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Evaluating the Economics for Energy Storage in the Midcontinent: A Battery Benefit-Cost Analysis

Steve Dahlke

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About the Author

Steve Dahlke works as a Policy Associate for the Great Plains Institute and also is working towards his PhD in Mineral and Energy Economics at the Colorado School of Mines.

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Executive Summary

The range of benefits energy storage can provide to the electricity system are widely known among those in industry and well documented in the literature. Among these are storage's abilities to help integrate wind and solar energy, improve grid reliability, and increase the economic efficiency of the electricity system. Despite the benefits, there has not yet been widespread deployment of energy storage. This is due to two main factors. First, there currently are not markets set up to allow storage owners to earn revenue for many of the services they provide.[1] Second, storage technologies have historically been more expensive than alternative resources that can provide comparable services. However, both of these barriers have been easing recently.

Given the changing dynamics and a growing interest in battery storage technology, we took a look at the economic opportunity for a grid-connected battery in the Midcontinent Independent System Operator (MISO) electricity market. Currently, a battery can earn revenue from the market in three ways:

1. It can store low-cost power and sell it at a later time for a higher price, a strategy known as price-arbitraging. This service is useful on systems with high wind penetrations to help manage wind generation overnight when demand is low.

2. It can provide frequency regulation, a reliability service where the resource receives payments to keep capacity available to balance the random fluctuations in supply and demand characteristic of the electricity system. This service is useful on systems of high wind and/or solar penetration, since the variability contributes to a larger uncertainty in frequency fluctuations.

3. It can participate in the capacity market, where the resource receives an annual payment in exchange for an agreement that it will be available during peak demand hours in the summer. This service is currently in high demand on systems seeing retirements of large baseload coal and nuclear plants.

Grid-scale battery storage has been deployed in a number of applications outside of the wholesale markets. This includes enhancing reliability for sensitive customers such as hospitals and universities, and reducing demand charges for commercial and industrial customers. Furthermore, a regulated utility may be able to internalize additional non-monetizable benefits and convince its regulators to approve a storage investment with a guaranteed rate of return for reasons like lowering renewable integration costs, improving reliability, or deferring transmission/distribution/substation investments. [2] However, in this analysis we focus on the market-based applications for storage that can be explicitly monetized by an investor.

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[1] A number of studies have pointed this out. See Denholm, et al. 2012 and Chang, et al. 2014.
[2] See Akhil, et al. 2013 for a comprehensive overview of the benefits storage can provide to utilities, consumers, and system operators.

An additional revenue opportunity that may be available in the future is to provide ramping support during periods when there are large shifts in demand such as in the morning or evening, or during large shifts in supply from wind and solar generation variability. MISO recently implemented a ramping product in the spring of 2016, however prices for this service have been negligible to date.

Using recent prices from the MISO energy, regulation, and capacity markets, we find that a battery will earn the most money by providing frequency regulation. Specifically, we estimate that a 2 megawatt, 4 megawatt-hour battery providing frequency regulation for ten years will earn a total present-value revenue equivalent to $377/kWh, compared to only $60/kW from price arbitrage in the energy market. The battery could earn an additional estimated $64/kWh in present value revenue from the capacity auction if it were located in Illinois, which has a higher demand for capacity than Minnesota. If the battery were able to simultaneously participate in the frequency regulation and capacity markets its present value of revenue would total $441/kWh. [3] Comparing to costs, a prominent lithium-ion battery supplier announced last summer their batteries would soon be priced at $250/kWh.[4] However, a product quote from their website at the time of writing estimates a 2 MW / 4 MWh battery currently would cost $606/kWh, excluding installation. This means a battery resource is currently not economic from MISO revenues alone, although it would be at projected battery costs.

In part due to a lack of experience operating battery resources in MISO, the revenue estimates rest on a number of assumptions regarding MISO's market rules and dispatch procedures. Energy arbitrage revenue estimates assume the battery is able to switch between generator and load classifications throughout the day, similar to how pumped hydro storage is accommodated in MISO. Frequency regulation revenue estimates assume a battery-specific regulation dispatch signal is used that is sensitive to battery constraints. This regulation signal involves operating the resource at a mean output of zero over a relatively short time frame (usually an hour or less) to consistently maintain a sufficient state of charge. Finally, in order to simultaneously earn capacity and regulation revenue, the battery is assumed to be able to provide frequency regulation most of the year, and then switch to an energy resource when needed as a last resort during grid emergencies. This is similar to how MISO awards capacity credit to Load Modifying Resources for making capacity available during NERC Energy Emergency Alert (EEA) events.

Viewing these assumptions as examples of potential market participation strategies for battery storage provides insights into how electricity markets are evolving as conventional baseload resources retire and are replaced by emerging technologies including storage. Overall, it is concluded that grid-connected storage will be economic

[3] Capacity market prices in Illinois have historically been much higher than other parts of MISO. It is unlikely the battery would see this level of capacity revenue if it were located in other areas of the footprint.

[4] Savenije 2015

from MISO market revenues alone if cost declines projected by suppliers in the near future come to fruition.

Overview of Methods and Results

Arbitrage

The first market application for storage evaluated was energy price arbitrage, which involves buying energy/charging the battery when prices are low (usually overnight), and selling/discharging when prices are high (usually the next day). To evaluate the revenue opportunity, an optimal dispatch model developed by Byrne and Silva-Monroy at Sandia National Laboratory was programmed.[5] The model is formulated as a linear programming optimization problem, choosing dispatch quantities to maximize revenue with given prices, subject to the battery's technical constraints. A mathematical summary of the model is included in the appendix.

The battery was assumed to have a power rating of 2 MW, maximum storage capacity of 4 MWh, a 90 percent energy conversion efficiency, and 100 percent storage efficiency (the battery does not lose charge when sitting idle). Additionally, the model can accommodate dispatch costs in the form of battery degradation over time or from cycling. However, since the focus was on maximizing revenue, these costs were assumed to be zero.

An optimal dispatch schedule was calculated using 2015 historical day-ahead hourly prices from the Minnesota hub of MISO's energy market. From this, the maximum revenue possible for the battery performing arbitrage during this year is estimated to be $27,503. In reality, a battery would not earn all this revenue due to lack of perfect foresight of future prices and maintenance outages. However, a trading strategy based on charging overnight and discharging during the afternoon (perhaps during the hours when the previous day(s) prices were at a minimum and maximum) will likely do well for most weekdays. An example output from the model is shown in Figure 1, showing hourly prices and the optimal dispatch schedule for the last week of July 2015. The battery performs as expected, fully charging overnight when prices are at the daily minimum, and selling energy in the afternoon when prices are at the daily maximum, earning $969 from arbitraging the energy market during this week.

[5] Byrne and Silva-Monroy 2012

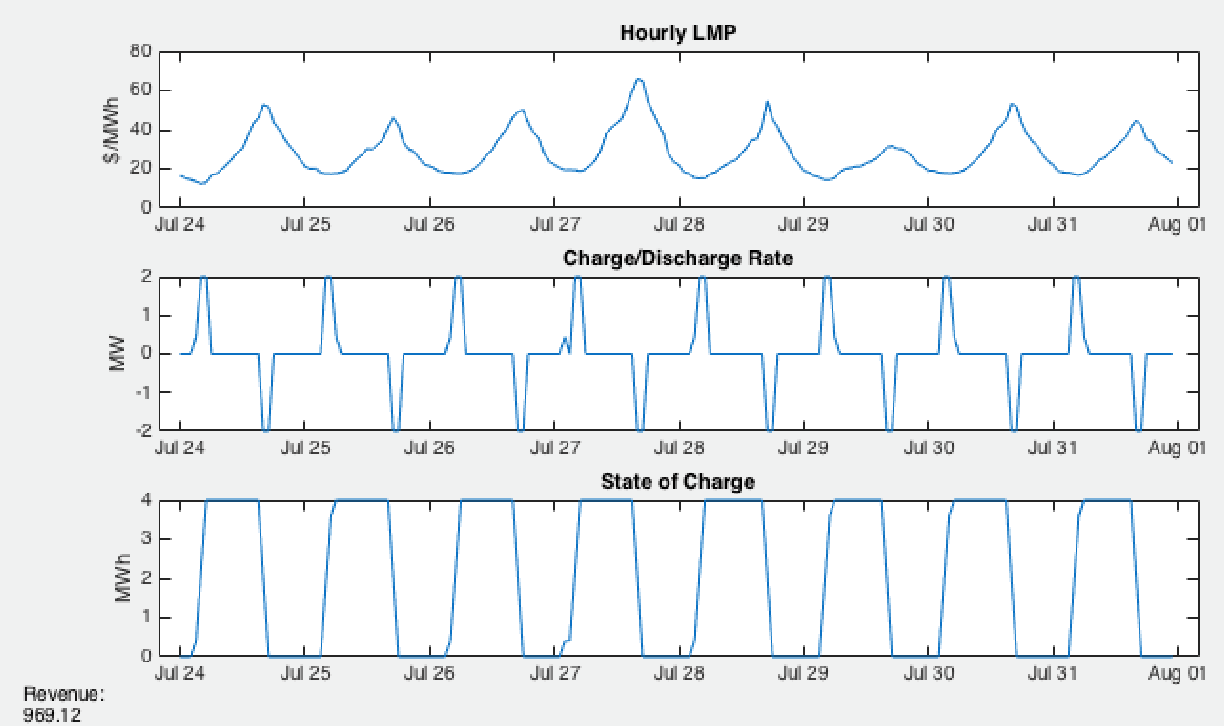

Figure 1 Hourly prices and optimal battery dispatch schedule at MISO Minnesota Hub prices during the last week of July 2015

Frequency Regulation

Frequency regulation involves receiving payments for making capacity available to discharge (reg up) or recharge (reg down) as often as every few seconds to maintain the frequency of the system. Regulation prices are calculated every five minutes and are equal to the offer cost of the marginal regulation resource at that period of time. The 5-minute prices are then aggregated to hourly average prices which are reported by the system operator. Historical hourly regulation prices from 2013-15 were analyzed. During these three years, regulation prices averaged $9.83. Prices occasionally spiked during critical periods; there were 54 hours when prices averaged over $100, and the maximum hourly price of $1,360 occurred during the hour ending 8:00 am on January 7th, 2014.

Given the inherent uncertainty associated with short-term fluctuations in system frequency, we did not attempt to explicitly model dispatch of a battery in the frequency regulation market. Instead, it was assumed the battery offered its full 2 MW of capacity into the regulation market for all hours. Some analyses assume that a battery providing regulation will spend time purchasing or selling “make-up” energy to re-establish its state of charge. However, makeup energy is not necessary if the operator uses a regulation dispatch signal sensitive to the battery’s state of charge and capacity constraints. This involves charging and discharging the battery at a mean output of zero over a relatively short-time frame, such as an hour or less. This is how PJM operates its battery regulation resources, and it is assumed MISO will operate similarly when a battery comes online.

Recently, regulation markets including MISO have been working to implement pay-per-performance rules that provide extra mileage payments for resources that accurately provide more service than their cleared capacity when needed by the operator. These rules also impose financial penalties for regulation resources that do not accurately respond to the operator's signal.[6] Given that batteries have superior ramping abilities relative to conventional thermal generators, it is likely that battery storage will benefit from these rules. However, due to uncertainty regarding the operator's dispatch needs, it is assumed that all mileage payments and financial penalties, additional to the reported hourly real-time price, to be zero.

In the frequency regulation market, it is assumed that the battery settles at the real-time hourly prices. Using the average prices from 2013-2015, maximum annual revenue for the battery is estimated to be $172,251. Historically, regulation prices have rarely, if ever, deviated across MISO. It is assumed the battery will earn this revenue in both Minnesota and Illinois. One could place a battery anywhere on the MISO system and earn these revenues if this trend of non-deviating regulation prices continues (which may be unlikely given MISO's expanding size).

Capacity Market

Another source of revenue for a battery is from MISO's capacity market. This is an annual auction in which cleared resources receive an annual payment in exchange for an obligation that the storage resource will be available during peak demand hours over the summer. Revenue from this market is mostly additive to the revenue earned in the other markets. For example, when a resource fulfills its capacity obligation to generate during peak demand, it is selling that energy and earning revenues from the energy market. A regulation resource that receives capacity credit may have to switch from the regulation market to the energy market for short period of time to fulfill its obligation, but the overall impact on annual regulation revenue from this is likely to be negligible.

MISO capacity auction prices over the past three years were analyzed, and the annual average prices during this period was used to estimate the revenue opportunity for the 2 MW battery. Recent historical capacity auction prices for MISO's Minnesota and Illinois zones are in Table 1.

[6] See Midcontinent ISO 2012

Table 1 MISO zone 1 capacity auction prices

Planning year	Minnesota Price, $/MW-day	Illinois Price, $/MW-day
2014/15	3.29	16.75
2015/16	3.48	150.00
2016/17	19.72	72.00
Average	8.83	79.58

MISO's market rules require a capacity resource be able to run for a minimum of four hours when called. Since our 2 MW / 4 MWh battery can't operate at full capacity for four hours, it would only earn 1 MW of capacity credit. Based off these average prices, it is estimated the battery will earn $3,223 in annual revenue from the capacity market in Minnesota, (8.83 $/MW-day)*(2 MW)*(365 days), and $29,048 in Illinois. It is worth noting that capacity prices across all zones in MISO have been trending upwards, as plant retirements increase the demand for new capacity. If this trend continues it will improve the economics of the battery relative to our estimates.

Economic Analysis

The revenue estimates described in previous sections were used in a cash flow analysis to determine the present value of revenue over the life of the project. This is equivalent to the present value of project costs (including all capital, operations and maintenance costs) for which the project would break-even. The battery is assumed to operate for a 10-year life in the MISO frequency regulation and capacity markets, since these markets provide the greatest revenue opportunity.

To account for the time value of money, future revenues are discounted at 2.5% annually, equal to the interest rate on a 30-year U.S. treasury bond at the time of writing. It is assumed that frequency regulation and capacity market prices in future years are equal to the average of the previous three years' prices. The economics of the project would improve if future prices increase relative to today, and vice-versa if prices decline. A summary of the project's estimated annual revenue at Minnesota and Illinois prices is provided in Table 2.

Table 2 Estimated annual revenue for battery

	Minnesota	Illinois
Frequency regulation	$172,521	$172,521
Capacity market	$3,223	$29,048
Total annual revenue	$175,744	$201,569

Assuming the battery earns this annual revenue for the next ten years, the estimated present value of project revenue is equal to $1.54 million in Minnesota, and $1.76 million in Illinois. This translates to a break-even value of $385/kWh and $441/kWh, respectively.

The estimated revenues were compared to a cost estimate of $606/kWh obtained from the website of Tesla, a supplier of lithium-ion batteries for grid applications including capacity and frequency regulation. Their cost estimate for a 2 MW / 4 MWh battery resource is outlined in Table 3.

Table 3 Estimated costs for 2 MW / 4 MWh battery

40 batteries (50 kW / 100 kWh each)	$1,880,000
8 bi-directional 250 kW inverters	$520,000
Cabling & site support hardware	$22,000
Total costs excluding installation	$2,422,000 ($606/kWh)

With these estimates, costs currently outweigh the benefits of owning a battery in MISO. However, if battery costs drop to levels at or below $250/kWh, as forecasted by suppliers, then it will be economic to develop a battery in the MISO market.

Conclusion

This report evaluates the economics of owning a battery in the Midcontinent ISO electricity markets. To do this, the value of a 2 MW / 4 MWh battery participating in MISO's energy, frequency regulation, and capacity markets was estimated using recent historical prices. An optimal dispatch model was employed to estimate the maximum revenue available from price arbitraging at the Minnesota hub, which was $27,503 in 2015.

Greater opportunity was found in the frequency regulation market. Using recent average prices, the battery is estimated to earn $172,521 in annual revenue. Additional revenue is available in the capacity market. Using the average of prices from the past three years, annual capacity market revenue is estimated to be $3,223 in Minnesota and $29,048 in Illinois. Assuming these revenue estimates are realized as annual cash-flows over a 10-year project life, the present value of total project revenues was calculated as $1.54 and 1.76 million in Minnesota and Illinois. Additionally, cost estimates were obtained from a li-ion battery supplier. This is all summarized in Table 4.

Table 4 summary of revenues and costs for battery project in MISO

	Minnesota	Illinois
Frequency regulation revenue	$172,521	$172,251
Capacity market revenue	$3,223	$29,048
Present value of total project revenue	$1,538,000 ($385/kWh)	$1,762,000 ($441/kWh)
Project cost estimate	$2,422,000 ($606/kWh)	$2,422,000 ($606/kWh)

In conclusion, a battery does not generate revenues in excess of costs from participating solely in the MISO markets at current prices and cost estimates. However, a regulated utility may find other benefits from owning a battery that are not quantified in this study, such as substituting for needed transmission or distribution investments. Furthermore, near term cost projections from lithium-ion battery suppliers would put costs below the revenues available in the MISO markets. If these projected costs come to fruition, then a battery resource would be economic on a stand-alone basis in the MISO region.

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Appendix: Summary of Battery Dispatch Model

From Byrne and Silva-Monroy: "Estimating the Maximum Potential Revenue for Grid Connected Electricity Storage: Arbitrage and Regulation." Sandia National Lab report, December 2012.

Introduction

This section summarizes the mechanics of the model used to calculate optimal dispatch schedules to maximize revenue for a grid-connected battery operating in wholesale power markets. The model is formulated as a linear programming optimization problem, following the methods used by Byrne and Silva-Monroy. Revenues earned are from arbitraging intertemporal price differences in the energy market.

Battery parameters

t	Time period.
$\bar{q}^D$	Maximum quantity that can be sold in a single period (MWh). Equals (max discharge power level) x (time pd).
$\bar{q}^S$	Maximum quantity that can be bought in a single period (MWh). Equals (max recharge power level) x (time pd).
$\bar{S}$	Maximum storage capacity (MWh).
γ_s	Storage efficiency, fraction of stored energy maintained over one period.
γ_c	Conversion efficiency, fraction of input energy that gets stored.

For a battery, the ramp rate is negligible compared to the dispatch period being modeled, so we will ignore this parameter. If the technology being modeled is constrained by its ramp rate, then $\bar{q}^D$ and $\bar{q}^S$ may not be equal to the maximum charge level multiplied by time period.

Financial quantities of interest

P_t	Price of electricity (LMP) at time t ($/MWh)
C_d	Cost of discharging at time t ($/MWh)
C_r	Cost of recharging at time t ($/MWh)
r	Interest rate over one time period

Decision variables

For a battery only performing arbitrage service, there are two decision variables:
q_t^D = quantity of energy sold/discharged at time t (MWh)
q_t^R = quantity of energy purchased/recharged at time t (MWh).

The decision variables are constrained to be non-negative. The state of charge S_t at any time t is given by:

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

The state of charge at time t is the state of charge at time t-1 adjusted for storage losses, plus any net charging adjusted for conversion losses.

Additional constraints include:
- $0 \le S_t \le \bar{S}$ for all t: the state of charge must not exceed the maximum storage capacity
- $0 \le q_t^R \le \bar{q}^R$ for all t
- $0 \le q_t^D \le \bar{q}^D$ for all t: the quantity of energy purchased and sold must not exceed the max recharge and discharge power levels for all t

Linear programming optimization problem

The standard linear programming optimization formulation is defined as:

$$\min_x f^T x \text{ such that } \begin{cases} Ax \le b \\ A_{eq}x = b_{eq} \\ lb \le x \le ub \end{cases}$$

For a battery providing arbitrage, we will maximize the profit from buying energy at low prices and selling at high prices, subject to the constraints of the storage facility. We solve for the amount of energy sold and bought at each time step:

$$x = \begin{bmatrix} q_1^D \\ q_2^D \\ \vdots \\ q_T^D \\ q_1^R \\ q_2^R \\ \vdots \\ q_T^R \end{bmatrix}$$

By splitting x in half and subtracting one half from the other, we can convert to a vector of discharge (negative) and recharge (positive) quantities q_t for each time step:

$$\begin{bmatrix} q_1^R \\ \vdots \\ q_T^R \end{bmatrix} - \begin{bmatrix} q_1^D \\ \vdots \\ q_T^D \end{bmatrix} = \begin{bmatrix} q_1 \\ \vdots \\ q_T \end{bmatrix}$$

Assuming an uncharged initial condition, $S_0 = 0$, the state of charge for the first few time steps are as follows:

$t = 1$ $\quad S_1 = \gamma_c q_1^R - q_1^D$

$t = 2$ $\quad S_2 = \gamma_s(\gamma_c q_1^R - q_1^D) + \gamma_c q_2^R - q_2^D$

$t = 3$ $\quad S_3 = \gamma_s[\gamma_s(\gamma_c q_1^R - q_1^D) + \gamma_c q_2^R - q_2^D] + \gamma_c q_3^R - q_3^D$

$t = 4$ $\quad S_4 = \gamma_s[\gamma_s[\gamma_s(\gamma_c q_1^R - q_1^D) + \gamma_c q_3^R - q_3^D] + \gamma_c q_4^R - q_4^D$

Writing this in matrix form yields an equality constraint $A_s x = S$, where

$$A_s = \left[\underbrace{\begin{matrix} -1 & 0 & 0 & 0 & \cdots & 0 \\ -\gamma_s & -1 & 0 & 0 & \cdots & 0 \\ -\gamma_s^2 & \gamma_s & -1 & 0 & \cdots & 0 \\ -\gamma_s^3 & -\gamma_s^2 & -\gamma_s & -1 & \cdots & 0 \\ \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\ -\gamma_s^{T-1} & -\gamma_s^{T-2} & -\gamma_s^{T-3} & -\gamma_s^{T-4} & \cdots & -1 \end{matrix}}_{q_t^D \text{ coefficients}} \; \underbrace{\begin{matrix} \gamma_c & 0 & 0 & 0 & \cdots & 0 \\ \gamma_s\gamma_c & \gamma_c & 0 & 0 & \cdots & 0 \\ \gamma_s^2\gamma_c & \gamma_s\gamma_c & \gamma_c & 0 & \cdots & 0 \\ \gamma_s^3\gamma_c & \gamma_s^2\gamma_c & \gamma_s\gamma_c & \gamma_c & \cdots & 0 \\ \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\ \gamma_s^{T-1} & \gamma_s^{T-2} & \gamma_s^{T-3} & \gamma_s^{T-4} & \cdots & \gamma_c \end{matrix}}_{q_t^R \text{ coefficients}} \right]$$

The battery cannot charge or discharge more than $\bar{q}^D$ and $\bar{q}^R$ in each period. Thus the lower and upper bounds on x are

$$lb^{2T} = \begin{bmatrix} 0 \\ \vdots \\ 0 \end{bmatrix} \qquad ub^{2T} = \begin{bmatrix} \bar{q}^D \\ \vdots \\ \bar{q}^D \\ \bar{q}^R \\ \vdots \\ \bar{q}^R \end{bmatrix}$$

Additionally, the state of charge $S_t = A_s x$ must be greater than zero and less than $\bar{S}$. This last constraint is handled with the following system of equations:

$$Ax \leq b, \text{ where } \quad A = \begin{bmatrix} -A_s \\ A_s \end{bmatrix}, \quad b = \begin{bmatrix} 0 \\ \vdots \\ 0 \\ \bar{S} \\ \vdots \\ \bar{S} \end{bmatrix}$$

The profit function we are maximizing is:

$$J = \sum_{t=1}^{T} [(P_t - C_d)q_t^D - (P_t + C_r)q_t^R]e^{-rt}$$

Since the standard LP formulation is a minimization problem, we define a new cost function J^* that is the negative of J, so that minimizing J^* maximizes profits for the battery:

$$J^* = -f^T x$$

$$f = \begin{bmatrix} (P_1 - C_d)e^{-r} \\ (P_2 - C_d)e^{-2r} \\ (P_3 - C_d)e^{-3r} \\ \vdots \\ (P_T - C_d)e^{-Tr} \\ -(P_1 + C_r)e^{-r} \\ -(P_2 + C_r)e^{-2r} \\ -(P_3 + C_r)e^{-3r} \\ \vdots \\ -(P_T + C_r)e^{-Tr} \end{bmatrix}$$