Opportunities for Energy Storage in CAISO: Day-Ahead and Real-Time Market Arbitrage

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Outline

Introduction
Energy storage model
Formulating the revenue optimization problem
Perfect foresight results
  - DA market arbitrage
  - DA/RT market arbitrage
  - DA arbitrage and frequency regulation (not in paper)
DA prices as a forecast
Limit order algorithm
Summary

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Energy Storage Applications

Energy storage is capable of providing a number of grid services.

“Energy applications” – typically transpire over long periods of time, often up to several hours.

“Power applications” - happen on a much quicker time scale, seconds to minutes, and are often aimed at maintaining grid stability.

<table>
<thead>
<tr>
<th>Energy Applications</th>
<th>Power Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arbitrage</td>
<td>Frequency regulation</td>
</tr>
<tr>
<td>Renewable energy time shift</td>
<td>Voltage support</td>
</tr>
<tr>
<td>Demand charge reduction</td>
<td>Small signal stability</td>
</tr>
<tr>
<td>Time-of-use charge reduction</td>
<td>Frequency droop</td>
</tr>
<tr>
<td>T&amp;D upgrade deferral</td>
<td>Synthetic inertia</td>
</tr>
<tr>
<td>Grid resiliency</td>
<td>Renewable capacity firming</td>
</tr>
</tbody>
</table>

In market areas – remuneration only for services associated with market products.

This paper focuses on day-ahead (DA) market and real-time (RT) market arbitrage opportunities in CAISO.
Energy Storage Model

Energy flow model

\[ S_t = S_{t-1} \gamma_s + q_t^R \gamma_e - q_t^D \]

\( S_t \): state of charge at time step \( t \) (MWh)
\( \gamma_s \): storage efficiency (percent)
\( q_t^R \): quantity of energy purchased for recharging at time step \( t \) (MWh)
\( q_t^D \): quantity of energy sold for discharging at time step \( t \) (MWh)

Constraints:

\[ \bar{q} \]
maximum discharged/recharged energy in one period (MWh)

\[ \bar{S} \]
maximum storage capacity (MWh)

\[ \underline{S} \]
minimum storage capacity (MWh)

\[ \underline{S} \leq S_t \leq \bar{S}, \forall t \]

\[ 0 \leq q_t^D + q_t^R \leq \bar{q}, \forall t \]
CAISO Model – DA/RT Market Arbitrage

State of charge model

\[ S_t = S_{t-1} \gamma_s + (q_t^{R-DA} + q_t^{R-RT}) \gamma_c - q_t^{D-DA} - q_t^{D-RT} \]

Decision variables

- \( q_t^{D-DA} \): energy sold in the day-ahead market at interval \( t \) (MWh)
- \( q_t^{D-RT} \): energy sold in the real-time market at interval \( t \) (MWh)
- \( q_t^{R-DA} \): energy purchased in the day-ahead market at interval \( t \) (MWh)
- \( q_t^{R-RT} \): energy purchased in the real-time market at interval \( t \) (MWh)

Constraints

\[ 0 \leq q_t^{D-DA} + q_t^{D-RT} + q_t^{R-DA} + q_t^{R-RT} \leq \bar{q}, \forall t \]
CAISO MODEL – DA/RT Market Arbitrage

Objective function

$$\max \sum_{t=1}^{T} \left[ (P_t^{DA} - C_d)q_t^{DA} + (P_t^{RT} - C_d)q_t^{RT} - (P_t^{DA} + C_r)q_t^{DA} - (P_t^{RT} + C_r)q_t^{RT} \right] e^{-rt}$$

Analyzed 3 years for market data (2014-2016) for ~2200 CAISO nodes

Energy storage model parameters

**ENERGY STORAGE SYSTEM PARAMETERS**

<table>
<thead>
<tr>
<th>parameter</th>
<th>value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma_c$</td>
<td>0.80</td>
</tr>
<tr>
<td>$\gamma_s$</td>
<td>1.0</td>
</tr>
<tr>
<td>$\bar{q}$</td>
<td>1.0 MWh</td>
</tr>
<tr>
<td>$\bar{S}$</td>
<td>4.0 MWh</td>
</tr>
<tr>
<td>$\bar{S}$</td>
<td>0.0 MWh</td>
</tr>
</tbody>
</table>
Estimating the Value of Energy Storage – CAISO Example

Analyzed ~2200 LMP nodes in CAISO
- Day ahead market arbitrage
- Day ahead and real time market arbitrage

Key takeaways
- Revenue opportunity is highly location dependent
- Significantly more potential revenue if the real time market is included

Storage model
1 MW, 4 MWh
80% efficiency
Results for DA/RT market arbitrage

Results for DA market arbitrage and frequency regulation

Estimating the Value of Energy Storage – CAISO Example

**Bottom 10**
- SYLMARDC_2_N501, $53.87K
- JBBBLACK1_7_B1, $54.42K
- JBBBLACK2_7_B1, $54.65K
- PIT3_7_N001, $55.83K
- PIT6U2_7_B1, $56.02K
- PIT5_7_N001, $56.22K
- PIT5_7_B1, $56.22K
- PIT6U1_7_B1, $56.34K
- PIT3_2_B1, $56.41K
- PIT1U1_7_B2, $56.65K

**Top 10**
- ELCAPTN_1_N001, $145.87K
- MERCED_1_N001, $146.12K
- ATWATER_1_B2, $146.28K
- ATWATER_1_N001, $146.28K
- ELCAPTN_1_N004, $146.38K
- LIVNGSTN_1_N001, $146.52K
- CRESSEY_1_N001, $147.44K
- CRESSEY_1_N003, $147.44K
- ELNIDO_1_N001, $155.05K
- ELNIDO_1_N004, $155.05K

DAM Arbitrage Revenue
20 highest/lowest revenue nodes
Estimating the Value of Energy Storage – CAISO Example

DAM Arbitrage/Regulation Revenue

20 highest/lowest revenue nodes

Distribution of potential revenue
- DA market arbitrage (perfect foresight)
- DA/RT market arbitrage (perfect foresight)
**DA/RT arbitrage results by node**

<table>
<thead>
<tr>
<th>Node</th>
<th>DA ($)</th>
<th>DA+RT ($)</th>
<th>Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>EBMUDGRY_1_N001</td>
<td>$94,235.10</td>
<td>$224,593.29</td>
<td>2.38</td>
</tr>
<tr>
<td>CALISTGA_6_N001</td>
<td>$88,691.72</td>
<td>$212,577.50</td>
<td>2.40</td>
</tr>
<tr>
<td>GUALALA_6_N001</td>
<td>$91,374.96</td>
<td>$219,734.66</td>
<td>2.40</td>
</tr>
<tr>
<td>SOUTHBAS_1_N001</td>
<td>$90,819.80</td>
<td>$218,607.46</td>
<td>2.41</td>
</tr>
<tr>
<td>LAKEWOOD_1_N009</td>
<td>$92,159.73</td>
<td>$222,571.35</td>
<td>2.42</td>
</tr>
<tr>
<td>SEGS2G_7_B1</td>
<td>$87,360.28</td>
<td>$211,968.66</td>
<td>2.43</td>
</tr>
<tr>
<td>CLAYTN_1_N030</td>
<td>$87,982.69</td>
<td>$214,220.14</td>
<td>2.43</td>
</tr>
<tr>
<td>CLAYTN_1_N001</td>
<td>$87,982.69</td>
<td>$214,220.14</td>
<td>2.43</td>
</tr>
<tr>
<td>CLAYTN_1_N029</td>
<td>$87,982.98</td>
<td>$214,221.15</td>
<td>2.43</td>
</tr>
<tr>
<td>MEDWLNE_1_N001</td>
<td>$91,738.45</td>
<td>$223,629.49</td>
<td>2.44</td>
</tr>
<tr>
<td>MERCEDFL_7_N002</td>
<td>$124,710.46</td>
<td>$516,831.58</td>
<td>4.14</td>
</tr>
<tr>
<td>MERCEDFL_7_N001</td>
<td>$124,710.46</td>
<td>$517,638.12</td>
<td>4.15</td>
</tr>
<tr>
<td>INDNFLT_6_N001</td>
<td>$129,071.10</td>
<td>$541,035.85</td>
<td>4.19</td>
</tr>
<tr>
<td>MARIPOS2_6_N003</td>
<td>$128,469.67</td>
<td>$539,897.66</td>
<td>4.20</td>
</tr>
<tr>
<td>MARIPOS2_6_N001</td>
<td>$128,462.06</td>
<td>$540,021.40</td>
<td>4.20</td>
</tr>
<tr>
<td>BERVLLY_6_N001</td>
<td>$125,862.96</td>
<td>$535,814.84</td>
<td>4.26</td>
</tr>
<tr>
<td>EXCHQRTP_7_B1</td>
<td>$121,978.50</td>
<td>$533,175.58</td>
<td>4.37</td>
</tr>
<tr>
<td>EXCHQUER_7_B1</td>
<td>$121,525.31</td>
<td>$532,702.53</td>
<td>4.38</td>
</tr>
<tr>
<td>CRAGVIEW_1_N101</td>
<td>$61,458.74</td>
<td>$281,385.47</td>
<td>4.58</td>
</tr>
<tr>
<td>SYLMARDC_2_N501</td>
<td>$53,869.57</td>
<td>$280,612.88</td>
<td>5.21</td>
</tr>
<tr>
<td>MONA_3_N501</td>
<td>$65,793.67</td>
<td>$355,897.56</td>
<td>5.41</td>
</tr>
</tbody>
</table>
In addition to the strong dependence on location, there was also a significant temporal variation in revenue (e.g., some months are much better than others).

Monthly day-ahead arbitrage revenue profile for the minimum node, the median node, and the maximum node 2014-2016.

Estimating the Value of Energy Storage – CAISO Example

Characteristics of the highest revenue node

<table>
<thead>
<tr>
<th>Statistic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Percentage of DAM discharging, $q^{D-DA}$</td>
<td>18.49%</td>
</tr>
<tr>
<td>Percentage of RTM discharging, $q^{D-RT}$</td>
<td>17.39%</td>
</tr>
<tr>
<td>Percentage of DAM charging, $q^{R-DA}$</td>
<td>9.23%</td>
</tr>
<tr>
<td>Percentage of RTM charging, $q^{R-RT}$</td>
<td>35.69%</td>
</tr>
<tr>
<td>Periods recharge RT, discharge DA, (6175/105216)</td>
<td>5.87%</td>
</tr>
<tr>
<td>Periods recharge DA, discharge RT, (1254/105216)</td>
<td>1.19%</td>
</tr>
<tr>
<td>Periods recharge RT alone, (34474/105216)</td>
<td>32.76%</td>
</tr>
<tr>
<td>Periods discharge RT alone, (17781/105216)</td>
<td>16.90%</td>
</tr>
<tr>
<td>Periods recharge DA alone, (9224/105216)</td>
<td>8.77%</td>
</tr>
<tr>
<td>Periods discharge DA alone, (16721/105216)</td>
<td>15.89%</td>
</tr>
</tbody>
</table>
Estimating the Value of Energy Storage – CAISO Example

Using price data for the highest revenue node (INDNFLT 6 N001), two different algorithms were tested:

- DA prices as a forecast for RT prices, arbitrage in the RT market
- Buy/sell limit prices for the DA and RT markets

The DA prices as a forecast for RT prices did not perform well, ~$113K revenue for the three year period (compared to $541K for perfect foresight)
Estimating the Value of Energy Storage – CAISO Example

CAISO analysis included:

- Best case scenario assuming perfect foresight
- Results for a simple limit order trading algorithm that did not require perfect foresight
  - INDNFLT 6 N001 LMP node (maximum revenue node)
  - Purchase energy if price less than $P_{low}$
  - Sell energy if price less than $P_{high}$

- Maximum revenue: $280K for 2014-2016 time period
  - $P_{low} = $70/MWh
  - $P_{high} = $80/MWh
- Significantly better than DA arbitrage alone ($129K)
- Still leaves significant potential revenue on the table ($541K max)
Summary

The paper formulates the LP optimization for maximizing arbitrage revenue in the CAISO RT and DA energy markets

Several different strategies were tested:
- Best case scenario using perfect foresight (DA only, DA + RT)
- RT market arbitrage using the DA prices as a forecast
- Buy/sell limit prices for the DA and RT energy markets

The limit price strategy performed better than arbitrage in the DA market with perfect foresight, but left significant potential revenue on the table

More sophisticated forecasting algorithms are required to improve the performance of DA/RT market arbitrage algorithms