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Break-even capital costs for energy storage participating in the CAISO day-ahead energy and ancillary service markets

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Abstract – The break-even capital cost for a generic battery energy storage system (BESS) participating in the CAISO day-ahead energy and ancillary services market was obtained and analyzed for 2,065 nodes over a five year period (2018-2022).

Revenue optimization formulation:

$$
\begin{aligned}
max\ \mathrm{J} = \sum_{t=1}^{T} \Big[& P_t \cdot q_t^D - P_t \cdot q_t^C + \left(P_t^{RU} + \gamma_{ru} P_t\right) q_t^{RU} \\
& + \left(P_t^{RD} - \gamma_{rd} P_t\right) q_t^{RD} + \left(P_t^{NSP} + \alpha_t^{NSP} P_t\right) q_t^{NSP} \\
& + \left(P_t^{SP} + \alpha_t^{SP} P_t\right) q_t^{SP} \Big]
\end{aligned}
$$

Such that:

$$0 \leq q_t^C + q_t^{RD} + q_t^D + q_t^{RU} + q_t^{NSP} + q_t^{SP} \leq \bar{q}$$

$$S_{min} + 2 \cdot q_t^{SP} + 2 \cdot q_t^{NSP} + 2 \cdot q^{RU} \leq S_t \leq \bar{S}_{max} - 2 \cdot q_t^{RD}$$

$$
\begin{aligned}
S_t = \gamma_s S_{t-1} + \gamma_c q_t^C - q_t^D + \gamma_c \gamma_{rd} q_t^{RD} - \gamma_{ru} q_t^{RU} \\
- \alpha_t^{NSP} \cdot q_t^{NSP} - \alpha_t^{SP} \cdot q_t^{SP}
\end{aligned}
$$

where

S_t	is the state of charge at any time t,
q_t^C	is the quantity of energy charged at time t,
q_t^D	is the quantity of energy discharged at time t,
q_t^{RD}	is the quantity of energy discharged in the regulation down market at time t,
q_t^{RU}	is the quantity of energy charged in the regulation up market at time t,
q_t^{NSP}	is the quantity of energy offered into the non-spinning reserve market at time t,
q_t^{SP}	is the quantity of energy offered into the spinning reserve market at time t,
γ_s	is the storage efficiency,
γ_c	is the conversion efficiency,
γ_{rd}	is the regulation down efficiency,
γ_{ru}	is the regulation up efficiency,
α^{NSP}	is the non-spinning reserves selector per schedule (0 or 1),
α^{SP}	is the spinning reserves selector per schedule (0 or 1),
P_t	is the price of electricity (LMP) at time t,
P_t^{RU}	is the regulation up price of electricity at time t,
P_t^{RD}	is the regulation down price of electricity at time t

The break-even cost formulation for each node:

The break-even capital cost for each node is obtained by first setting the NPV of the total cost equal to the NPV of the revenue streams for T years for each LMP node.

$$
\begin{aligned}
\mathrm{NPV}\{\mathrm{revenue}\} &= \mathrm{NPV}\{\mathrm{total\ cost}\} \\
&= \mathrm{CAP} + \mathrm{NPV}\{\mathrm{O\&M\ costs}\}
\end{aligned}
$$

The break-even capital cost for each node is:

$$\mathrm{CAP} = \frac{\mathrm{GAF}_{r,g}^{T} \times \mathrm{REV}}{1 + k \times \mathrm{AF}_r^T}$$

Where

$$\mathrm{AF}_r^T = \frac{1}{r} \cdot \left(1 - \frac{1}{(1+r)^T}\right)$$

and

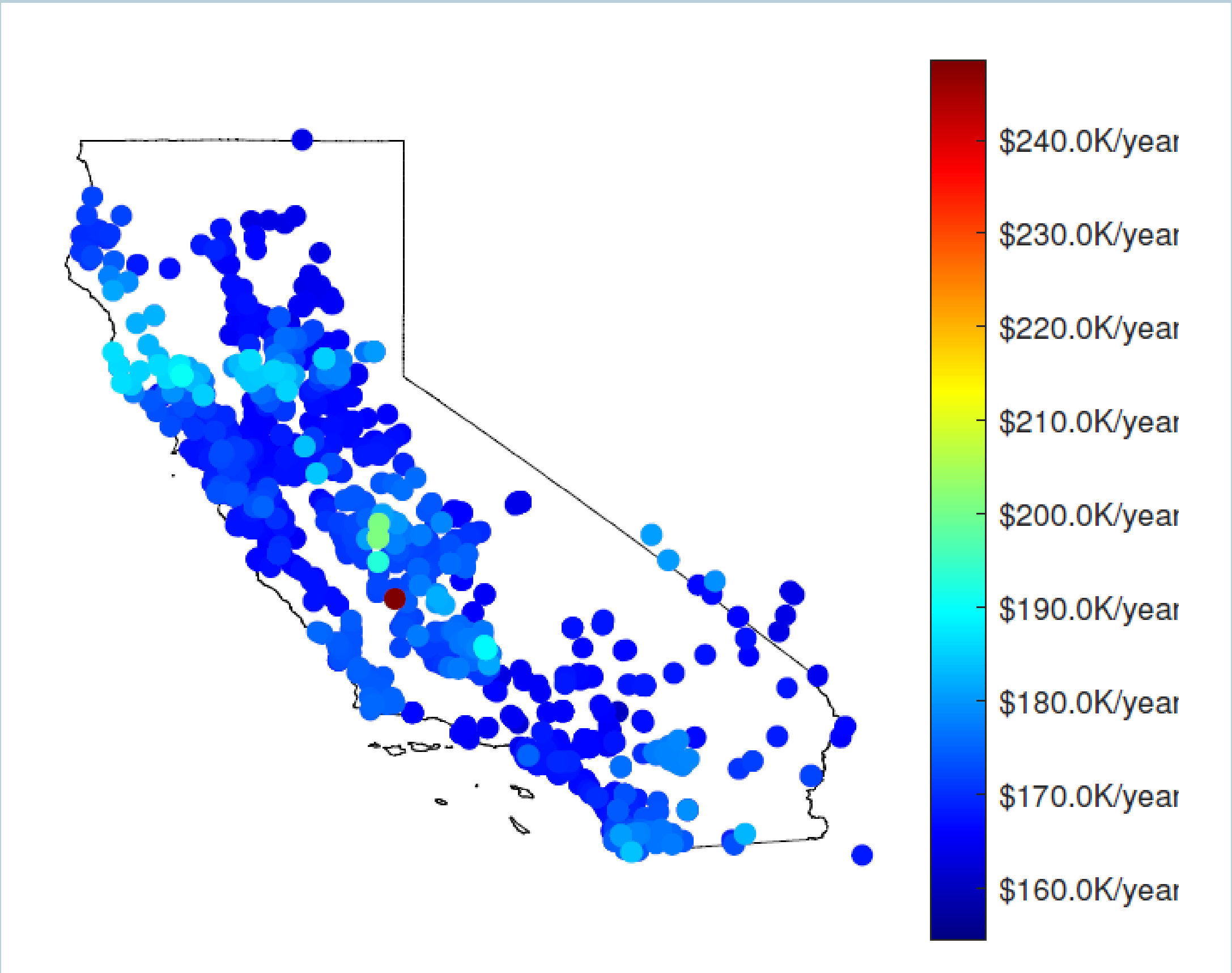
$$\mathrm{GAF}_{r,g}^{T} = \frac{1}{r-g} \cdot \left[1 - \left(\frac{1+g}{1+r}\right)^T\right]$$

System parameters and case studies:

Value	Parameter
1	P_{max}, maximum power rating (MW)
4	$\bar{S}$, maximum state of charge (MWh)
1	$\bar{q}^C$ maximum quantity that can be bought/recharged in a period t (MWh)
1	$\bar{q}^D$ maximum quantity that can be sold/discharged in a period t (MWh)
1.0	γ_s, storage efficiency (fraction)
0.85	γ_c, conversion efficiency (fraction)
0.25	γ_{rd}, regulation down efficiency (fraction)
0.25	γ_{ru}, regulation up efficiency (fraction)
1	Δt (hours)

IRR = 2.5%, 5%, 7.5%, 10%
Annual revenue growth rates (g) = 0%, 3%, 6%
Project lifetimes (*T*) = 10 and 15 years
k = 2%

Average yearly revenue for 2,065 CAISO nodes for the period 2018-2022 (thousands of dollars.)



Arbitrage

Break-even capital cost statistics for different values of IRR. Project lifetime of 15 years, and average annual revenue growth at 0, 3, and 6%.

Rev Growth	$/kWh	IRR (%) 2.5	5	7.5	10
0 %	mean	185	160	140	123
	median	182	157	137	121
	std. dev.	24	21	18	16
3 %	mean	226	193	167	145
	median	222	190	164	142
	std. dev.	29	25	21	19
6 %	mean	279	236	201	172
	median	275	232	197	169
	std. dev.	36	30	26	22

Arbitrage and frequency regulation

Break-even capital cost statistics for different values of IRR. Project lifetime of 15 years, and average annual revenue growth at 0, 3, and 6%.

Rev Growth	$/kWh	IRR (%) 2.5	5	7.5	10
0 %	mean	416	361	315	277
	median	412	357	311	274
	std. dev.	13	11	10	8
3 %	mean	509	435	375	326
	median	504	431	371	323
	std. dev.	15	12	11	10
6 %	mean	629	531	452	388
	median	622	525	447	384
	std. dev.	19	16	14	12

Arbitrage, frequency regulation, spinning, and non-spinning reserves

Break-even capital cost statistics for different values of IRR. Project lifetime of 15 years, and average annual revenue growth at 0, 3, and 6%.

Rev Growth	$/kWh	IRR (%) 2.5	5	7.5	10
0 %	mean	421	364	318	280
	median	417	361	315	277
	std. dev.	13	11	10	8
3 %	mean	515	440	379	330
	median	510	436	376	327
	std. dev.	16	13	11	10
6 %	mean	636	537	457	392
	median	630	531	452	388
	std. dev.	19	16	14	12

Conclusion:

In previous work we reported that, when using only arbitrage as a source of revenue, the capital cost for a BESS had to be reduced by 80% in order for the storage system to be profitable.

In this study we show that when adding ancillary services (frequency regulation, spinning, and non-spinning reserves) to arbitrage, we see a considerable increase in revenue (depending on annual revenue growth and IRR.)

Considering the current capital cost of $493/kWh, we see that by adding ancillary services to the BESS revenue formulation, this cost can be reduced between 43% to 15% and in some cases the revenue is even higher than this capital cost, making the BESS profitable.

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