It can be observed that at low power ratings, increases in energy capacity have minimal effect on potential revenue. Conversely, even at small energy capacities, increases in power rating have a significant effect on estimated revenue.

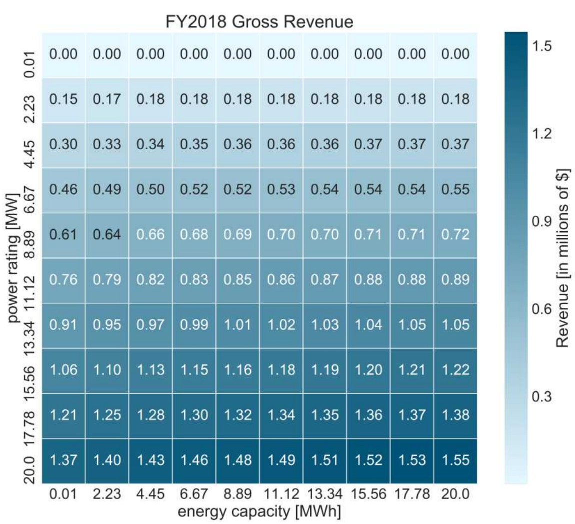

Fig. 7: Gross annual revenue for ESRs with different energy capacity and power ratings.

V. Conclusions

This paper examines revenue opportunities for ESRs in the SPP DAM, trading in energy and frequency regulation products. The study uses an LP formulation to maximize the revenue generated through those revenue streams. The results show that offering capacity for regulation up and down services can produce significant amounts of revenue for the ESR. The paper also explores several methods for inferring frequency control signals from ACE data, showing that averaging positive and negative ACE values separately each hour produces optimization results similar to when using historical average values of expected regulation capacity deployment. Finally, this work analyzes the effect of power rating and energy capacity on revenue generated, showing that it is largely a function of power rating.

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