How Storage Will Transform Electric Power Emissions and Markets

Roger Lueken & Jay Apt
The Problem

• Current electric power systems lack storage
  \[\text{at all times, Generation} = \text{Load}\]

• Market inefficiency

• Recent advances may make bulk storage possible
Research Question

How will bulk storage affect power systems?
- Storage changes market behavior
- Storage only used for arbitrage (reg market small)

4 perspectives:
1. Consumers
2. Generators
3. Storage operators
4. Emissions – CO2, NOx, and SO2

Technique: Simulate 2010 PJM Interconnection energy market with and without storage.
Effect of transmission constraints

PJM eData System:
https://edata.pjm.com/eContour
PJM reduced-form topology
Unit commitment

- Used by PJM system operator
- **Technique:** Mixed integer linear optimization

\[
\text{Minimize} \sum_{t} \sum_{g} \text{VariableCost} \times P_{gen} + \text{StartupCost}
\]

Subject to
- \(\text{Load} = \text{generation } + \text{ imports (for each region)}\)
- Transmission constraints
- Generator minimum & maximum generation
- Generator ramp rates
- Generator minimum runtime & downtime
Storage technologies

- Pumped storage
- Compressed air (CAES)
- Advanced batteries
  - Lead-acid
  - Sodium-sulfur
Storage modeling

• Modeled parametrically:
  – Capacity (MW)
  – Duration (hours)
  – Round-trip efficiency (RTE) (%)
  – Location (region 1 – 5)

• Updated optimization constraints:
  – Regional load = generation + imports + discharge – charge
  – \( \text{SOC}_t = \text{SOC}_{t-1} + \text{charge}_t \cdot \sqrt{\text{RTE}} - \frac{\text{discharge}_t}{\sqrt{\text{RTE}}} \)
  – \( 0 \leq \text{SOC} \leq \text{capacity} \times \text{duration} \)

• Vary capacity from 0.25% - 100% of peak annual load
  (0.3 – 137 GW)
RESULTS
Storage benefits consumers

- Consumer savings = Lower generator revenues

Diagram:
- Reduced electricity prices
- Storage Discharging
- Operational savings
- Peak annual demand
- Capacity savings

Graph showing cost per MWh versus GW.
Total consumer savings

<table>
<thead>
<tr>
<th>Technology</th>
<th>RTE</th>
<th>Duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lead acid</td>
<td>87.5%</td>
<td>4-hr</td>
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<tr>
<td>CAES</td>
<td>76.5%</td>
<td>20-hr</td>
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<tr>
<td>Pumped hydro</td>
<td>80%</td>
<td>8-hr</td>
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<tr>
<td>Sodium-sulfur</td>
<td>75%</td>
<td>6-hr</td>
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</table>

Savings ($Billions) vs. Storage capacity [GW]

Lead-acid - 87.5% RTE, 4-hr duration
CAES – 76.5% RTE, 20-hr duration
Pumped hydro - 80% RTE, 8-hr duration
Sodium-sulfur – 75% RTE, 6-hr duration
Net consumer savings

- Consumer benefits – storage cost
Sensitivity analysis

Savings [$Billions]

Storage capacity [GW]

100% RTE

70% RTE

Lead acid

8-hr duration

2-hr duration

Lead-acid (87.5% RTE, 4-hour duration)
Storage replaces peaking plants

- Similar for other technologies
- Total PJM capacity: 155 GW
- 2010/2011 capacity payment: $175/MW-day – savings reach $2B
Generator output & revenues

- Lead-acid, 37 GW

Percent Change

-100% -80% -60% -40% -20% 0% 20%

Generation
Revenue

Nuclear
Hydro
Coal Steam
Combined Cycle
Oil/Gas Steam
Combustion Turbine
Storage is unprofitable

- 8% blended cost of capital, 10% discount rate
Storage marginally increases emissions

<table>
<thead>
<tr>
<th>Storage Capacity [GW]</th>
<th>Emissions Increase (%)</th>
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<td>7</td>
<td>0.5%</td>
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<tr>
<td>34</td>
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<tr>
<td>136</td>
<td>1.3%</td>
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- Due to storage inefficiency & fuel switching
- Does not include startup emissions

Lead-acid (87.5% RTE, 4-hour duration)
How about other scenarios?

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Consumer savings [$Billions]</th>
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<tr>
<td>2010 (base case)</td>
<td>3.2</td>
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<tr>
<td>5x wind</td>
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<td>$100/ton CO2</td>
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<tr>
<td>2x 2010 gas price</td>
<td>6.4</td>
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</table>

Lead-acid (87.5% RTE, 4-hour duration), 13.6 GW
Policy Implications

• Pumped hydro & CAES provide net consumer benefits
• Advanced batteries do not
• No storage is profitable

• Market changes needed to encourage deployment
  – Updated market rules
  – Direct subsidies to storage operators
  – Storage operated by PJM
Work sponsored by Carnegie Electric Industry Center members

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Questions?
PHORUM model

• Plan to release as public, open source project
• Documented and streamlined code
• Useful for investigating effect of policies, new technologies, fuel price, etc
• Goal – users will continue to improve and expand model
• If interested, email me: rlueken@gmail.com
BACKUP
Validation

- BAU: 2010 day-ahead market without storage
- Compare computed LMPs to actual 2010 LMPs

<table>
<thead>
<tr>
<th></th>
<th>Region 1</th>
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Data

• Generator data
  – EPA databases (eGRID & NEEDS)
  – National Emissions Inventory (NEI)
  – Continuous Emission Monitoring System (CEMS)

• Hourly data (PJM databases)
  – Load
  – Transmission capacity
  – Wind generation
  – Imports / exports
## Technologies

<table>
<thead>
<tr>
<th>Technology</th>
<th>Duration (hours)</th>
<th>% RTE (total cycles)</th>
<th>Cost ($/kWh)</th>
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<tbody>
<tr>
<td>Pumped hydro</td>
<td>8</td>
<td>80% (&gt;13,000)</td>
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<td>CAES</td>
<td>20</td>
<td>76.5% (&gt;13,000)</td>
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<tr>
<td>Sodium-sulfur</td>
<td>6</td>
<td>75% (4,500)</td>
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<tr>
<td>Lead-acid</td>
<td>4</td>
<td>87.5% (4,500)</td>
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The PJM Interconnection

PJM Control Area Transmission Zones:
http://pjm.com/documents~/media/about-pjm/pjm-zones.ashx
## LMP Correlations within regions

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</table>
Operational savings

Savings [$Millions]

Storage capacity [GW]

Lead acid
Pumped hydro
CAES
Sodium-sulfur

Lead-acid - 87.5% RTE, 4-hr duration
CAES – 76.5% RTE, 20-hr duration
Can technology improvements help?

Change in consumer benefit from 10% change

- +10% RTE: 16%
- -10% capital cost: 12%
- +10% lifespan: 4%
- -10% duration: 0%

Lead-acid (87.5% RTE, 4-hour duration), 13.6 GW
Dispatch nonlinearities

- **Power Output**
- **MaxGen**
- **MinGen**
- **Off**

- **Startup**
- **Minimum Runtime**
- **Shutdown**
- **Time**
Day boundary problem

4 variables passed between days:
- Gen on/off state
- How long gen must stay on/off
- Power output
- Storage state of charge
Effect of considering utilization

<table>
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<tr>
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<tbody>
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<tr>
<td>Charge/discharge speed</td>
<td>-10% +10%</td>
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<tr>
<td>Max cycles</td>
<td>-10%</td>
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<tr>
<td>Capital Cost</td>
<td>+10% +10%</td>
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## Marginal Environmental Damages

<table>
<thead>
<tr>
<th>Storage Capacity [GW]</th>
<th>Emissions Increase (%)</th>
<th>Env. Damage Increase [$M] (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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Lead-acid (87.5% RTE, 4-hour duration)
Sensitivity Analysis

Energy savings [$Billions]

Storage capacity [GW]

- 100% RTE
- 2-hr duration
- 8-hr duration
- 70% RTE
Sensitivity Analysis

![Graph showing sensitivity analysis for capacity savings in billions versus storage capacity in GW. The graph includes lines for 8-hour duration, 100% RTE, 2-hour duration, and 70% RTE.]