Battery Operations in Electricity Markets: Strategic Behavior and Distortions

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Motivation

Batteries have grown a lot recently, complementing intermittent renewables.

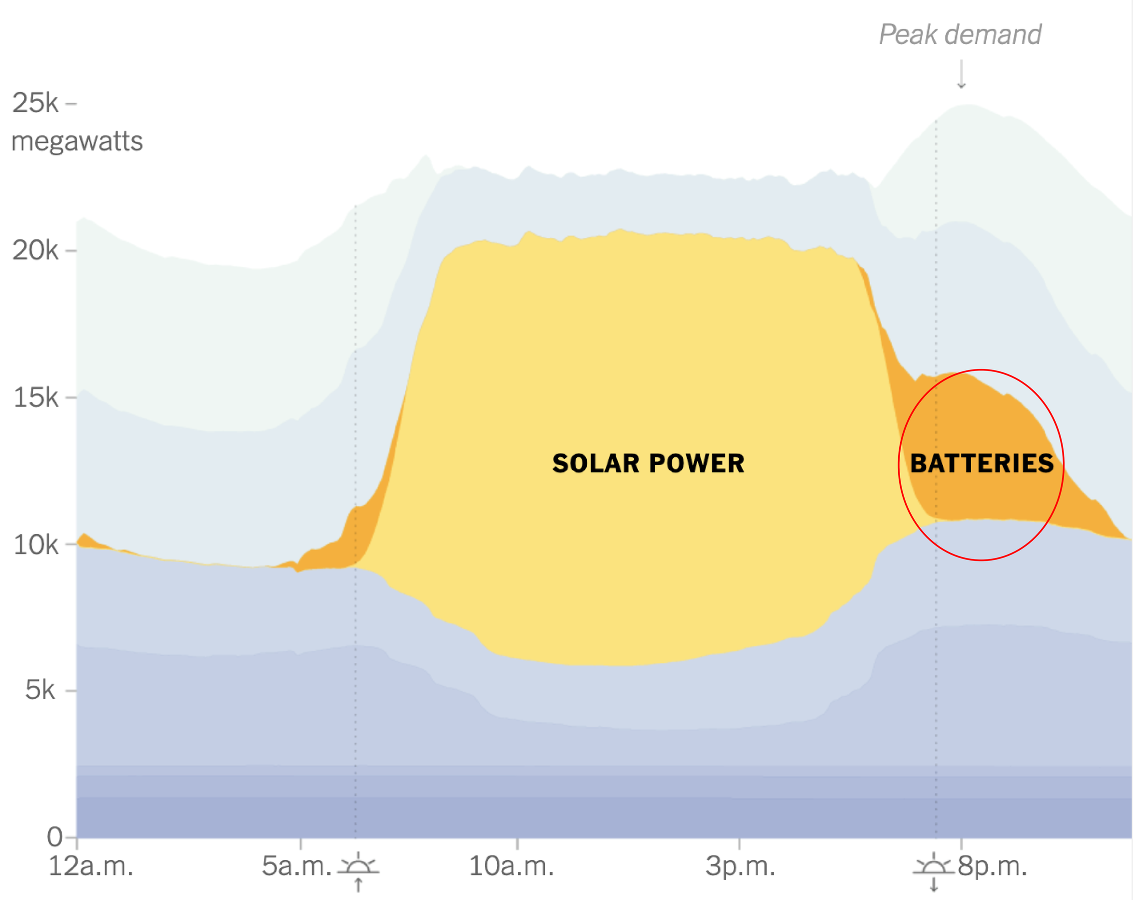
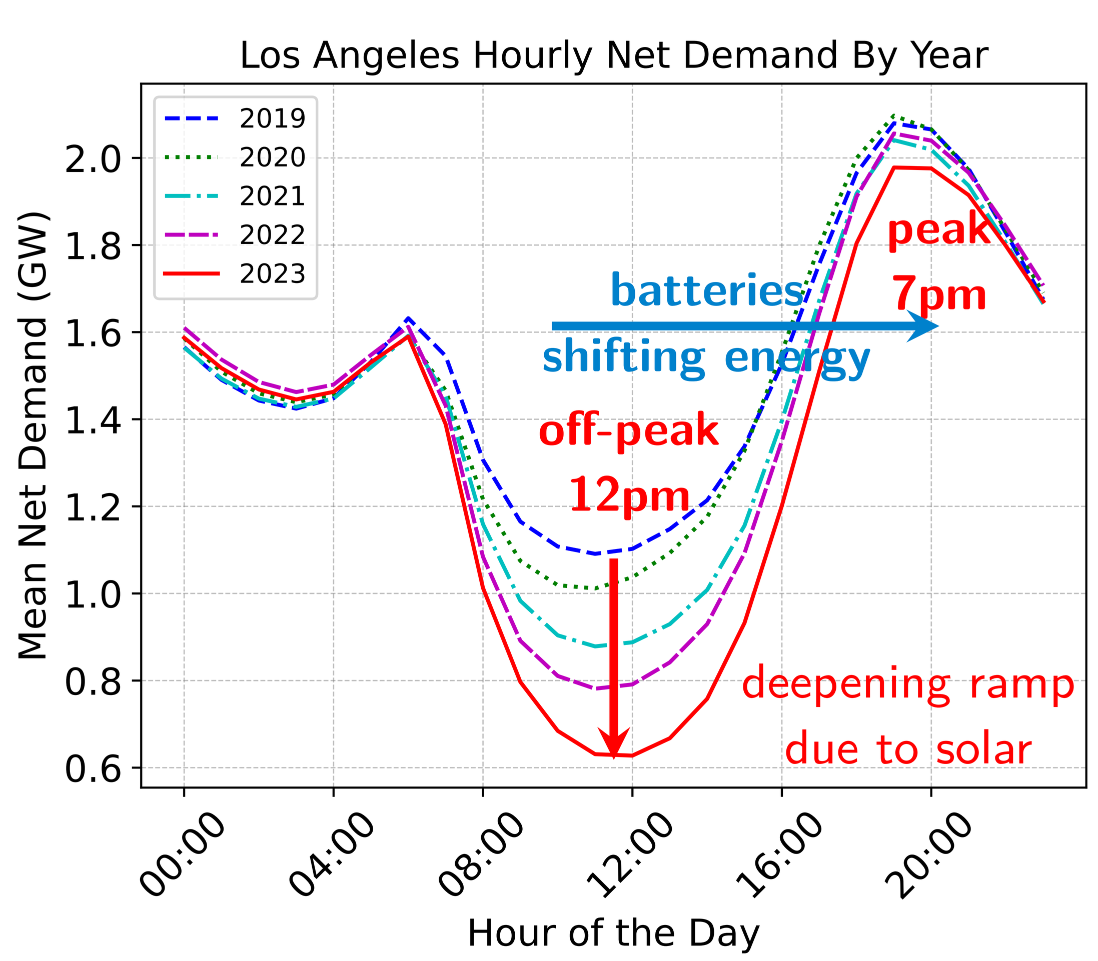


Figure: California's battery growth, 2021–2024

Batteries shave the peak of net demand (ramping fast conventional generators).

$$\text{net demand} = \underbrace{\text{system demand}}_{\text{(constant)}} - \underbrace{\text{renewables}}_{\text{(increasing)}}$$



Research Questions

Big batteries are no longer price takers, so

How do batteries operate in electricity markets?

How does the strategic behavior of decentralized batteries distort decisions compared to centralized batteries?

Electricity markets are highly complex. Our contribution: we propose and analyze a **tractable analytical model** = economic intuition + rich enough

Three Operating Regimes

(1) **No Battery** (NB): status quo benchmark
(2) **Centralized** (CN): min generation cost
(3) **Decentralized** (DCN): max battery profit

Two-Stage Market Clearing

T periods ($\approx$ 24 hrs in DA, 24 hrs in RT)

Day-Ahead Market (DA)
based on forecast $\mathbb{E}[D_t]$

- (1) forward market reduces uncertainty
- (2) some generators slow to start/ramp

Real-Time Market (RT)
based on realized demand D_t

- demand must equal supply at all times

Battery Decisions

A battery decides discharges z's for each time period $t = 1, \ldots, T$ in DA and RT:

- z_t^{DA} (scalars) in DA
- $z_t^{RT}(\cdot)$ (policies, depending on realized demand history) in RT

Discharge ($z > 0$) or charge ($z < 0$).

Constraints: net discharge is zero. $\Sigma_t z_t^{DA} = \Sigma_t z_t^{RT} = 0$.

Price Formation Process

Let p^{DA} = DA price, p^{RT} = RT price.

Two types of conventional generators:

"slow" (DA only, e.g. coal & nuclear)
"fast" (DA + RT, e.g. gas)

Let the cost CDFs be $G_s(p)$ and $G_f(p)$.
Let $k_f \equiv$ share of fast generators.

$$G_s(p_t^{DA}) + G_f(p_t^{DA}) = \mathbb{E}[D_t] - z_t^{DA} \quad \text{(DA)}$$
$$G_s(p_t^{DA}) + G_f(p_t^{RT}) = D_t - z_t^{DA} - z_t^{RT} \quad \text{(RT)}$$

RHS = net demand − battery discharge.

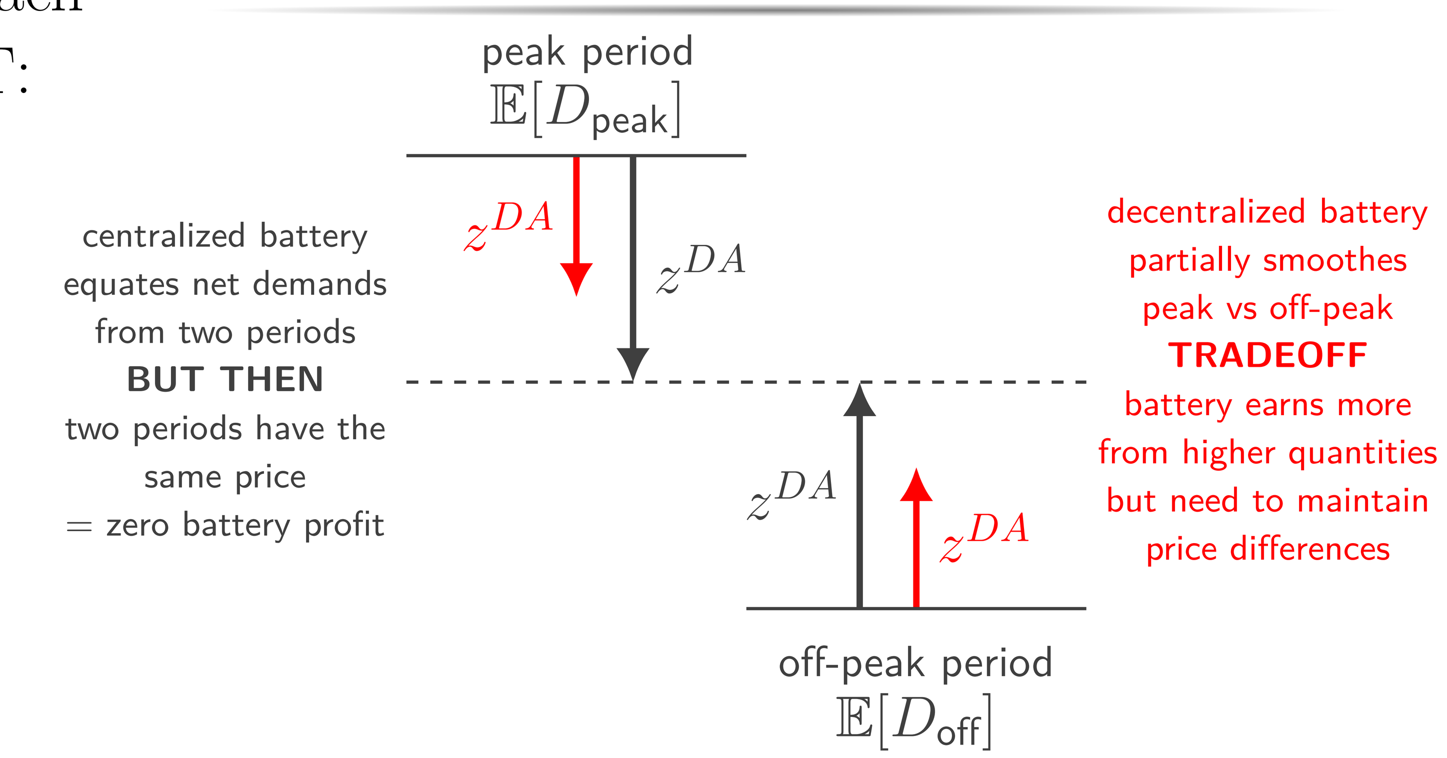
Results: Battery Behavior

CN and DCN = **convex** + **closed-form**.
3 types of DCN distortions from CN:

(1) **quantity withholding**
(2) **shift from day-ahead to real-time**
(3) **reduction in RT responsiveness**

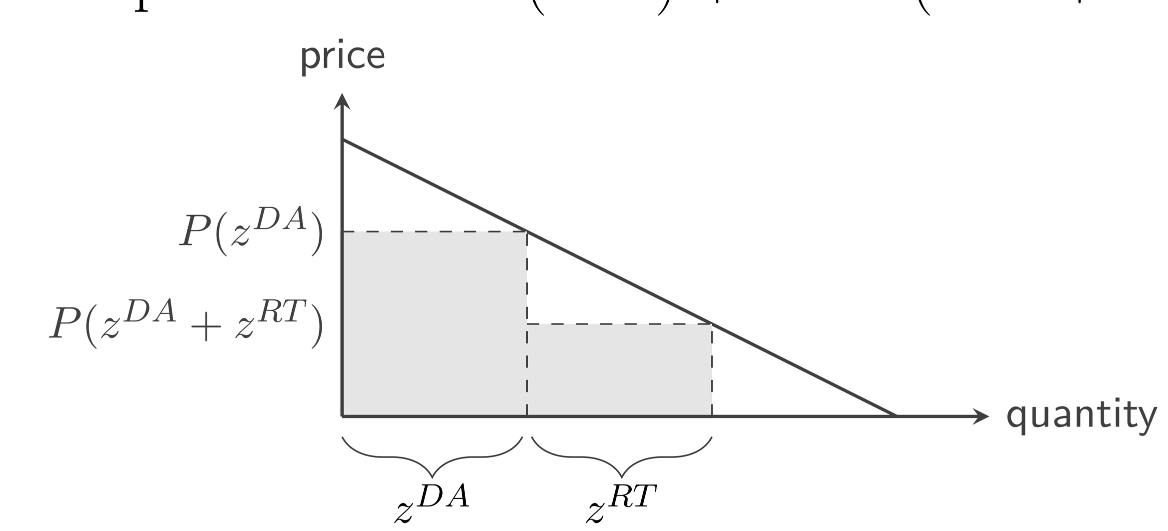
We quantify each as a function of k_f.

Distortions 1 & 3: Quantity Withholding in DA and RT



Distortion 2: Shift DA to RT

$$\text{Max profit} = z^{DA}P(z^{DA}) + z^{RT}P(z^{DA} + z^{RT}).$$



Results: Generation Cost

Define the Price of Anarchy (PoA) as an incentive misalignment metric:

$$\text{PoA} = \frac{\text{Cost(NB)} - \text{Cost(CN)}}{\text{Cost(NB)} - \text{Cost(DCN)}}$$

PoA ≥ 1. Lower PoA = better alignment.

Theorem. PoA $\in [9/8, 4/3]$ for every market parameter, decreasing in k_f.

Calibration: Los Angeles, Houston.
PoA and all 3 distortion types significant!