Public Benefits of Energy Storage

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Motivation: Batteries

- Global energy storage market is expected to grow to \$2.5B/yr by 2020
- CA: mandate for 1.3GW by 2020
- PG&E: 567MW storage projects to replace 3 gas peaker plants.
- Capital cost: $\sim$ \$6M/MW
- Private profits from intra-day electricity price arbitrage, but are there **public benefits**?

Motivation

- Engineering literature examines private net revenues (Sioshansi et al., 2009; Bradbury et al., 2014), mostly using simulations.
- Carson and Novan (2013); Hittinger and Azevedo (2015) examine net emissions effects, but do not examine price effects.

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  Relative to private total cost?

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  Public spillovers ⇒ policy justification

Roadmap

How does storage provide a public benefit?

- **Price effects**:
  First empirical estimates
  Main focus of paper

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- Environmental Benefits
  - When charging (discharging), some generator on grid increases (decreases) output
  - Net change in externalized damages

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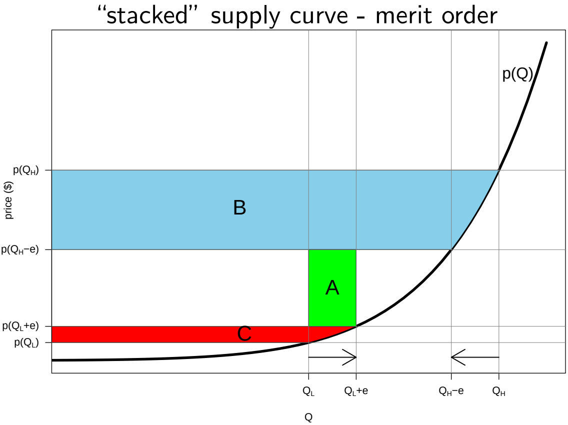
- Environmental Benefits
  - When charging (discharging), some generator on grid increases (decreases) output
  - Net change in externalized damages
- Market power
  - If congestion induces locational market power, storage may decrease distortion

Public Benefits

Price Effects

Public Benefits - A model of wholesale electricity prices



- p(Q): inverse supply

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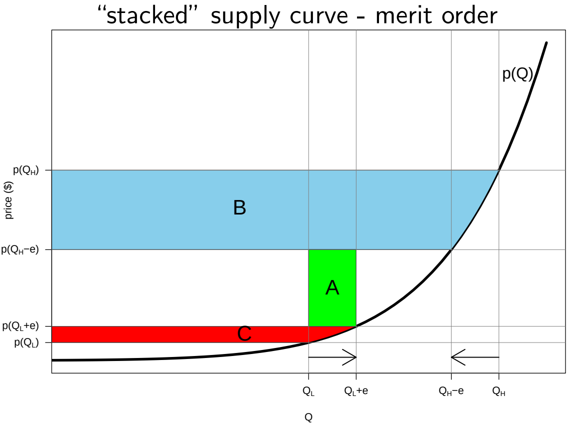

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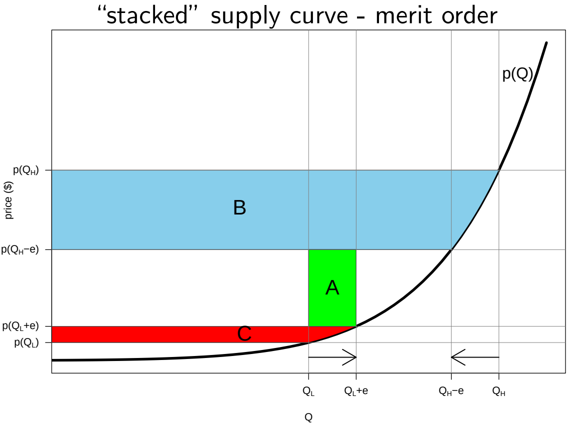

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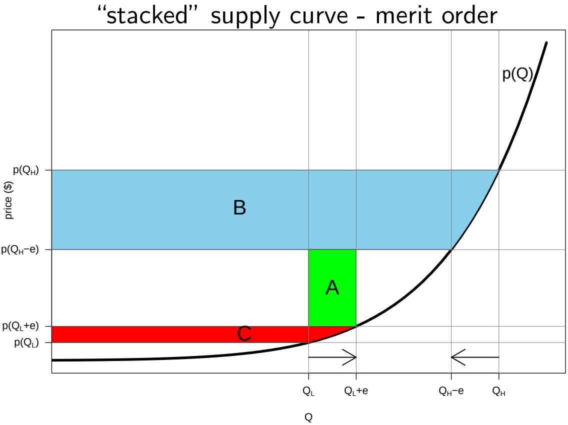

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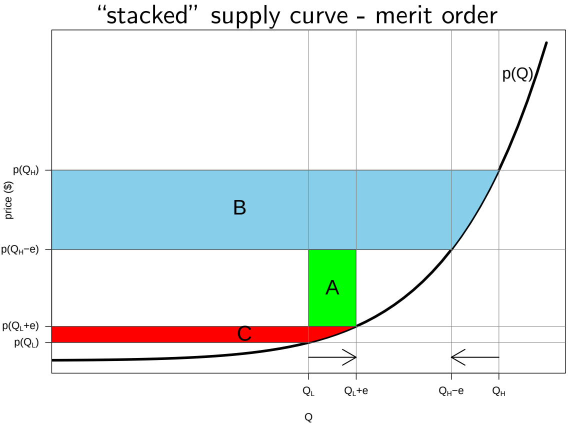

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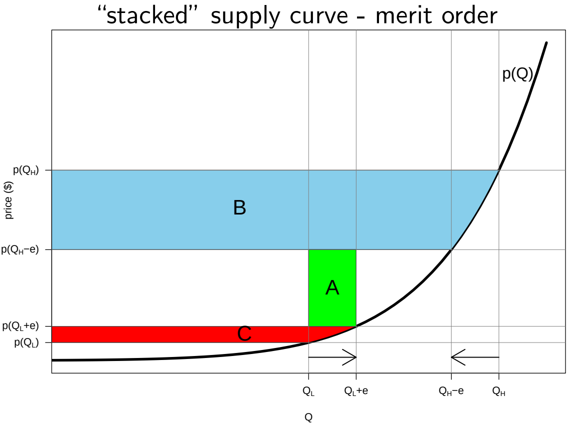

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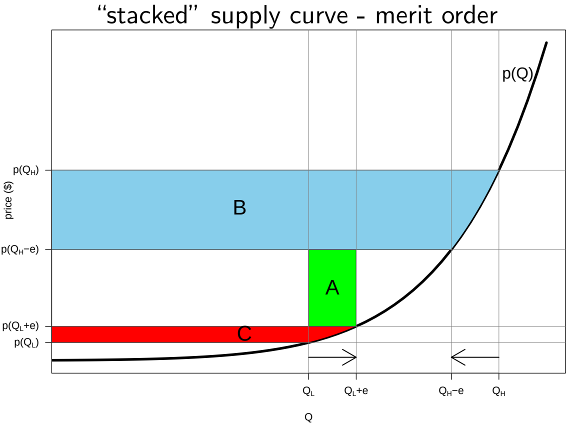

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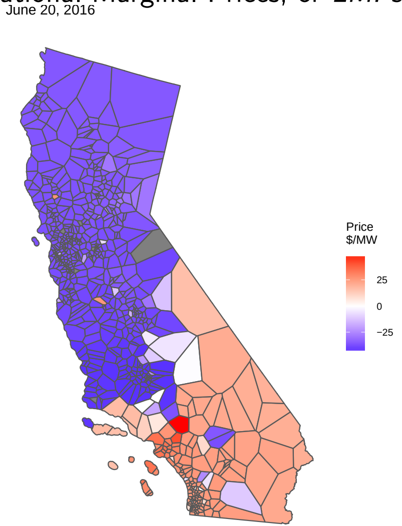
- A is the private profit

Spatial wholesale electricity prices

Locational Marginal Prices, or *LMPs*, usually written λ_n



- Each polygon is a “node“
- Congestion occurs when line limits require using an expensive generator
- Price effect @ each node
- Inverse supply curve *steepens* as congestion fragments the market

Spatial wholesale electricity prices

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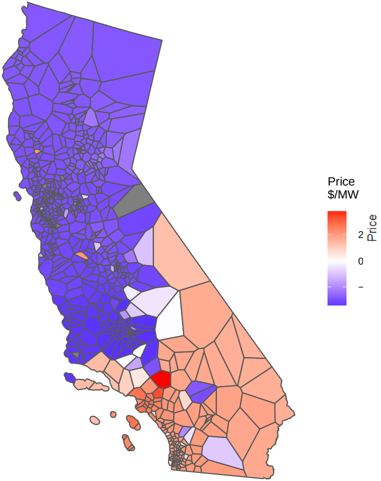
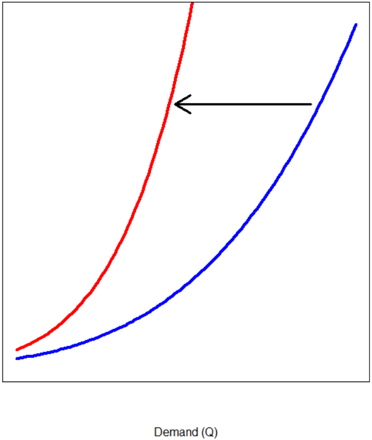




Data

California ISO

Hourly LMP, 2009-2016, λ

- $N = 771$ clusters
- $N \times T = 34.82$M
- Spatial data scraped from ISO interface

Hourly demand for each utility

Load Dist'n Factors (LDF) for each node

DoE Global Storage

MW, MWh, use, and Commission Date of Energy Storage

Coordinates of project location

PRISM Climate (Oregon State)

Local temp max, min, precipitation (daily)

Data

NREL - National Solar Radiation Database

Hourly index of grid-scale solar produced

Other

Henry Hub natural gas prices & Aliso Canyon gas storage blowout

FERC form 714: hourly plant-level natural gas generation

EPA eGrid: natural gas generator locations

Model 1: Own-node effects

Estimate $\frac{d\lambda_n}{dES_n}$, hourly nodal price change from ES.

$$log(\lambda_{nt}) = \beta_1 log(\lambda^{LAP}_{t,u(n)}) + \sum_{s=1}^{4}\sum_{h=1}^{24} \overbrace{\beta_{hs} ES_{nt} \times HR_t \times SEASON_t}^{\text{coef. of interest}} +$$
$$\sum_{n=1}^{N}\sum_{y=2009}^{2017}\sum_{s=1}^{4}\sum_{h=1}^{24} \delta_{nhsy} \times NODE_n \times YEAR_t \times SEASON_t \times HR_t + \varepsilon_{nt}$$

ES_{nt}: MW storage on node n, time t

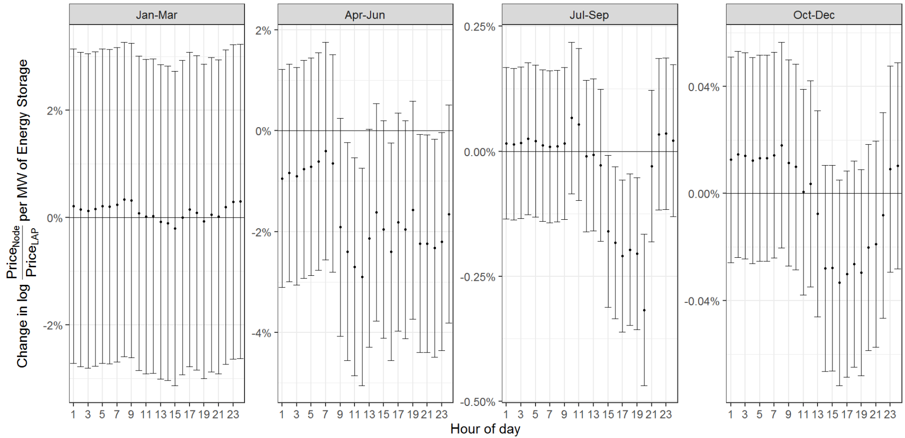
HR: Hour of day

SEASON: Season of sample

YEAR: Year of sample

$\lambda^{LAP}_{t,u(n)}$: Aggregate utility nodal price

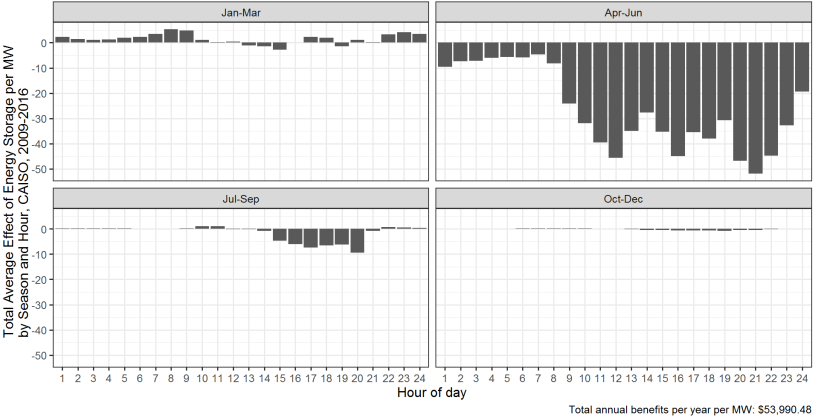
Model 1: Own-node effects results



Node-year-season-hour FE
controlling for temp deviation, solar generation, price NatGas, Aliso Canyon

Model 1: Own-node effects results

$$\sum_{n,2017} (\lambda_{n,t} \times Load_{n,t} \times \beta_{h,s} \times ES_{n,t})$$



$53,990, 7% discount rate, 10 years ⇒ NPV of $379,206 per MW

Model 2: Cross-node effects with LASSO (Manresa, 2016)

- Goal is to estimate treatment effects when the underlying network topology is unknown.
- Draws heavily on 2014-2017 series of papers on treatment effects in high-dimensional data by Belloni, Chernozhukov, Hansen, et al.

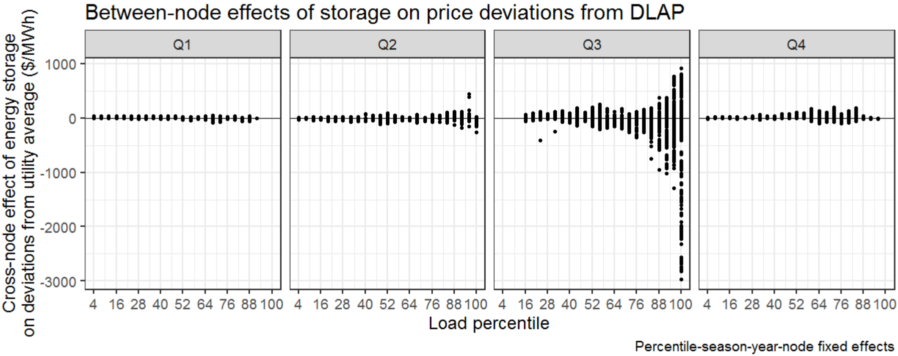
Would like to estimate:

$$\lambda_{nt} - \lambda^{LAP}_{t,u(t)} = \sum_{s=1}^{4} \sum_{b=1}^{25} \beta_{bs} ES_t \times BIN_t \times SEASON_t + \beta_p w_{nt} + \underbrace{\sum_{i \neq n}^{N_{ES}} \gamma_{nibs} ES_{it}}_{\text{LASSO}} + \delta_{nbsy} + \varepsilon_{nt}$$

Where γ is high-dimensional and w_{nt} is: node deviation from mean temp, Aliso Canyon, solar generation, rainfall, and 12-month cumulative rainfall (hydro).

Model 2: Cross-node effects with LASSO - Results

Each plotted point is a non-zero coefficient selected by LASSO.



$32,320, 7% discount rate, 10 years ⇒ NPV of $227,002 Very preliminary

Public Benefits

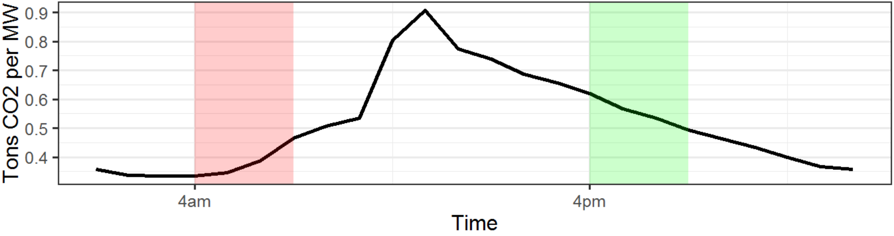
Environmental Benefits

Environmental Benefits

Using Sexton, Kirkpatrick, Harris and Muller (2017):

- Estimate plant response by hour, month (Holland and Mansur, 2008; Holland et al., 2015)
- Value emissions w/AP3 (Muller, 2018)
- Sum over all storage charges and discharges

Example: July 3, CAISO marginal responding plant CO_2 emissions



Shaded areas indicate storage charge (red) and discharge (green)

- ▶ Total environmental benefits: $6,587 per MW per year

Public Benefits

Market Power

Market Power

When congestion "islands" a generator, may behave as a monopolist due to imperfectly competitive markets

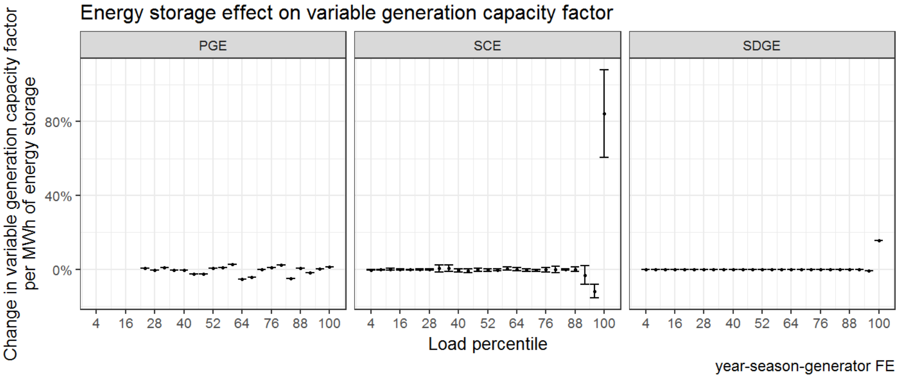
- Under congestion, electricity cannot flow to high-priced areas
- No price discrimination - to compete at other nodes, must lower price on island; trade-off between selling to region and extracting monopoly rents (Bushnell and Wolak, 2000).

⇒ Test for *increase* in generator output when storage is added near a node.

Market Power Results

Regress using only nodes with natural gas generators, g

$$CapacityFactor_{gt} = \beta_0 + \sum_{bin} \beta_{bin} ES_{nt} \times BIN_t + \delta_{gsy} + \varepsilon_{gt}$$



Natural gas generators are observed to *increase* output during the peak load periods, which suggests some degree of market power was previously present.

Sum of results

Battery capital cost: \$6M per MW (Penna et al., 2016) as of 2016

Public Benefit	Per MW/year	NPV 7%, 10 years
Price effect		
Own-node	\$53,990	\$379, 206
Cross-node	\$32,320	\$227,002
Environmental Benefit	\$6,587	\$46,264
Market Power	+	+
Sum	\$92,897	\$652,473

Thanks!

Questions? Comments?

Kirchoff's Law

Gustav Kirchoff
(Wikimedia Commons)

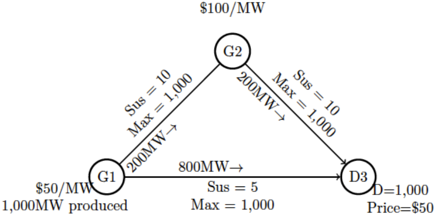
Electricity flows by *line suseptance*

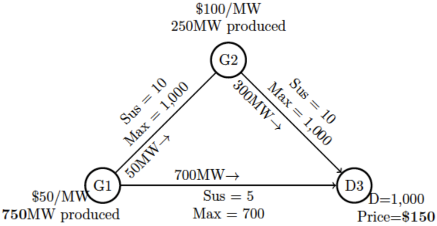
Given suseptance on lines ***E***

and injections ***G***

and withdrawals ***D***, then...

⇒ Flows are fully determined by





Locational Marginal Prices

$$\begin{aligned} LMP_n = \lambda_n^{tot} &= \lambda + \lambda_n^c \\ &= \lambda + \sum_{e=1}^{E} \kappa_{en} \mu_e \end{aligned}$$

where $\kappa_{.n}$ is the *n*th column of the constant shift factor matrix, which is wholly determined by line suseptance and network topology. Of particular interest is the vector of price effects:

$$\begin{aligned} \frac{d\boldsymbol{LMP}}{dQ_n} &= \mathbf{1}\frac{d\lambda}{dQn} + \frac{d\boldsymbol{\lambda^c}(\boldsymbol{Q})}{dQ_n} \quad \text{where } \boldsymbol{Q} = \boldsymbol{G} - \boldsymbol{D} \\ &= \mathbf{1}\frac{d\lambda}{dQn} + \boldsymbol{\kappa}' \left(\frac{d\boldsymbol{\mu}(\boldsymbol{Q})}{dQ_n} \right) \\ &= \mathbf{1}\frac{d\lambda}{dQn} + \left[\sum_{e=1}^{E} \frac{d\mu_e(\boldsymbol{Q})}{dQ_n} \kappa'_{1e}, \sum_{e=1}^{E} \frac{d\mu_e(\boldsymbol{Q})}{dQ_n} \kappa'_{2e}, \ldots, \sum_{e=1}^{E} \frac{d\mu_e(\boldsymbol{Q})}{dQ_n} \kappa'_{Ne} \right]' \end{aligned}$$

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