Optimal dispatch and pricing for battery energy storage systems

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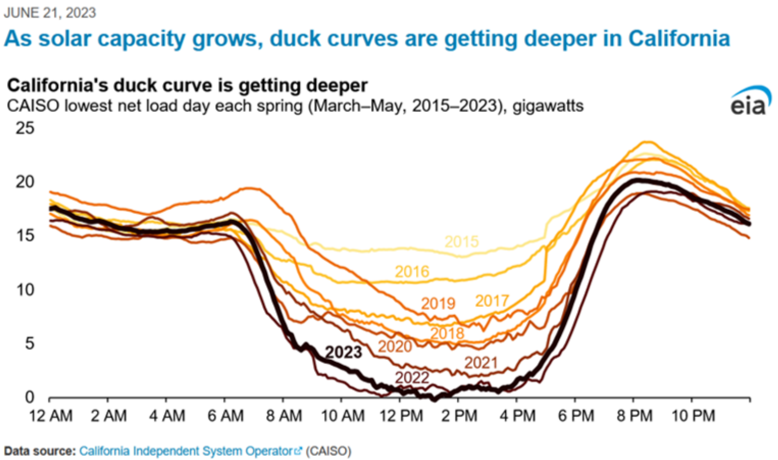
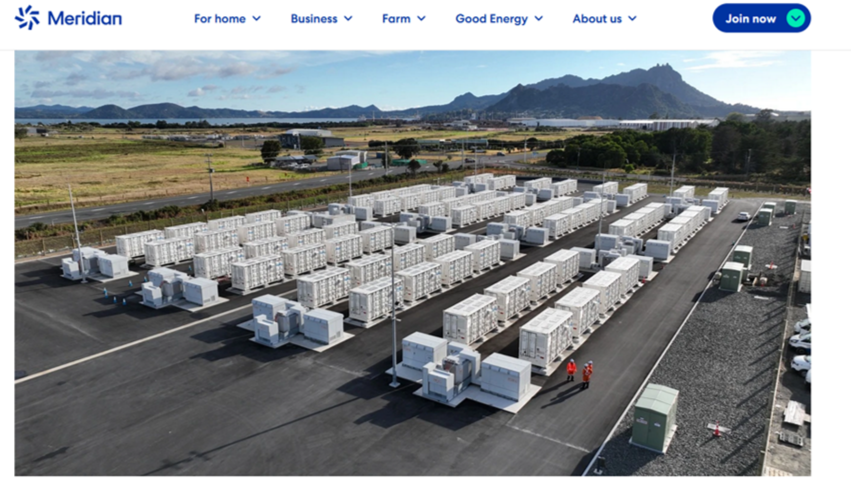


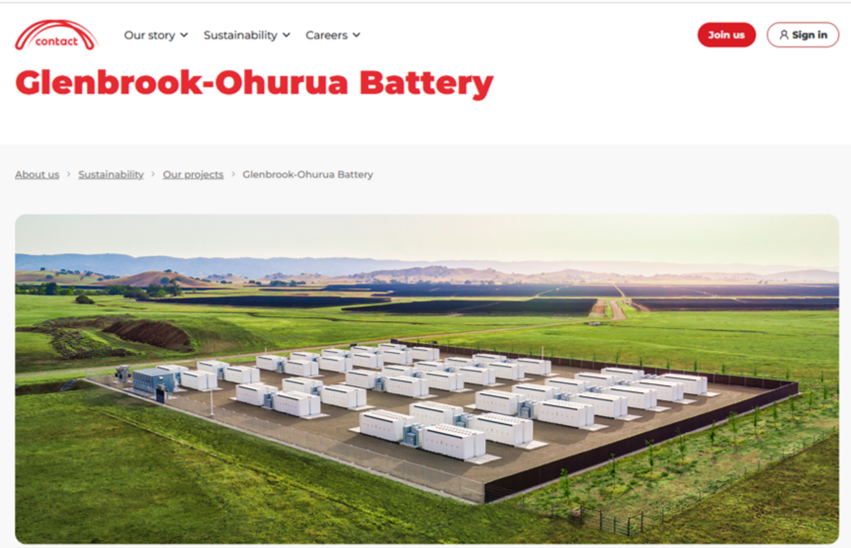
CAISO Duck curves [California Independent System Operator]

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]



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

Self dispatch versus central dispatch

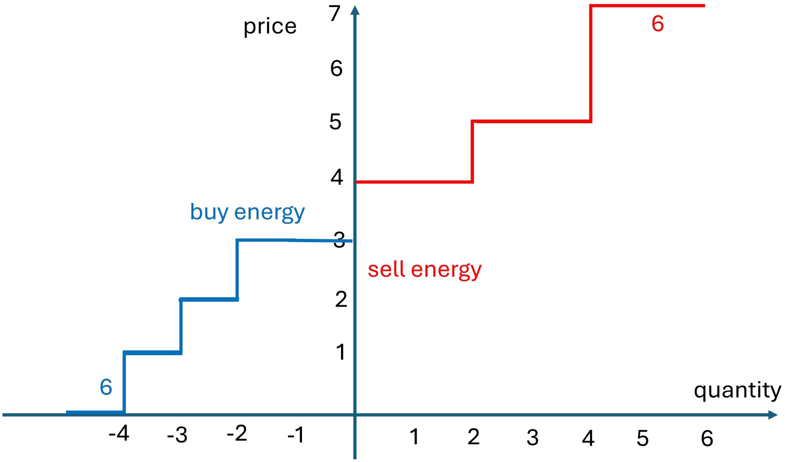
Self dispatch

- 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

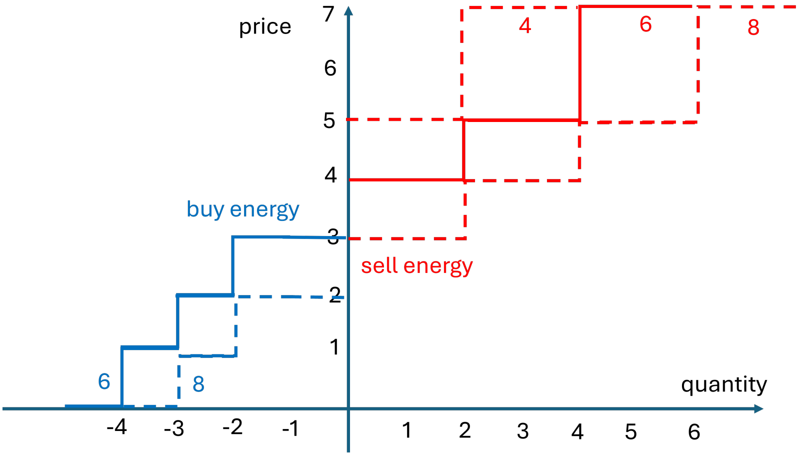
- Battery provides supply/demand curve defining what battery will sell/buy as price increases.
- System operator optimizes dispatch problem including endogenous battery operation.

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.

BESS central dispatch in New Zealand

- In NZ the system operator solves a dispatch problem every five minutes.
- Gate closure: Generators and BESS operators have offer curves for each five minute period, but cannot change offer curves within one hour of real time.
- Locational marginal energy prices are published in real time and affect the dispatch of plant and BESS.
- However, the settlement price of energy is the average of the six five-minute prices in each half hour.
- BESS operators are not paid the true value of arbitraging five minute prices.

Five minute gate closure?

- BESS operators currently lobbying for five minute gate closure and settlement.
- System operator needs offers locked in to stress test security of grid between each (security constrained) dispatch.
- Proposed compromise: maintain gate closure but enable state-dependent offers also known as agent decision rules.

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:

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

Single-node electricity dispatch with ABFs

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

$$
\begin{aligned}
\text{ADR}(t)\text{: min} \quad & \sum_{a\in\mathcal{G}} c_a x_a(t) + Lz(t) - \sum_{a\in\mathcal{B}} W_a^t(y_a) \\
\text{s.t.} \quad & \sum_{a\in\mathcal{G}} x_a(t) + \sum_{a\in\mathcal{B}} u_a(t) - \sum_{a\in\mathcal{B}} v_a(t) + z(t) = d(t), \quad [\pi(t)] \\
& x_a(t) \in \mathcal{X}_a(x_a(t-1)), \quad a \in \mathcal{G}, \\
& (y_a(t), u_a(t), v_a(t)) \in \mathcal{Y}_a(y_a(t-1)), \quad a \in \mathcal{B}, \\
& z(t) \in [0, d(t)].
\end{aligned}
$$

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 ADR(t) and computes dispatch and system marginal price $\$\pi(t)/$MWh.
- Generator is paid $\pi(t)$ per MWh
- Battery is paid $\pi(t)$(charge - 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?

What can go wrong?

- In ADR(t), dispatch $x_a^*(m)$ will vary with $\pi^*(m)$.
- But BESS offer in market is an increasing function of $\pi^*(m)$.
- BESS offers use an ABF $W_a^t(y)$ that depends on the state of charge y at the end of period.
- $W_a(y)$ depends on agent's beliefs of future prices.
- If agent believes future prices are conditioned on current price π^* then $W_a^t(y)$ should be $W_a^t(y, \pi^*)$.
- We want $x_a^*(n)$ to solve

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

- $x_a^*(n)$ can be decreasing in $\pi^*(n)$.

Social optimality

- Can ADR offers give a socially optimal solution?
- Assume:
  - All agents and SO have the same probability distribution of future events;
  - Each agent knows all system parameters including marginal costs of other agents;
  - Each agent can compute the social future cost function C^t.
  - $-\partial C^t = \Pi_{a \in \mathcal{G} \cup \mathcal{B}} \partial W_a^t$, i.e., $-C^t$ is gradient separable by agent.
- If agent a uses ABF W_a with $\frac{\partial W_a}{\partial y_a} = -\frac{\partial C^t}{\partial y_a}$ then this gives the same solution as social optimum.
- The optimal agent generation might not be increasing in price.

Restrictions to ensure monotonicity for dispatch problem

- Can we iron optimal offers to make them nondecreasing?
- Yes, but ...
- ... a dispatch problem with

$$C^t(x, \pi) = - \sum_{a \in \mathcal{G} \cup \mathcal{B}} W_a(x_a, \pi)$$

  where π is the system marginal price is not convex, and can yield multiple dispatch solutions.
- So instead we restrict the form of ADRs to only allow agent Bellman functions that preclude decreasing offers.
- Example: ABFs that depend only on x_a.
- Restrictions sacrifice some social optimality.

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;

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

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

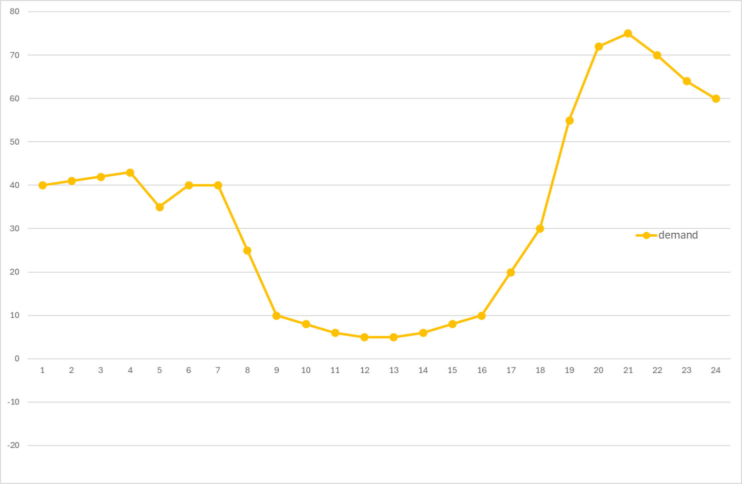
An example: one battery, one ramping generator

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

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

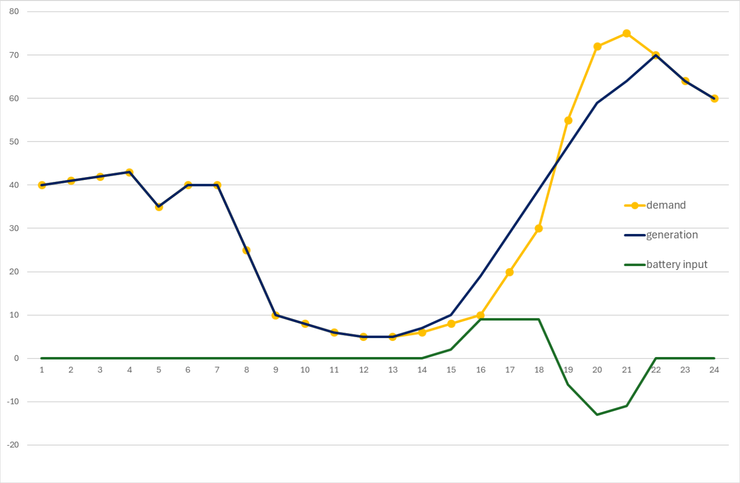
Parameter values for example

Example demand



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

Deterministic solution



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

SDP versus ADR with noise

- Solve SDP with independent noise. Expected cost =\$52,377, and optimal future cost function $C^t(x, y), t = 1, \ldots, 24$.
- Let $(\tilde{x}^t, \tilde{y}^t)$ denote values of generation and values of battery storage at each stage of zero-noise solution.
- Suppose ABF is a separable approximation of C^t:

$$W_a^t(x) = -C^t(x, \tilde{y}^t), \quad a \in \mathcal{G};$$

$$W_a^t(y) = -C^t(\tilde{x}^t, y), \quad a \in \mathcal{B}.$$

- Simulated policy gives \$52,688 $\pm$ 55. Some social optimality is lost since $(\tilde{x}^t, \tilde{y}^t) \neq (x^*(t), y^*(t))$ (varying with each sample path).

Conclusions

- Under restrictive assumptions there is a set of ADRs for each agent that maximizes expected welfare.
- In practice, social optimality is compromised by lack of gradient separability, lack of information, or decreasing generation with price.
- ADRs can encompass different beliefs.
- System operator does not influence future prices through imperfect forecasts of demand - this falls on aggregating agents' beliefs through ADRs.
- Changes required to update dispatch software are relatively simple, but offer data must be constrained to ensure convexity.

The End

Any questions?

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