Economics of Grid-Scale Energy Storage

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The Plan

1. Algorithm to Find Energy Storage’s Impact

2. Results for Southern Australia Electricity Market
Arbitrage of a Grid-Scale Battery

Private Return: If there is variance in prices, creates revenue

Change in Social Returns:

- **Pecuniary Externality**
  Transfer between consumer and producer surplus

- Change in Market Power of Incumbent Firms

- Efficiency of Production
  Change in cost of electricity production
  Change in CO$_2$ emissions
  Decrease in renewable curtailment (waste)
Arbitrage of a Grid-Scale Battery

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  Change in CO₂ emissions
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These changes are particularly significant if storage is large.
Research Question

Are incentives for investing and operating an energy storage in a wholesale electricity market **socially efficient**?
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Are incentives for investing and operating an energy storage in a wholesale electricity market socially efficient?

- Is investing on energy storage welfare improving?
- Do prices create socially efficient incentives to operate?
- How does energy storage change CO$_2$?
- How energy storage interacts with renewables?
- Who should own energy storage?
I build a **dynamic** equilibrium framework to quantify a **hypothetical** energy storage’s impact in a wholesale electricity market

- allow for storage’s **uncertainty**
- allow for **incumbent firms’ response**
- **endogenize** storage’s **price impact**
I build a dynamic equilibrium framework to quantify a hypothetical energy storage’s impact in a wholesale electricity market

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Two technical challenges

- Storage’s dynamic arbitrage problem
- Calculating new equilibrium prices (SFE)

Compute a SFE using estimated best responses to observed variation in demand volatility

Simulate a grid-scale energy storage in South Australia
Example: Hornsdale Power Reserve’s Arbitrage

Figure 1: Production of Hornsdale Power Reserve Electricity Prices for Two Days

A day with **stable** prices and a day with **volatile** prices
Imperfectly Competitive Markets: Market Power

Market power, $P^m(Q) > P^c(Q), \forall Q$

Arbitrage, Energy Storage shifts demand

Consumer surplus increases, price variation decreases
Observed variation of demand in data conditional on $X_k$
Storage smooths demand
Look for a similar observed variation of demand

Use firms strategies conditional on $X_m$ as a best response to storage
South Australia July 2016 – December 2017

- Firms use step functions for each 48 half-hour of the following day
- Wind generators make up 40% of the generation
- High price volatility
- Three firms make up 95% of the combustion generation
- The largest lithium-ion battery came online in 2018
South Australia July 2016 – December 2017

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- Wind generators make up 40% of the generation
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I use data on

- Forecast and realized demand and prices
- Unit level half-hourly bids
- Forecast and realized renewable generation
- Industry cost and emissions estimates
Road Map Results

- Storage’s Price Impact
- Storage’s Ownership Impact
- Renewables and Storage
A hypothetical monopoly storage with 120 MWh 30 MW capacities and 85% round-trip efficiency, 2%-10% of net demand in South Australia.

To disentangle the storage’s impact, I compare following cases:

- No Price Effect
- Storage’s Price Effect, No Firms’ Best Response
- New Equilibrium Prices
### Table 1: Yearly Returns Per 1 MWh Under Alternative Modeling Assumptions

<table>
<thead>
<tr>
<th></th>
<th>(1)</th>
<th>(2)</th>
<th>(3)</th>
<th>(4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Revenue (1000 AU$ per MWh)</td>
<td>46.66</td>
<td>23.31</td>
<td>12.38</td>
<td>11.18</td>
</tr>
<tr>
<td>Cost (1000 AU$ per MWh)</td>
<td>25.27</td>
<td>25.27</td>
<td>25.27</td>
<td>25.27</td>
</tr>
<tr>
<td>Profit (1000 AU$ per MWh)</td>
<td>21.39</td>
<td>-1.96</td>
<td>-12.89</td>
<td>-14.09</td>
</tr>
<tr>
<td>Production (MWh)</td>
<td>845</td>
<td>716</td>
<td>511</td>
<td>450</td>
</tr>
<tr>
<td>Δ CS (1000 AU$ per MWh)</td>
<td>-</td>
<td>-</td>
<td>24.56</td>
<td>27.08</td>
</tr>
</tbody>
</table>

**Model Assumptions**

- Price Uncertainty: ✕ ✓ ✓ ✓ ✓
- Price Effect: ✕ ✕ ✓ ✓ ✓
- Firms' Response: ✕ ✕ ✕ ✓ ✓

- Price Effect has significant impact on profit
- Allowing firms’ response affects profit
3 Ownership structures

– Monopoly Storage

– Load-Owned Storage

– Perfectly Competitive Storage Market
There is an **under-investment** and **under-utilization** problem
### Table 2: Storage's Private and Social Returns Under Different Ownerships

<table>
<thead>
<tr>
<th>Ownership</th>
<th>Storage's Δ in Market's Profit</th>
<th>Consumer Surplus</th>
<th>Cost</th>
<th>Production</th>
</tr>
</thead>
<tbody>
<tr>
<td>Monopoly</td>
<td>1.69</td>
<td>3.25</td>
<td>-1.54</td>
<td>54</td>
</tr>
<tr>
<td>Load-Owned</td>
<td>-2.44</td>
<td>5.45</td>
<td>-2.21</td>
<td>114</td>
</tr>
<tr>
<td>Competitive</td>
<td>-1.97</td>
<td>3.56</td>
<td>-1.77</td>
<td>84</td>
</tr>
</tbody>
</table>

There is an **under-investment** and **under-utilization** problem.

Two distortions in prices:

- Market Power of Monopoly Storage
- Others, e.g. Market Power of Incumbent Firms
Renewables and Storage

Table 3: Under Different Renewable Penetration Levels

<table>
<thead>
<tr>
<th>Per Year</th>
<th>Million AU$</th>
<th>Thousand Ton</th>
<th>Thousand MWH</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Storage's</td>
<td>Δ in Market's</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Revenue</td>
<td>Cost</td>
<td>Profit</td>
</tr>
<tr>
<td>Baseline</td>
<td>1.34</td>
<td>3.03</td>
<td>-1.69</td>
</tr>
<tr>
<td>Double Wind</td>
<td>2.75</td>
<td>3.03</td>
<td>-0.28</td>
</tr>
<tr>
<td>Double Solar</td>
<td>1.65</td>
<td>3.03</td>
<td>-1.38</td>
</tr>
</tbody>
</table>

Increase capacity of wind from 40% to 80% and solar from 10% to 20%

Energy storage hurts renewables when there is no curtailment
**Table 3: Under Different Renewable Penetration Levels**

| Storage's | Δ in Market's | Per Year | | | | | | | | | CO2 Impact | Effect on Other Incumbents |
|-----------|--------------|----------|----------|----------|----------|----------|----------|----------|----------|---------------|---------------------------|
|           |              | Million AU$ | Thousand Ton | Thousand MWH | Δ in CO₂ Emissions | Curtailment |
| Revenue   | Cost         | Profit     | Consumer Surplus | Wind Revenue | Solar PV Save |          |          |
| Baseline  | 1.34         | 3.03       | -1.69       | 3.25       | -1.54       | -1.70     | -0.44    | -3.12    | 0         |               |
| Double Wind| 2.75         | 3.03       | -0.28       | 6.12       | -3.12       | 1.63      | -0.38    | -8.89    | -18.6     |               |
| Double Solar| 1.65         | 3.03       | -1.38       | 4.30       | -2.12       | -1.43     | -0.78    | -4.15    | -0.1      |               |

Increase capacity of wind from 40% to 80% and solar from 10% to 20%

Energy storage **hurts** renewables when there is no curtailment

Two drivers for the impact

- Change in average prices
- Correlation of renewable production and prices
Summary and Discussion

A model to **quantify** hypothetical energy storage’s impact in wholesale electricity market, by endogenizing price impact

Market failures and welfare improving policies

- **Under-investment**: Not profitable, but consumer welfare improving

Ownership Discussion

An independent energy storage **does not** seems support renewables when there is **no curtailment**
Thank you very much
Ancillary services provide a good source of income, but will evaporate quickly with larger storage investment.

Average cost for grid-scale energy storage doesn’t decrease much with the size after 5-10 MWh, but lumpiness in investment still can be a problem.

Energy storage can provide some other products, because of renewable replacement of fossil fuel, spinning reserve, capacity etc.
- 4 GW Pump Hydro in 2020, contracted or announced 2.3 GW

- 250 MW Battery in 2020, contracted or announced 1.5 GW
Energy Storage need for 100% Wind Solar? 30 min calculation

- Take 2020 renewable generation profiles
- Invest 100 GW capacity in each wind and solar, where the peak system demand of CAISO is 50 GW.

There are days with almost no wind or solar in the whole system

Need for **200-300 GWh** storage to maintain the short-run balance
Seasonal variation is around 50-60%

Need 1-2 TWh cheap storage to shift renewable generation between seasons
Storage’s Impact on Prices

Figure 3: Storage’s Price Impact Under Different Models for a Representative Day

- Storage smooths the price path
- Firm’s response further smooths
Ownership’s Impact on Operation

**Figure 4:** Energy under Different Ownership Structures for a Representative Day

- Monopoly Storage under-produces relative to Competitive Storage
- Load-Owned Storage searches for higher price impact
## Storage’s CO$_2$ Impact

### Table 4: Storage’s CO$_2$ Impact Under Different Ownerships

<table>
<thead>
<tr>
<th>Ownership</th>
<th>Storage’s Revenue</th>
<th>Storage’s Cost</th>
<th>Storage’s Profit</th>
<th>Δ in CO$_2$ Emissions</th>
<th>Per Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Monopoly</td>
<td>1.34</td>
<td>3.03</td>
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<td>1.06</td>
<td>3.03</td>
<td>-1.97</td>
<td>-2.64</td>
<td>84</td>
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Energy storage decreases CO$_2$ emissions
## Storage’s CO₂ Impact

**Table 4:** Storage’s CO₂ Impact Under Different Ownerships

<table>
<thead>
<tr>
<th>Ownership</th>
<th>Storage's Revenue</th>
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<th>Storage's Profit</th>
<th>Δ in CO₂ Emissions</th>
<th>Per Year</th>
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Energy storage **decreases** CO₂ emissions

**Two drivers for CO₂ impact**

- Round-trip efficiency
- CO₂ efficiency differences of marginal units
### Table 5: Storage’s Production and Revenue Impact on Incumbent Generators

<table>
<thead>
<tr>
<th>Ownership</th>
<th>Δ in Production of</th>
<th>Per Year</th>
<th>Million AU$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Natural Gas Generators</td>
<td>Diesel-Oil Generators</td>
<td>Natural Gas Generators</td>
</tr>
<tr>
<td>Monopoly</td>
<td>6.70</td>
<td>-4.31</td>
<td>-0.90</td>
</tr>
<tr>
<td>Load Owned</td>
<td>21.92</td>
<td>-8.34</td>
<td>-1.86</td>
</tr>
<tr>
<td>Competitive</td>
<td>14.38</td>
<td>-6.34</td>
<td>-0.93</td>
</tr>
</tbody>
</table>

- Gas Generators increase production but lose revenue.
- Load-Owned Storage has the largest revenue impact.
CAISO Curtailment

Wind and solar curtailment totals by month

- May '19
- Sep '19
- Jan '20
- May '20
- Sep '20

MW/h