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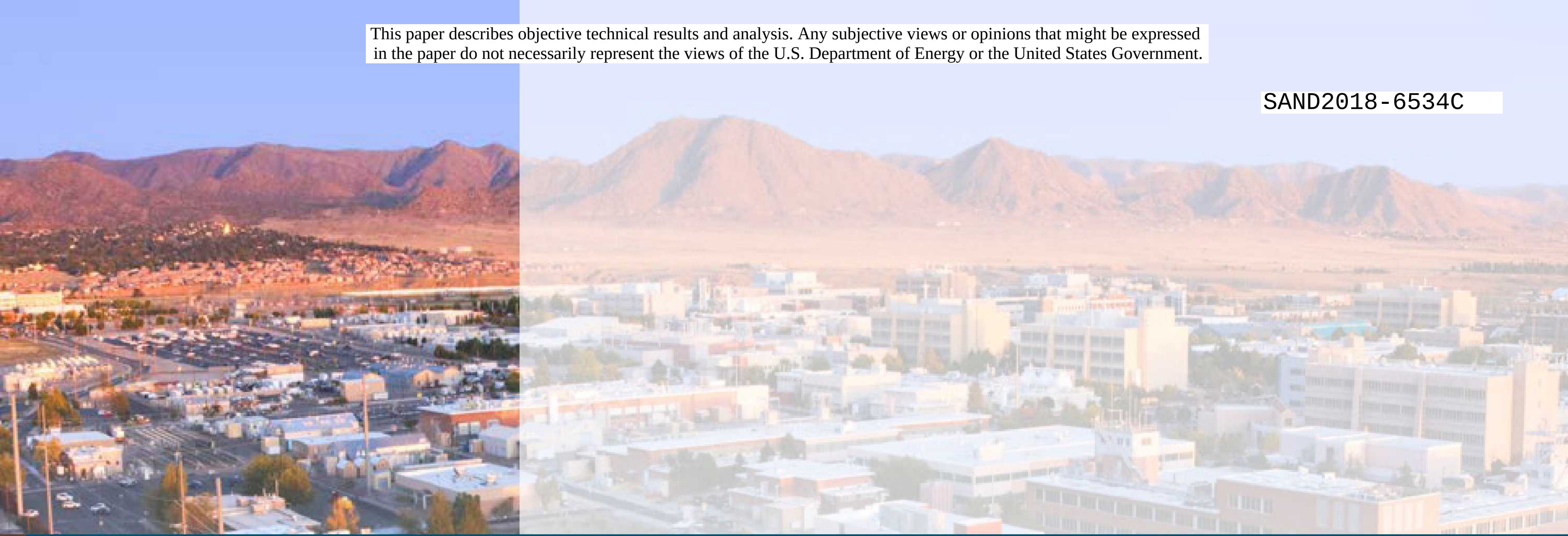

Opportunities for Energy Storage in CAISO: Day-Ahead and Real-Time Market Arbitrage

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Speedam 2018

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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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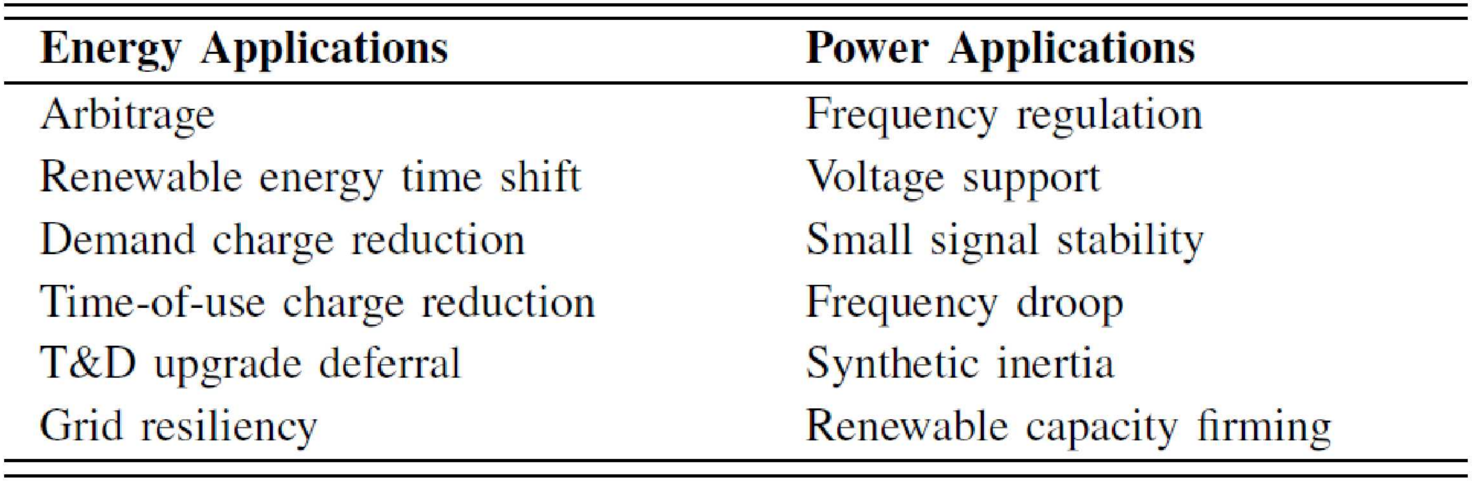
Energy Storage Applications

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



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 – 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

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

S_t: state of charge at time step t (MWh)

γ_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)
$\underline{\mathrm{S}}$	minimum storage capacity (MWh)

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

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

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

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

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

Energy storage model parameters

ENERGY STORAGE SYSTEM PARAMETERS

parameter	**value**
γ_c	0.80
γ_s	1.0
$\bar{q}$	1.0 MWh
$\bar{S}$	4.0 MWh
$\underline{S}$	0.0 MWh

Estimating the Value of Energy Storage – CAISO Example

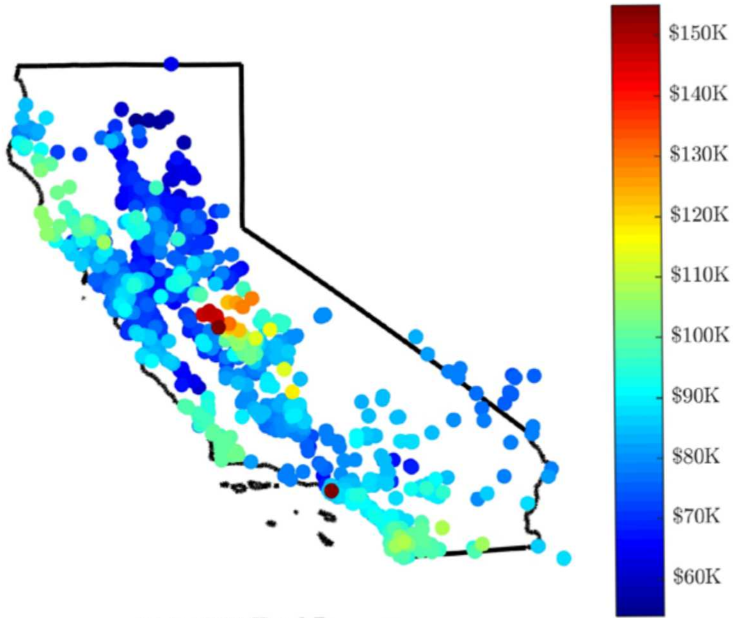
Analyzed ~2200 LMP nodes in CAISO

- Day ahead market arbitrage
- Day ahead and real time market arbitrage

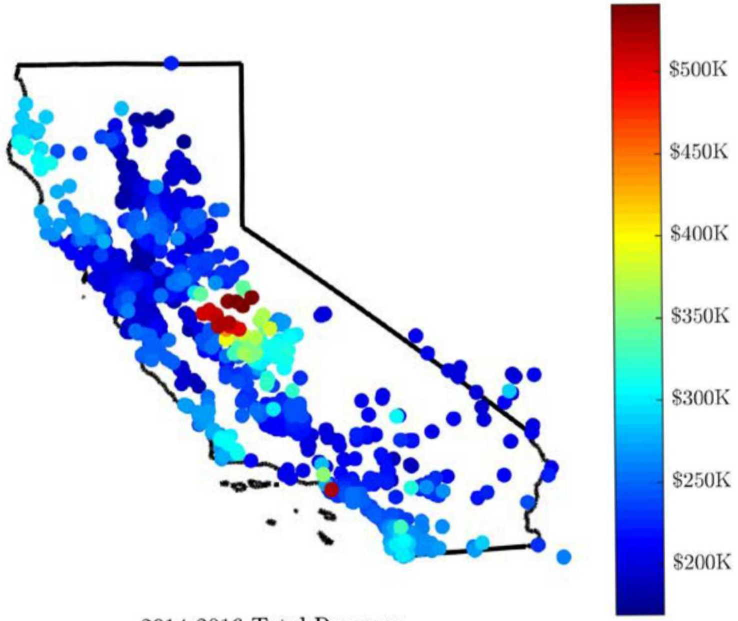
Key takeaways

- 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



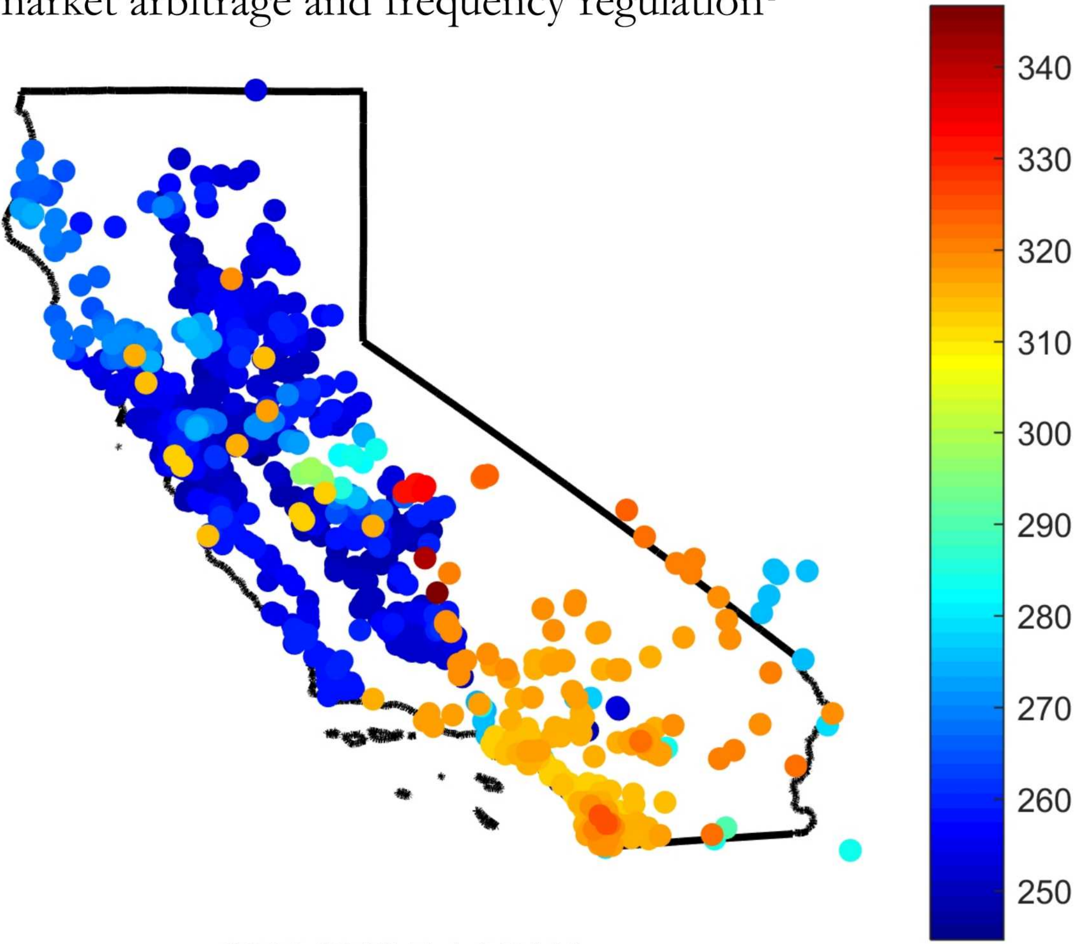
2014-2016 Total Revenue
DA Arbitrage



2014-2016 Total Revenue
DA+RT Arbitrage

Estimating the Value of Energy Storage – CAISO Example

Results for DA market arbitrage and frequency regulation[1]



2014-2016 Total DAM
Arbitrage plus Regulation Revenue ($K)

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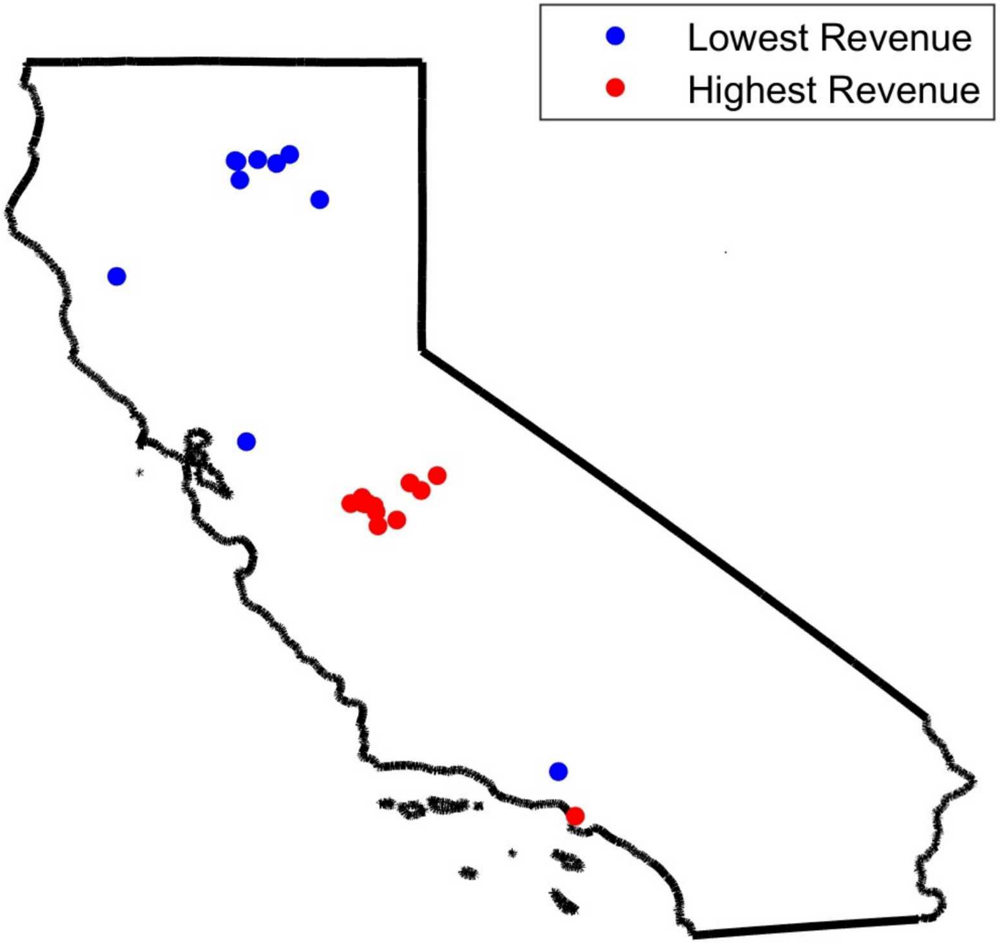
[1] R. H. Byrne, T. A. Nguyen and R. J. Concepcion, “Opportunities for energy storage in CAISO," accepted for publication in the 2018 IEEE Power and Energy Society (PES) General Meeting, August 5-9, 2018.

Estimating the Value of Energy Storage – CAISO Example



DAM Arbitrage Revenue

20 highest/lowest revenue nodes

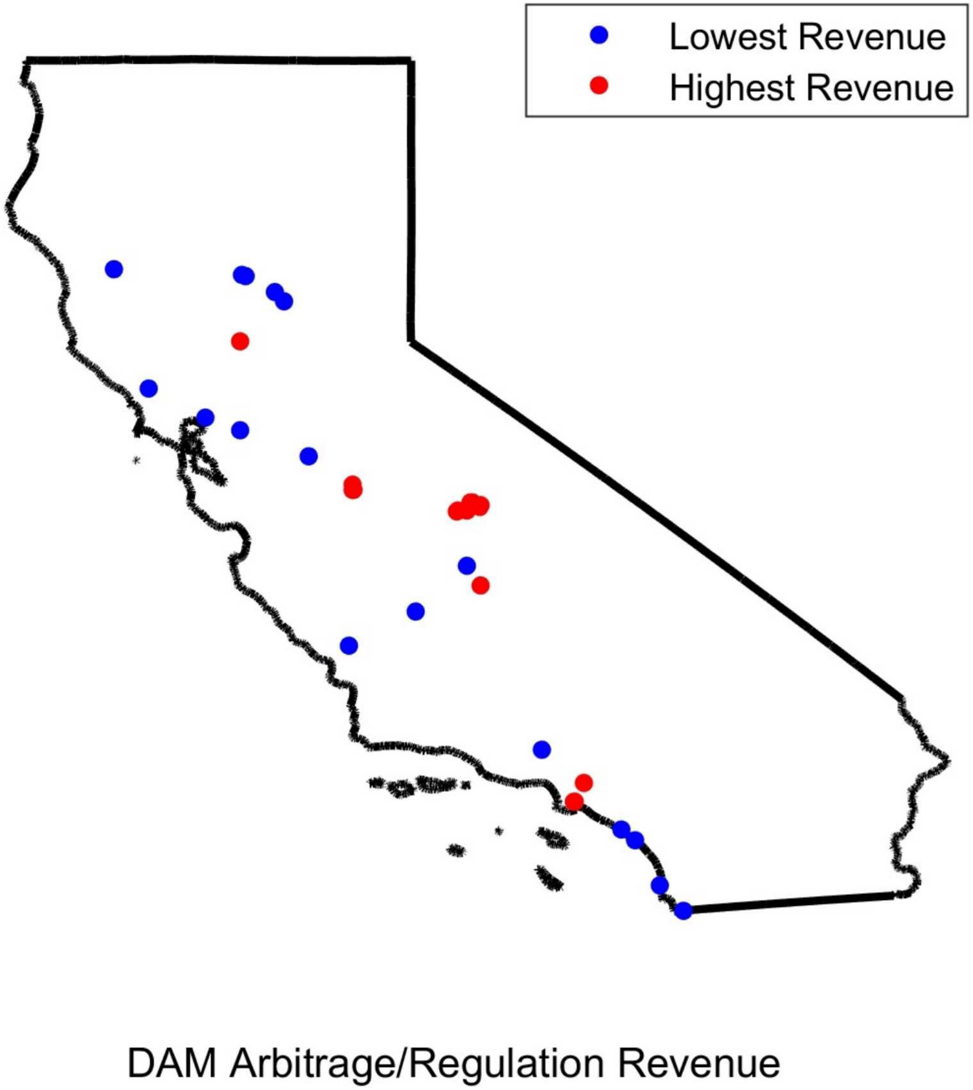
BOTTOM 10

SYLMARDC_2_N501, $53.87K
JBBLACK1_7_B1, $54.42K
JBBLACK2_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

Estimating the Value of Energy Storage – CAISO Example



20 highest/lowest revenue nodes

BOTTOM 10

CHICOB_1_N002, $244.64K
TJI-230_2_N101, $244.78K
FULTON_2_N049, $244.79K
TLRELKE_6_N001, $244.79K
KANAKA_1_N001, $244.97K
KANAKA_1_N003, $245.02K
BUTTE_1_N101, $245.05K
HYATT5_7_B1, $245.60K
PIT6U1_7_B1, $246.70K
COVERD_7_B1, $246.70K

TOP 10

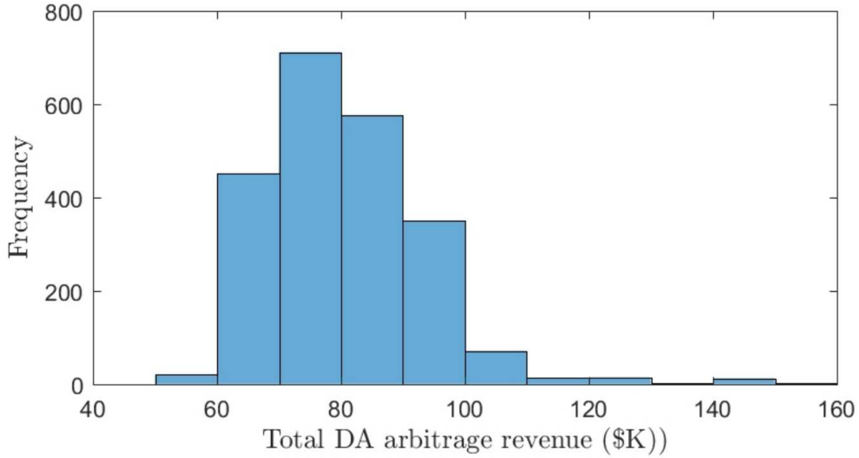
BIGCRK1_2_B1, $333.00K
RECTOR_6_N009, $340.56K
CRESSEY_1_N001, $340.56K
CRESSEY_1_N003, $340.56K
JRWOOD_1_N001, $340.56K
JRWDGEN_1_N001, $340.56K
HINSON_6_N001, $346.68K
LBEACH1G_7_N001, $346.68K
LBEACH2G_7_N001, $346.68K
LBEACH2G_7_N002, $346.68K

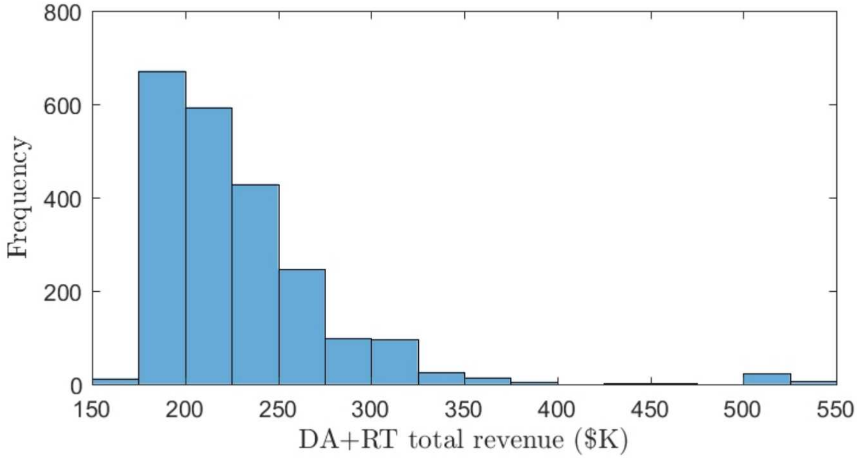
R. H. Byrne, T. A. Nguyen and R. J. Concepcion, “Opportunities for energy storage in CAISO," accepted for publication in the 2018 IEEE Power and Energy Society (PES) General Meeting, August 5-9, 2018.

Estimating the Value of Energy Storage – CAISO Example

Distribution of potential revenue

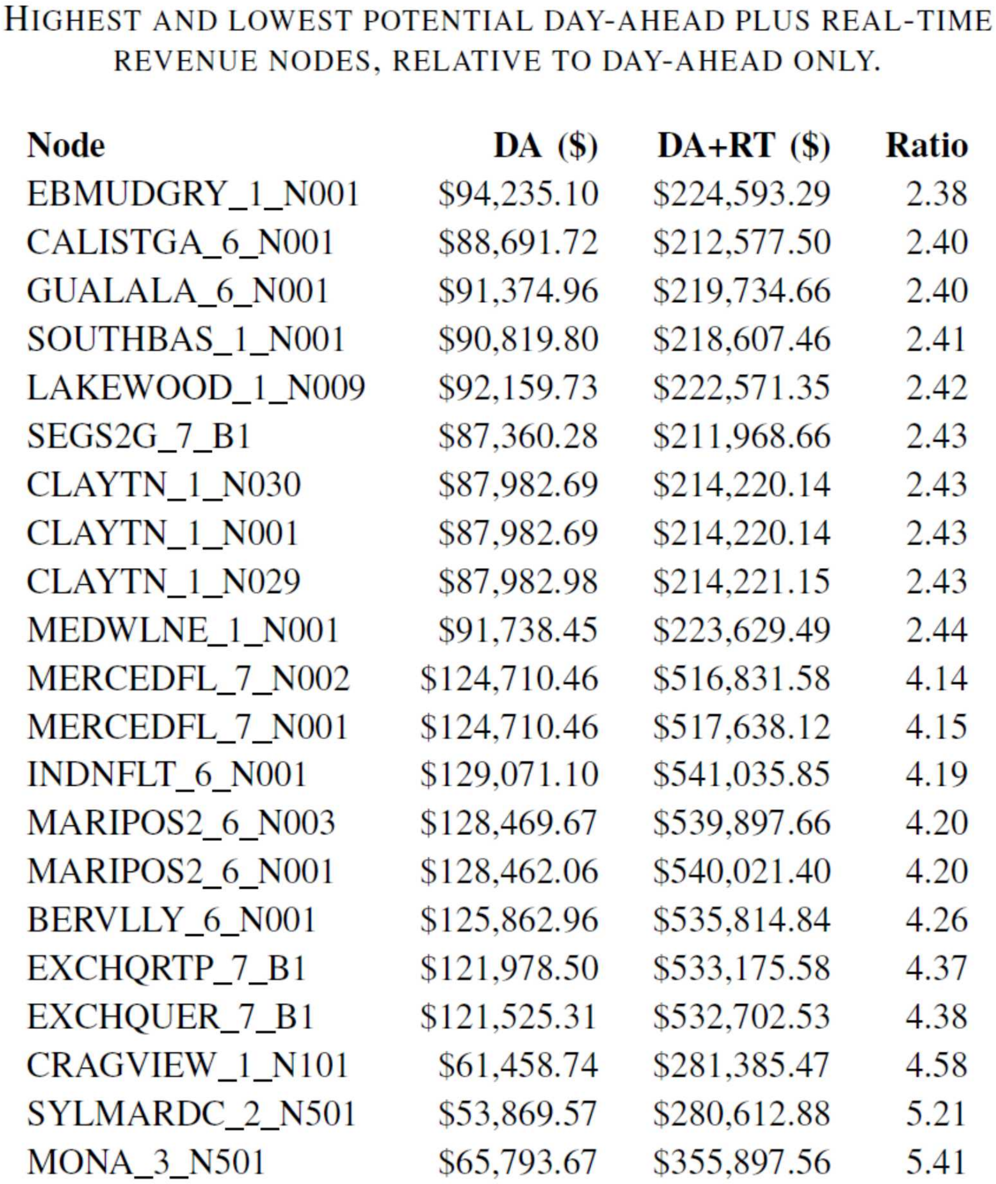
- DA market arbitrage (perfect foresight)
- DA/RT market arbitrage (perfect foresight)





Estimating the Value of Energy Storage – CAISO Example

DA/RT arbitrage results by node

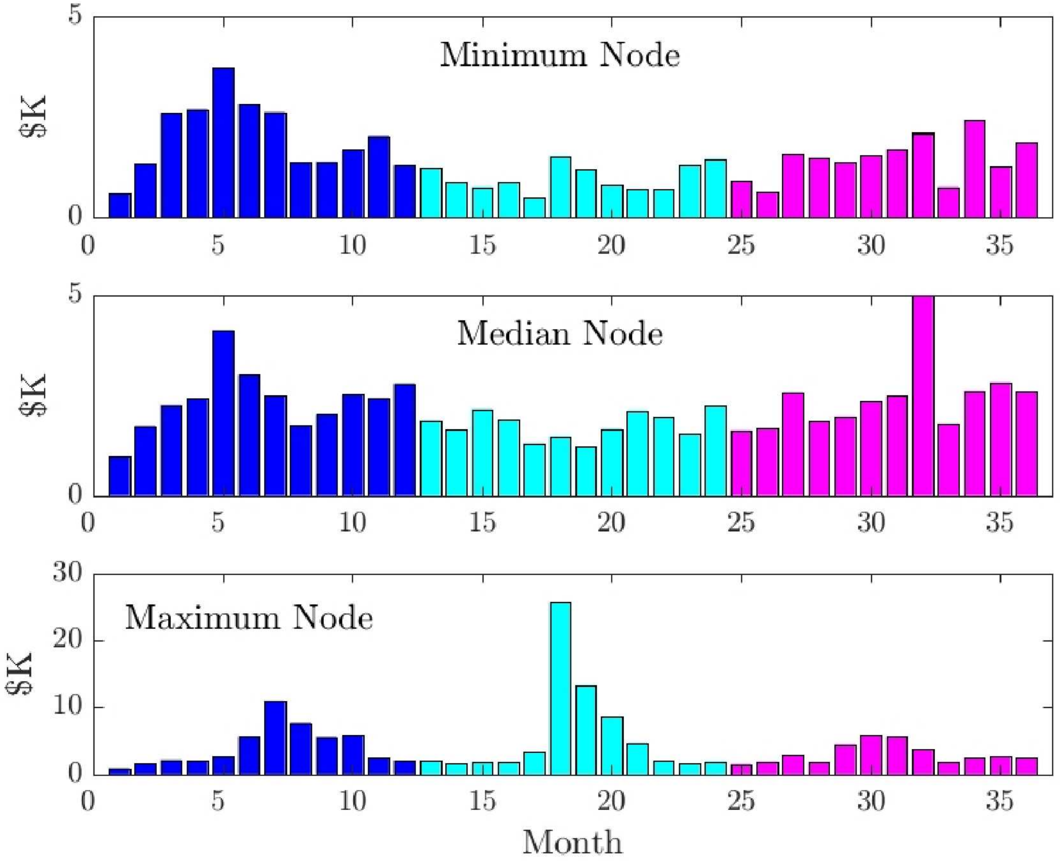


HIGHEST AND LOWEST POTENTIAL DAY-AHEAD PLUS REAL-TIME REVENUE NODES, RELATIVE TO DAY-AHEAD ONLY.

Node	**DA ($)**	**DA+RT ($)**	**Ratio**
EBMUDGRY_1_N001	$94,235.10	$224,593.29	2.38
CALISTGA_6_N001	$88,691.72	$212,577.50	2.40
GUALALA_6_N001	$91,374.96	$219,734.66	2.40
SOUTHBAS_1_N001	$90,819.80	$218,607.46	2.41
LAKEWOOD_1_N009	$92,159.73	$222,571.35	2.42
SEGS2G_7_B1	$87,360.28	$211,968.66	2.43
CLAYTN_1_N030	$87,982.69	$214,220.14	2.43
CLAYTN_1_N001	$87,982.69	$214,220.14	2.43
CLAYTN_1_N029	$87,982.98	$214,221.15	2.43
MEDWLNE_1_N001	$91,738.45	$223,629.49	2.44
MERCEDFL_7_N002	$124,710.46	$516,831.58	4.14
MERCEDFL_7_N001	$124,710.46	$517,638.12	4.15
INDNFLT_6_N001	$129,071.10	$541,035.85	4.19
MARIPOS2_6_N003	$128,469.67	$539,897.66	4.20
MARIPOS2_6_N001	$128,462.06	$540,021.40	4.20
BERVLLY_6_N001	$125,862.96	$535,814.84	4.26
EXCHQRTP_7_B1	$121,978.50	$533,175.58	4.37
EXCHQUER_7_B1	$121,525.31	$532,702.53	4.38
CRAGVIEW_1_N101	$61,458.74	$281,385.47	4.58
SYLMARDC_2_N501	$53,869.57	$280,612.88	5.21
MONA_3_N501	$65,793.67	$355,897.56	5.41

Estimating the Value of Energy Storage – CAISO Example

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)

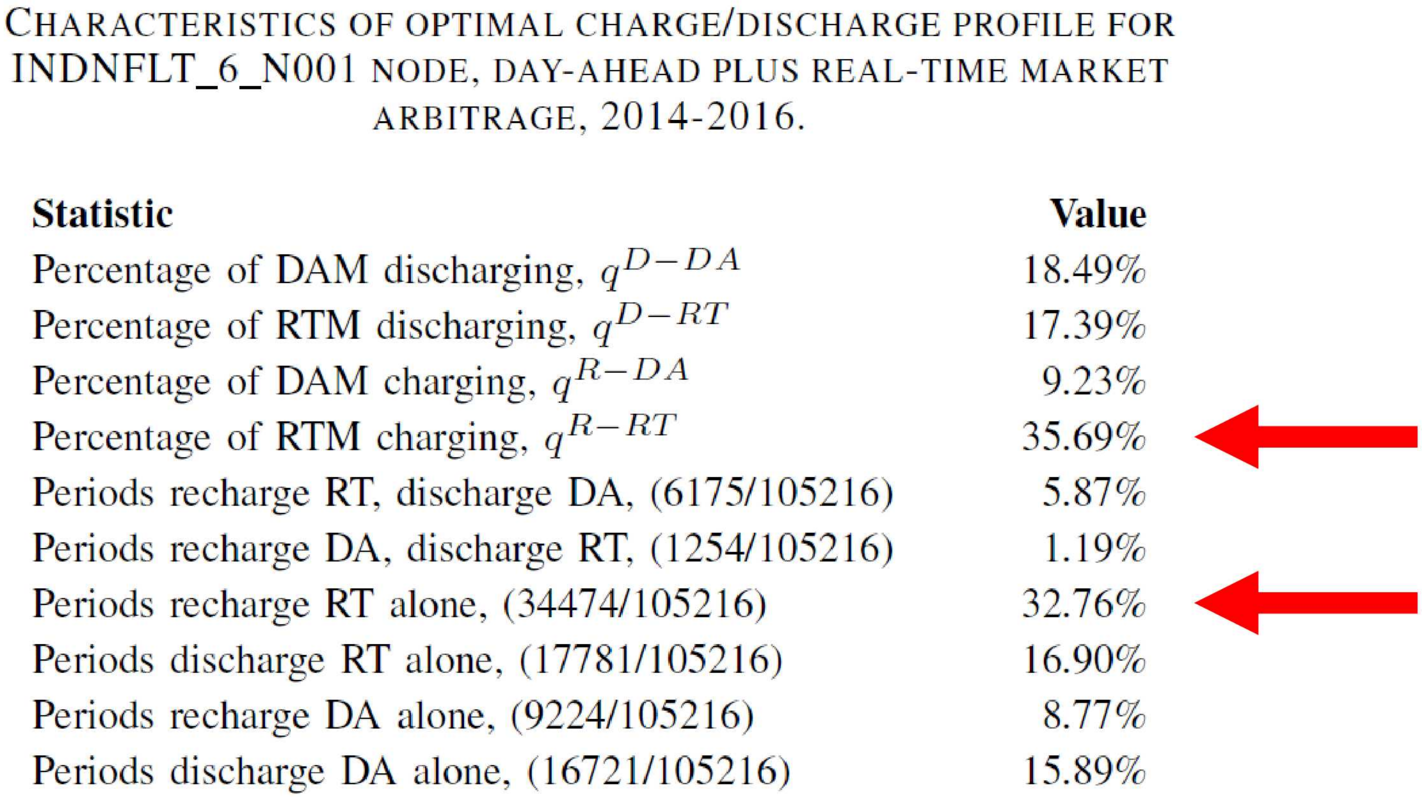


Monthly day-ahead arbitrage revenue profile for the minimum node, the median node, and the maximum node 2014-2016.

R. H. Byrne, T. A. Nguyen, D. A. Copp, R. J. Concepcion, B. R. Chalamala, I. Gyuk, "Opportunities for Energy Storage in CAISO: Day-Ahead and Real-Time Market Arbitrage," proceedings of IEEE Speedam Symposium, June 2018, pp. 1-6.

Estimating the Value of Energy Storage – CAISO Example

Characteristics of the highest revenue node



CHARACTERISTICS OF OPTIMAL CHARGE/DISCHARGE PROFILE FOR INDNFLT_6_N001 NODE, DAY-AHEAD PLUS REAL-TIME MARKET ARBITRAGE, 2014-2016.

Statistic	**Value**
Percentage of DAM discharging, q^{D-DA}	18.49%
Percentage of RTM discharging, q^{D-RT}	17.39%
Percentage of DAM charging, q^{R-DA}	9.23%
Percentage of RTM charging, q^{R-RT}	35.69%
Periods recharge RT, discharge DA, (6175/105216)	5.87%
Periods recharge DA, discharge RT, (1254/105216)	1.19%
Periods recharge RT alone, (34474/105216)	32.76%
Periods discharge RT alone, (17781/105216)	16.90%
Periods recharge DA alone, (9224/105216)	8.77%
Periods discharge DA alone, (16721/105216)	15.89%

Estimating the Value of Energy Storage – CAISO Example

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

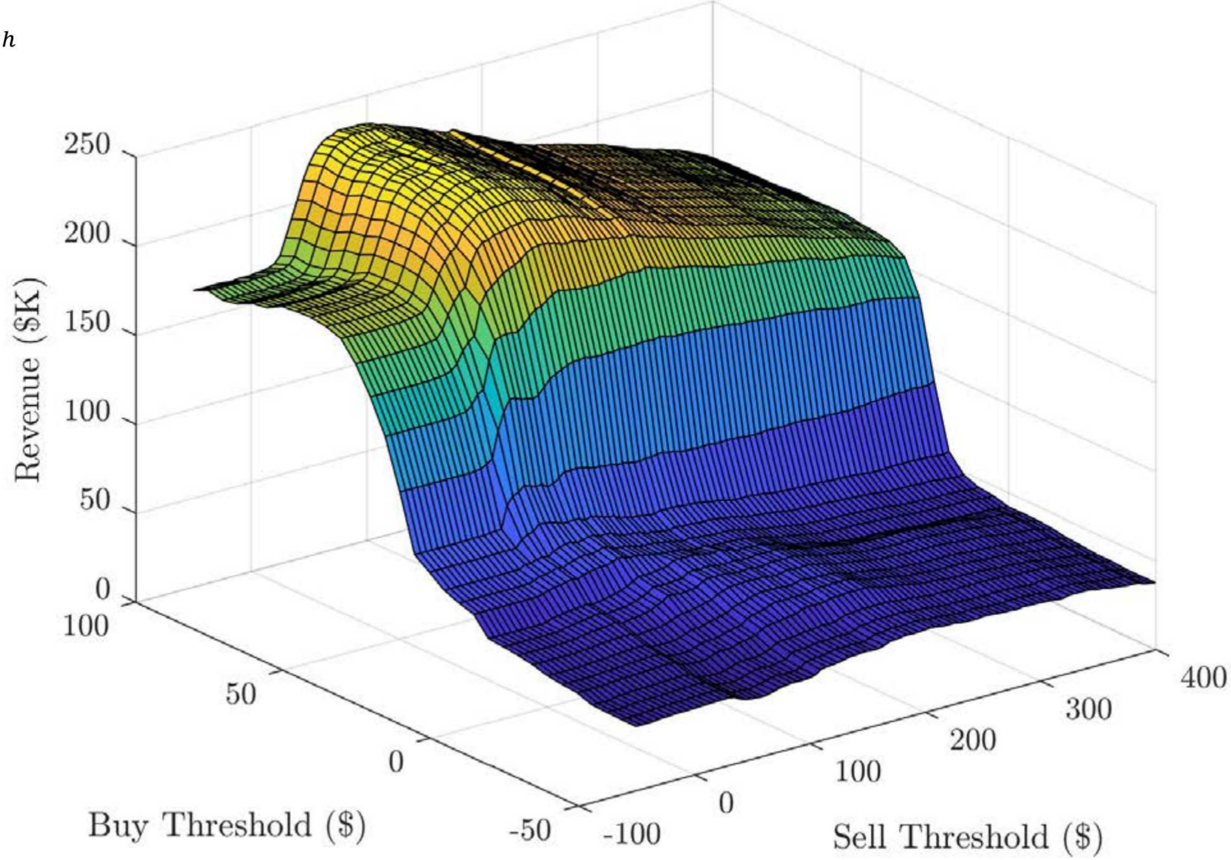
- DA prices as a forecast for RT prices, arbitrage in the RT market
- Buy/sell limit prices for the DA and RT markets

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