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The Value Proposition for Energy Storage at the Sterling Municipal Light Department

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***Abstract*—The Sterling Municipal Light Department (SMLD) is a progressive public power utility located 10 miles NNE of Worcester, Massachusetts in the Town of Sterling. SMLD has a long history of investment in renewable generation, with approximately 35% of generation coming from renewable sources. The goal of this report is to identify potential benefits and value streams from electrical energy storage. Benefits considered in this analysis include: energy arbitrage, frequency regulation, reduction in monthly network load, reduction in capacity payments to ISO New England, and grid resiliency.**

***Index Terms*—energy storage, ISO New England**

I. Introduction

The Sterling Municipal Light Department (SMLD) is a progressive public power utility located 10 miles NNE of Worcester, Massachusetts in the Town of Sterling. The primary building was originally the 1883 Sterling High School. Serving the town of Sterling for over 100 years, there are more than 3,700 residential, commercial, municipal and industrial customers. Customers are fed power through approximately 160 miles of distribution lines. The SMLD is a member of ISO New England (ISO-NE) and a wholesale aggregator of power with power purchases from generation throughout New England and New York.

The SMLD has a long history of investment in renewable generation. Approximately 35% of power generation comes from renewable sources, primarily wind, hydro, and solar. Solar accounts for approximately 30% of the departments peak load. Two 1-megawatt solar installations went on line in 2013, placing SMLD at the top of the Solar Electric Power Associations Top 10 utility rankings for the year for new solar watts per customer [1]. SMLD currently has 3 MW of solar installed.

Previous research on energy storage in ISO-NE is described in [2], where the authors discuss the integration of flywheel-based energy storage for frequency regulation in regulated and deregulated markets. Preliminary results were presented for 3 MW of flywheel storage in ISO-NE. Beacon Power's testing found that on average, a 1 MW system injects 180 kWh per hour, which corresponds to 6,300 equivalent charge/discharge cycles per year. Over a 20 year life, this results in approximately 125,000 full charge/discharge cycles. The authors argue that this charge/discharge profile would be difficult for chemical energy storage systems.

The methodology for estimating maximum potential revenue from an energy storage system participating in energy and regulation markets is outlined in [3]. The problem was formulated as a linear program (LP) optimization, and results for California Independent System Operator (CAISO) data were presented. For the CAISO data, frequency regulation provided significantly more revenue opportunity than arbitrage. An analysis of potential revenue from energy storage in the Electrical Reliability Council of Texas (ERCOT) is presented in [4]. An analysis of all load zones in ERCOT for 2011-2013 market data found that frequency regulation provided significantly more potential revenue than arbitrage. Because there is only one market for frequency regulation in ERCOT, and the majority of revenue was from frequency regulation, the location of the system does not impact potential revenue. The analysis also highlights the variability from year to year in potential revenue. A winter ice storm and a summer heat wave resulted in significantly higher prices in ERCOT in 2011, and led to significantly higher potential revenue from energy storage (more than twice the 2012/2013 potential revenue). An analysis of the PJM Interconnection, which includes pay-for-performance, is summarized in [5]. Once again, frequency regulation provided significantly more potential revenue than arbitrage in PJM for the data analyzed. An early summary of potential arbitrage revenue in various markets is found in [6].

The goal of this paper is to identify and quantify potential benefits of electrical energy storage for the SMLD. Benefits considered in this analysis include: energy arbitrage, frequency regulation, reduction in monthly network load, reduction in capacity payments to ISO New England, and grid resiliency. The paper is organized as follows. Section II provides an overview each potential benefit. Section III summarizes the results of a financial analysis of each potential benefit. The expected benefits are summarized in Section V.

II. Overview of Energy Storage Value Propositions

There are many potential benefits from electrical energy storage [7]. This paper considers benefits specific to SMLD, and includes: energy arbitrage, frequency regulation, reduction in monthly network load, reduction in capacity payments to ISO New England, and grid resiliency. Each benefit is described in more detail in the following subsections.

A. Energy Arbitrage

Energy arbitrage involves procuring energy when prices are low, and then selling the energy when prices are high. Energy prices are typically low in off peak hours, especially in the early morning hours. Prices tend to increase in late afternoon or early evening. Another source for low cost energy is renewable generation like wind or solar. Energy prices often spike in response to a shortage of generation. An example would be an unplanned generator outage. The efficiency of the energy storage has a significant contribution to the arbitrage opportunity. Efficiency is typically broken into two components: conversion efficiency and storage efficiency. Conversion efficiency, η_C, refers to the losses as power is stored and then provided back to the grid. Storage efficiency, η_S, refers to the losses as energy is stored over longer time periods. For many technologies, the storage efficiency is very close to 100% over short periods of time. Typical conversion efficiencies for lithium ion systems are between 85-90%. The arbitrage opportunity is given by:

$$\text{arbitrage opportunity} = q\eta_C LMP_H - qLMP_L \quad (1)$$

where $q\eta_C$ is the discharge quantity (MWh), LMP_H is the high locational marginal price, q is the charge quantity (MWh), and LMP_L is the low locational marginal price. In order for arbitrage to be profitable, the ratio of sell/buy price is related to the efficiency by

$$\frac{LMP_H}{LMP_L} \geq \frac{1}{\eta_C} \quad (2)$$

As the round trip efficiency decreases, the greater the difference in prices required to make arbitrage profitable.

B. Frequency Regulation

Frequency regulation is an ancillary service designed to maintain system frequency by dispatching controllable generation via an Automated Generation Control (AGC) signal. If the load increases while generation is held constant, the frequency will drop. In order to maintain tight tolerances on the frequency, generation must be constantly dithered so that load and generation are equal. Depending on the market, a balancing authority or vertically integrated utility will control generation on a second by second basis to track the load. The balancing authority must reserve enough regulation capacity to meet expected variations in load. In order to participate in the ISO-NE frequency regulation market, a non-generating asset must satisfy the following conditions [8]:

1) The minimum Automatic Response Rate is 1 MW/minute.
2) The minimum Regulation Capacity of a Resource that is not a generating unit is no less than one megawatt after aggregation.

ISO-NE compensates market participants that have been selected to provide regulation services for the regulation capacity and the regulation service (mileage).

$$\begin{aligned}\text{capacity payment} &= \text{Regulation Capacity}\times \\ &\quad \text{Regulation Capacity} \\ &\quad \text{clearing price}\end{aligned} \quad (3)$$

$$\begin{aligned}\text{service payment} &= \text{mileage}\times \\ &\quad \text{Regulation Service} \\ &\quad \text{clearing price}\times \\ &\quad \text{performance score}\end{aligned} \quad (4)$$

An energy-neutral dispatch option is available for non-generating assets.

C. Regional Network Service (RNS)

Regional Network Service (RNS) consists of payments for using the pool transmission facilities to move electricity into or within the New England balancing authority (BA) [9]. A transmission customer that takes RNS in a month shall pay to ISO-NE:

$$\begin{aligned}\text{RNS} &= (Pool\ RNS\ Rate)\times \\ &\quad (Monthly\ Network\ Load)\end{aligned} \quad (5)$$

The current pool RNS rate, effective June 1, 2015, equals $98.70147/kW-yr [3]. The monthly network load is defined as the hourly load coincident with the coincident aggregate load of all network customers served in each local network in the hour in which the coincident load is at its maximum for the month (Monthly Peak) [10].

D. Capacity Payment

ISO-NE has implemented a forward capacity market (FCM) because electricity markets alone do not provide adequate financial incentives to invest in new generating capability. Load serving entities receive an allocation for FCM charges based on:

$$\begin{aligned}\text{Capacity Payment} &= (Capacity\ Load\ Obligation)\times \\ &\quad (Net\ Regional\ Clearing\ Price)\end{aligned} \quad (6)$$

The *Capacity Load Obligation* is based on the peak contribution value, e.g., the load on the peak day/hour each year identified by ISO-NE. The *Net Regional Clearing Price (NRCP)* is calculated for each capacity zone as the sum of total payments made to resources divided by the total Capacity Supply Obligations, adjusted for self-supply MWs and excess RTEG MWs.

$$NRCP = \frac{(Total\ Capacity\ Credits)}{\begin{pmatrix} Total\ Capacity\ Supply\ Obligation\ MW - \\ Self\ Supply\ MW - Excess\ RTEG\ MW \end{pmatrix}} \quad (7)$$

The NRCP for the Rest-of-Pool, which includes SMLD, is summarized in Table I. By reducing the capacity load obligation (e.g., peak coincident load), energy storage offers the potential to reduce forward capacity market charges. The results of the capacity market auctions have increased significantly in the out years, with current rates to triple by 2018-2019. Deploying energy storage would serve as a hedge against potentially large increases in the future capacity clearing price.

TABLE I
SMLD CAPACITY CLEARING PRICE, ISO-NE. PERIOD RUNS FROM JUNE 1 TO MAY 31.

Year	Price ($/kW-Month)	Year	Price ($/kW-Month)
2010-2011	$4.254	2015-2016	$3.129
2011-2012	$3.119	2016-2017	$3.150
2012-2013	$2.535	2017-2018	$7.025
2013-2014	$2.516	2018-2019	$9.551
2014-2015	$2.855	2019-2020	$7.030

E. Grid Resiliency

Severe weather is the leading cause of power outages in the United States. In 2015, severe weather resulted in outages affecting 5,630,618 customers. Data for the last 2013-2015 is summarized in Table II. Therefore, grid resiliency is an important application for energy storage. This is especially true for first responders like police and fire departments. Value of Lost Load (VoLL) is defined as the cost of power not delivered ($/kWh or $/MWh). There are two primary methods for estimating interruption costs: indirect and direct [11]. Indirect methods are based on market prices while direct methods typically rely on surveys. For this paper, we rely on survey results found in [12]. SMLD has identified a critical load of 10 kW to maintain power to first responders. The value associated with improved grid resiliency is typically very high, especially if maintaining power to critical loads can prevent the loss of life. Unfortunately, there is no data available specifically for first responders. Therefore, we relied on the VoLL for public administration (small commercial and industrial) found in [12], which likely underestimates the Sterling benefit.

TABLE II
PERCENTAGE OF U.S. CUSTOMERS AFFECTED BY WEATHER RELATED ELECTRICAL OUTAGES [13].

Year	Total Customers Affected	Weather Customers Affected	Percent of Outages from Weather
2013	8,828,313	7,413,172	84.0%
2014	1,6850,947	16,788,947	99.6%
2015	6,665,918	6,579,359	98.7%

III. ANALYSIS OF BENEFITS

This section calculates the potential benefit of energy storage deployed by SMLD.

A. Energy Arbitrage

Using historical prices from January 2010 September 2015, an optimization algorithm was employed to determine the maximum potential revenue from different storage sizes. The optimization algorithms for arbitrage and frequency regulation are described in more detail in [3]. The optimization assumes perfect foresight, e.g., knowledge of all past and future data. Therefore, this estimate serves as an upper bound. Trading algorithms that do not have access to future knowledge will not be able to perform as well. Moderately simple trading algorithms can often achieve 85-90% of the maximum potential revenue [3]. The optimization considers the constraints of the storage system, e.g., minimum and maximum state-of-charge, as well as power limits. Depending on the type of cell chemistry, there can be a reduction in life from rapid charge/discharge cycles. These results do not incorporate any technology specific limitations, although they may be added as additional terms to the optimization cost function. The results are summarized in Table III.

TABLE III
STERLING ARBITRAGE MONTHLY AVERAGE REVENUE, 2010-2015

Power	Energy Rating (MWh)			
(MW)	1.0	2.0	3.0	4.0
0.25	$782.12	$1,060.69	$1,164.90	$1,231.23
0.50	$977.55	$1,564.24	$1,922.23	$2,121.38
0.75	$1,048.06	$1,800.54	$2,346.36	$2,733.70
1.00	$1,110.10	$1,955.09	$2,609.83	$3,128.48
1.25	$1,120.10	$2,033.93	$2,782.61	$3,399.64
1.50	$1,120.11	$2,096.13	$2,932.64	$3,601.08
1.75	$1,120.11	$2,158.31	$3,018.40	$3,760.31
2.00	$1,120.12	$2,220.21	$3,081.99	$3,910.19

Power	Energy Rating (MWh)			
(MW)	5.0	6.0	7.0	8.0
0.25	$1,282.03	$1,323.78	$1,358.79	$1,388.62
0.50	$2,243.29	$2,329.81	$2,401.12	$2,462.46
0.75	$2,999.93	$3,182.08	$3,312.03	$3,411.34
1.00	$3,537.62	$3,844.46	$4,070.66	$4,242.77
1.25	$3,910.60	$4,323.11	$4,657.31	$4,922.77
1.50	$4,189.12	$4,692.73	$5,108.58	$5,467.41
1.75	$4,410.36	$4,976.05	$5,474.85	$5,894.01
2.00	$4,587.43	$5,219.66	$5,758.21	$6,256.97

B. Frequency Regulation

Using historical prices from January 2010 September 2015, an optimization algorithm was employed to determine the maximum potential revenue from different storage sizes participating in arbitrage and frequency regulation. The results are summarized in Table IV. The results of the optimization identified frequency regulation as the optimum activity with the system participating in energy arbitrage only a few percent of the time, largely to maintain state-of-charge for the regulation activities. The potential revenue from frequency regulation is significantly higher than the arbitrage opportunity, which is consistent with results in other regions [3], [4], [5]. It should be noted that there is significant variation in the monthly potential revenue. For example, the statistics for the 1 MW, 1 MWh scenario are: average $5,039.67/month; minimum $2,395.69/month; maximum $19,763.60/month; standard deviation $3,632.40/month.

C. Regional Network Services

Using the current effective rate of $98.70147/kW-yr, the potential annual savings from different energy storage systems are summarized in Table V. Values are shown for different power levels. In order to achieve these savings, the energy

TABLE IV
STERLING ARBITRAGE/REGULATION MONTHLY AVERAGE REVENUE, 2010-2015

Power	Energy Rating (MWh)			
(MW)	1.0	2.0	3.0	4.0
0.25	$2,485.96	$2,622.80	$2,682.29	$2,721.70
0.50	$4,643.07	$4,971.91	$5,143.00	$5,245.61
0.75	$5,017.86	$7,172.67	$7,457.87	$7,643.68
1.00	$5,039.67	$9,286.14	$9,677.01	$9,943.82
1.25	$5,043.82	$10,003.90	$11,817.30	$12,168.05
1.50	$5,043.83	$10,035.69	$13,929.21	$14,345.34
1.75	$5,043.83	$10,057.82	$14,983.98	$16,460.45
2.00	$5,043.83	$10,079.33	$15,024.69	$18,572.28

Power	Energy Rating (MWh)			
(MW)	5.0	6.0	7.0	8.0
0.25	$2,752.17	$2,777.30	$2,798.80	$2,817.72
0.50	$5,313.77	$5,364.59	$5,406.94	$5,443.39
0.75	$7,773.33	$7,868.41	$7,940.41	$7,997.93
1.00	$10,138.42	$10,286.00	$10,400.23	$10,491.21
1.25	$12,429.78	$12,630.05	$12,788.46	$12,917.09
1.50	$14,658.96	$14,915.73	$15,118.27	$15,287.37
1.75	$16,861.72	$17,149.78	$17,401.69	$17,606.20
2.00	$18,990.71	$19,354.02	$19,640.22	$19,887.65

storage system would have to be fully charged and then discharge during the hour of monthly peak load. The probability of hitting this hour every month would increase if the storage system had increased capacity (e.g., the capability to discharge for several hours).

TABLE V
RNS SAVINGS FOR A 1-HOUR ENERGY STORAGE SYSTEM.

Power (MW)	Annual Savings ($)
1	$98,707
2	$197,403
3	$296,104
4	$394,806

D. Capacity Payment

Using the projected forward capacity market obligations, the potential savings from different energy storage systems are summarized in Table VI. Note that as the power output increases, there is the corresponding decrease in the Sterling peak load. The calculations use a peak load of 9.631 MW for SMLD and an ISO-NE peak load of 24.039 GW. Similar to the RNS charge, the storage system would have to be fully charged and discharge during the hour coincident with the ISO-NE peak load for the year. Having more capacity would increase the probability of hitting this hour.

E. Resiliency

SMLD has identified the critical load as 10 kW. The state-of-charge required to provide 7 days of back-up power to critical loads is 1.68 MWh. The number of days of back-up power provided by different systems is summarized in Table VII below. Using the VoLL for public administration (small commercial and industrial) found in [12], linear regression

TABLE VI
SMLD CAPACITY CLEARING PRICE, ISO-NE.

Year	Price ($/kW-Month)	Annual Savings ($) Power 1 MW	Power 2 MW	Power 3 MW	Power 4 MW
2015-16	$3.129	$51,477	$102,958	$154,443	$205,932
2016-17	$3.150	$51,822	$103,649	$155,479	$207,315
2017-18	$7.025	$115,572	$213,153	$346,744	$462,344
2018-19	$9.551	$157,128	$314,269	$471,424	$628,591

was used to estimate the VoLL for the backup times in Table VII. This VoLL does not account for improved public safety or public health achieved from providing back-up power to first responders. Therefore, the potential resiliency benefit to SMLD could be significantly greater.

TABLE VII
DAYS OF BACK-UP POWER FOR CRITICAL LOADS, VALUE OF LOST LOAD (VOLL) PER OUTAGE.

	Capacity 1 MWh	2 MWh	3 MWh	4 MWh
Days	4.167	8.333	12.5	16.667
VoLL	$40,819	$81,629	$122,448	$163,267

IV. ANALYSIS OF ISO-NE PEAK HOURS

The capacity of the energy storage system, e.g., the number of discharge hours, greatly affects the odds of discharging during a peak hour. The distribution of monthly peak hours from January 2003 through December 2013 is summarized in Figure 1 below. The greater the capacity of the storage

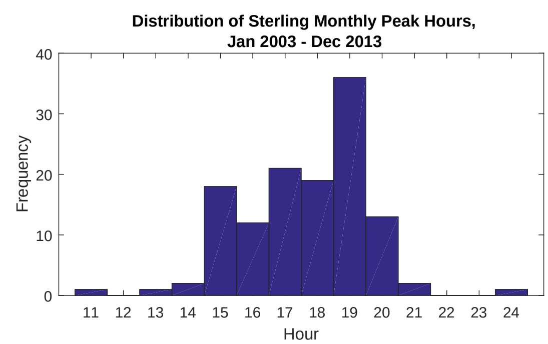

Fig. 1. Distribution of ISO-NE monthly peak hours, January 2003 through December 2013.

system, the greater the likelihood of hitting the peak monthly hour. It is assumed that the hour is the only criterion for discharging. Incorporating additional information can increase the odds of hitting the monthly peak hours. The cumulative density function for monthly peak hours, sorted by decreasing likelihood, appears in Figure 2.

A distribution of the annual peak hours is summarized in Figure 3. For the 15-year period, the annual peak occurred in one of three hours: 13, 15, or 17. Over this time range, more than two thirds of the annual peaks occurred during hour 15. This is evident in the cumulative density function of annual peak hours (in order of decreasing likelihood) shown in Figure 4. If future annual peaks continue the trend of the last 15 years,

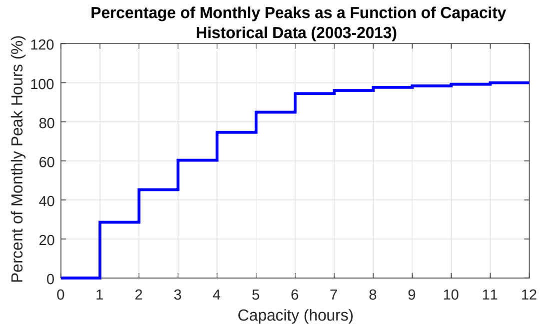

Fig. 2. Percentage of monthly peak hours as a function of storage capacity using historical data (2003-2013).

only three hours of capacity would be required to guarantee hitting the annual peak. Alternatively, with better forecasting, the additional capacity and power rating could be applied to further reduce the RNS payments.

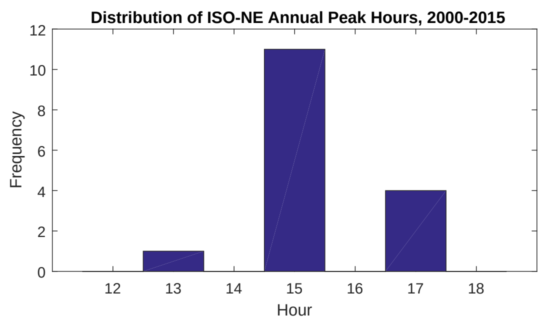

Fig. 3. Distribution of annual peak hours from historical data (2000-2015).

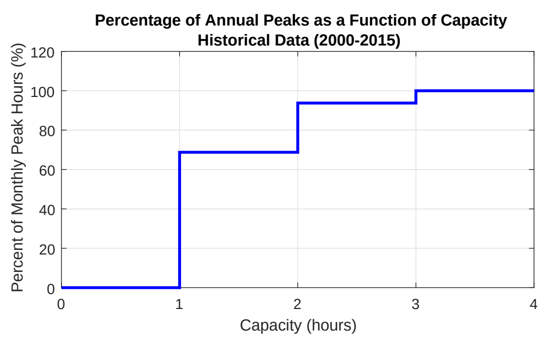

Fig. 4. Percentage of annual peak hours as a function of storage capacity using historical data (2000-2015).

V. Summary and Conclusions

This paper has explored the potential revenue from electrical energy storage for the Sterling Municipal Light Department, a public power utility in the Town of Sterling, MA. Potential value streams considered include: arbitrage, frequency regulation, reduction in RNS payments, reduction in FCM payments, and grid resiliency. The potential revenue for each application for a 1 MW, 1 MWh system is summarized below:

- Arbitrage $13,321.20/year
- Frequency regulation $60,476.04/year
- RNS savings $98,707.00/year
- FCM savings $115,572/year (2017-2018 pricing)
- Resiliency savings $40,819/event

The analysis of each value stream was performed independently. However, arbitrage and the peak shaving required to reduce RNS and FCM payments are synergistic activities. Because of the uncertainty in forecasting monthly and annual peak hours, additional capacity will be required to increase the likelihood of peak shaving during the proper time periods. It should be noted that this analysis assumes that the size of energy storage is small with respect to the market (i.e., a price taker). Large penetrations of energy storage and revisions to market rules could significantly impact these results. Future research will focus on simultaneously optimizing all value streams to maximize the benefit of energy storage in Sterling, MA, as well as algorithms to better predict the monthly peaks.

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