

Optimizing grid-scale battery operations

Andy Philpott

Electric Power Optimization Centre
University of Auckland
www.epoc.org.nz

Joint work with Michael Ferris and Jacob Mays

Research performed while the authors were participating in the Architecture of Green Energy Systems Program hosted by the Institute for Mathematical and Statistical Innovation (IMSI), and supported by the National Science Foundation (Grant No. DMS-1929348).

Paper downloadable at <https://www.epoc.org.nz/papers/ADRPaperForEPOC.pdf>



Rotohiko BESS (35 MWh, December, 2023) [<https://infratec.co.nz>]



Meridian's Ruakākā Battery Energy Storage System (BESS) is being officially opened in a ceremony later today.

Ruakaka BESS (100 MW, May, 2025) [<https://www.meridianenergy.co.nz>]



[Our story](#) ▾ [Sustainability](#) ▾ [Careers](#) ▾

[Join us](#)

[Sign in](#)

Glenbrook-Ohurua Battery

[About us](#) ▸ [Sustainability](#) ▸ [Our projects](#) ▸ Glenbrook-Ohurua Battery



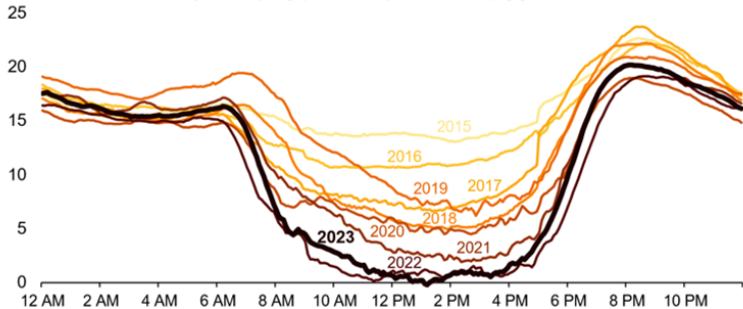
Contact Energy Glenbrook BESS (100 MW, March 2026) [<https://contact.co.nz>]

JUNE 21, 2023

As solar capacity grows, duck curves are getting deeper in California

California's duck curve is getting deeper

CAISO lowest net load day each spring (March–May, 2015–2023), gigawatts



Data source: [California Independent System Operator](#) (CAISO)

CAISO Duck curves [[California Independent System Operator](#)]

Self dispatch versus central dispatch

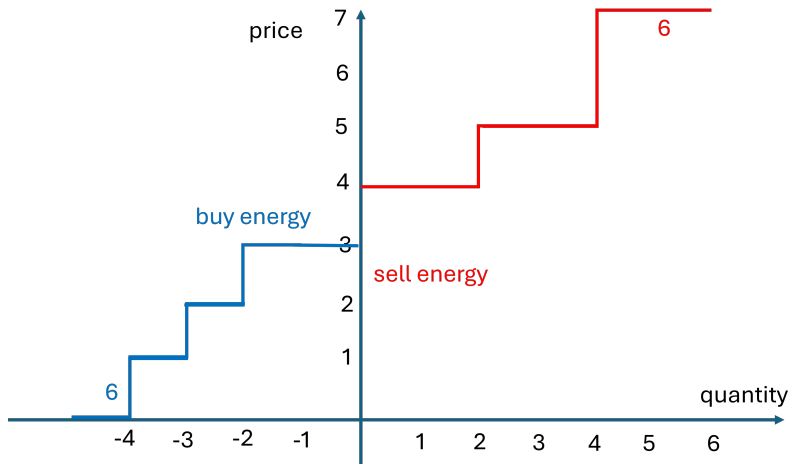
Self dispatch

- ▶ Battery forecasts/models prices and solves an optimization problem to maximize revenue from storage.
- ▶ System operator forecasts **exogenous** battery operation as part of net demand.

Central dispatch

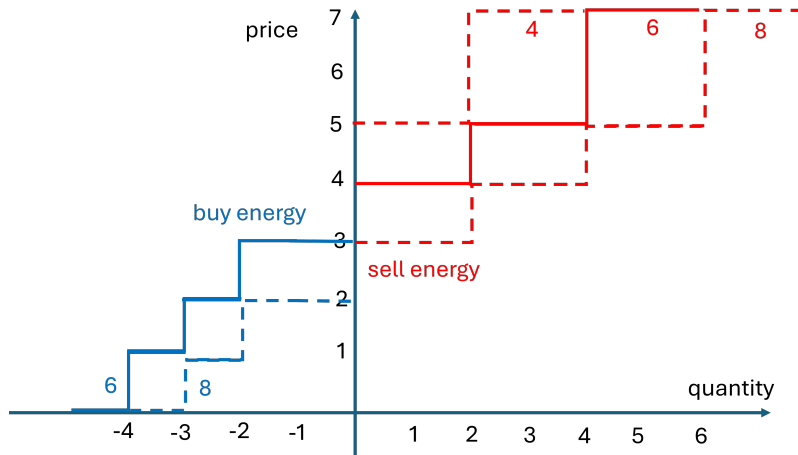
- ▶ Battery provides supply/demand curve defining what battery will sell/buy as price increases.
- ▶ System operator co-optimizes SPD and **endogenous** battery operation.

Supply/demand offer curve for battery



Supply-demand curve for battery with capacity 10 and charge 6.

Supply/demand offer curves for battery



Curves depend on battery charge.

Agent decision rules (ADRs)

- ▶ An **agent decision rule (ADR)** is a mapping from any known **parameter** of the stage t problem, and a 's state (storage) at end of t , to an energy offer in period t .
- ▶ An **agent Bellman function (ABF)** for agent a in period t is a **function** $W_a^t(y)$ that expresses the **expected future benefit** to a of being in **state** y at the end of period t .
- ▶ We can define an ADR for battery a using observed price $\pi(t)$ and its initial storage y_a and ABF W_a^t . Choose discharge u and charge v so as to:

$$\begin{aligned} \max_{u,v} \quad & \pi(t)(u - v) + W_a^t(y_a - u + \eta v) \\ \text{s.t.} \quad & 0 \leq y_a - u + \eta v \leq E_a \end{aligned}$$

Single-node electricity dispatch with ABFs

Given ABFs for battery agents \mathcal{B} , and state of charge $y(t-1)$:

$$\text{ADR}(t): \min \sum_{a \in \mathcal{G}} c_a x_a(t) + Lz(t) - \sum_{a \in \mathcal{B}} W_a^t(y_a)$$

$$\text{s.t.} \quad \sum_{a \in \mathcal{G}} x_a(t) + \sum_{a \in \mathcal{B}} u_a(t) - \sum_{a \in \mathcal{B}} v_a(t) + z(t) = d(t), \quad [\pi(t)]$$

$$x_a(t) \in \mathcal{X}_a(x_a(t-1)), \quad a \in \mathcal{G},$$

$$(y_a(t), u_a(t), v_a(t)) \in \mathcal{Y}_a(y_a(t-1)), \quad a \in \mathcal{B},$$

$$z(t) \in [0, d(t)].$$

New dispatch process with ADRs

- ▶ Generator agents provide system operator with marginal costs.
- ▶ Battery agent a provides system operator with ADR defined by increasing concave ABF W_a^t .
- ▶ System operator solves single-stage problem $\text{ADR}(t)$ and computes dispatch and system marginal price $\pi(t)/\text{MWh}$.
- ▶ Generator is paid $\pi(t)$ per MWh
- ▶ Battery is paid $\pi(t)(\text{charge} - \text{discharge})$.

Remarks

- ▶ $ADR(t)$ is a deterministic convex optimization problem (assuming no unit commitment).
- ▶ This means price $\pi(t)$ gives **budget balance** for system operator (i.e. revenue adequacy).
- ▶ Price $\pi(t)$ defines a perfectly competitive equilibrium for stage t , so **agents recover costs**.
- ▶ Does dispatch problem $ADR(t)$ yield **social optimum**?
- ▶ If all agents and system operator **agree on probability distribution of future demand** then ADRs can recover social optimum.

But agents have different probability distributions?

An **ADR partial equilibrium** occurs when the stochastic process of energy prices assumed by each agent in building their ADR yields the same prices in market clearing. In a scenario tree \mathcal{T} with the same outcomes but different \mathbb{P}_a for each agent $a \in \mathcal{G} \cup \mathcal{B}$:

1. for each $n \in \mathcal{T}$, $x^*(n)$ solves the stage dispatch problem with prices $\pi^*(n)$;
2. for each $n \in \mathcal{T}$ and $a \in \mathcal{G} \cup \mathcal{B}$, $x_a^*(n)$ solves

$$\max_{x_a \in \mathcal{X}_a(x^*(n-))} \{ \pi^*(n)^\top x_a - c_a^n(x_a) + W_a^n(x_a) \};$$

3. for each $n \in \mathcal{T}$ that is not a leaf node and $a \in \mathcal{G} \cup \mathcal{B}$,

$$W_a^n(x_a^*(n)) = \sum_{m \in n^+} \mathbb{P}_a(m | n) \{ \pi^*(m)^\top x_a^*(m) - c_a^n(x_a^*(m)) + W_a^m(x_a^*(m)) \}.$$

Example: one battery, one ramping generator

$x(t)$ = dispatch of generator in period t ;

\bar{x} = dispatch of generator in period $t - 1$;

$y(t)$ = storage in battery at end of period t ;

\bar{y} = storage in battery at end of period $t - 1$;

u = discharge from battery in period t ;

v = charge input to battery in period t ;

$$\mathcal{X}(\bar{x}) = \{x \mid 0 \leq x \leq q, x - \bar{x} \leq \rho, \bar{x} - x \leq \sigma\},$$

$$\mathcal{Y}(\bar{y}) = \{(y, u, v) \mid 0 \leq y \leq E, 0 \leq u \leq r, 0 \leq v \leq s, \\ y = \bar{y} - u + \eta v\}.$$

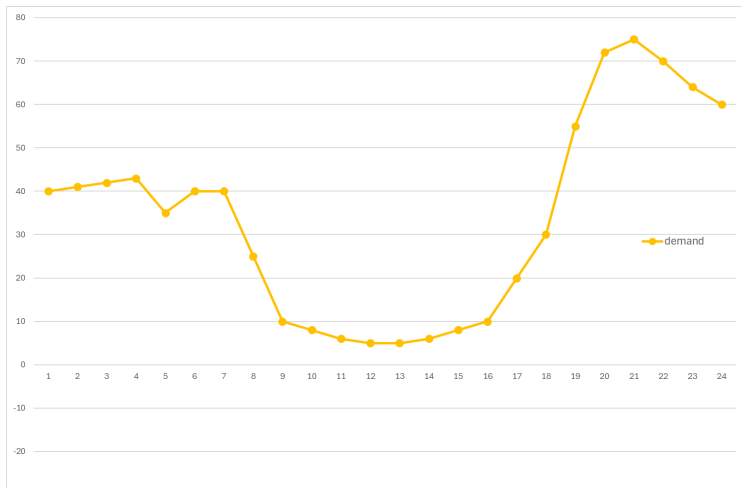
An example: one battery, one ramping generator

Assume $T = 24$, $c(x) = 70.0x$, $\sigma = \infty$. Other parameters are as follows.

$q = 70.0$	$E = 30.0$	$\eta = 0.8$
$r = 10.0$	$s = 10.0$	$\rho = 10.0$
$L = 500.0$	$x^0 = 35.0$	$y^0 = 4.0$

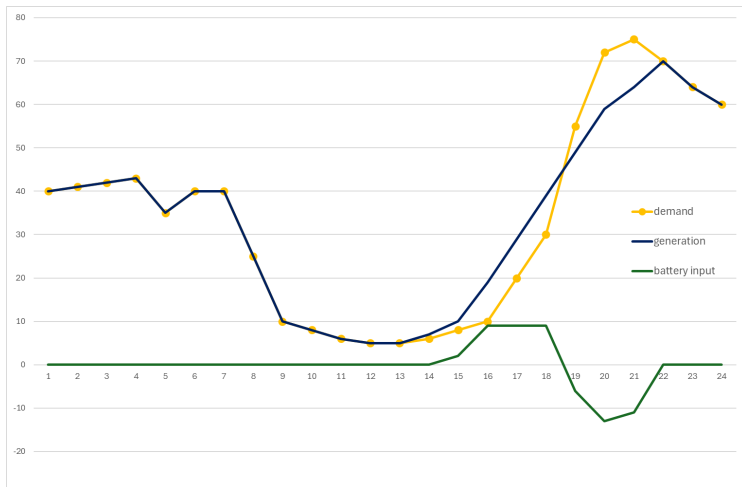
Parameter values for example

Example demand



Example values of $d(t)$ for $t = 1, 2, \dots, 24$. We add stagewise independent random noise chosen from $-4.0, -2.0, 0.0, 2.0, 4.0$ with equal probability

Deterministic solution



Zero-noise solution showing generation x superimposed on demand, and battery net input $v - u$ for $t = 1, 2, \dots, 24$.

SDP versus ADR with noise

- ▶ Solve SDP with independent noise. Expected cost = \$52,377, and optimal value function $V^t(x, y)$, $t = 1, \dots, 24$.
- ▶ Let $(\tilde{x}^t, \tilde{y}^t)$ denote average values of generation and average values of battery storage at each stage.

- ▶ ADR(t) uses separable approximation of the system Bellman function:

$$V^t(x, \tilde{y}^t) + V^t(\tilde{x}^t, y).$$

- ▶ Simulated ADR policy gives \$54,255 \pm 57. Some social optimality is lost since $(\tilde{x}^t, \tilde{y}^t) \neq (x^*(t), y^*(t))$ (varying with each sample path).

Conclusions

- ▶ In a perfectly competitive, convex, complete market where all agents share the **same probability distribution**, there is a set of ADRs for each agent that maximizes expected welfare.
- ▶ Agents with **different probability distributions** put their money where their mouths are.
- ▶ System operator does not influence future prices through their imperfect forecasts of demand - this falls on aggregating agents' views.
- ▶ Changes required to single-period SPD are relatively simple, but form of offer data is more complicated.

The End

Any questions?

a.philpott@auckland.ac.nz

For the paper go to <https://www.epoc.org.nz/papers/ADRPaperForEPOC.pdf>