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)

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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 $\mathbf{CO_2}$?
- How energy storage interacts with **renewables**?
- Who should **own** energy storage?

Framework

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**

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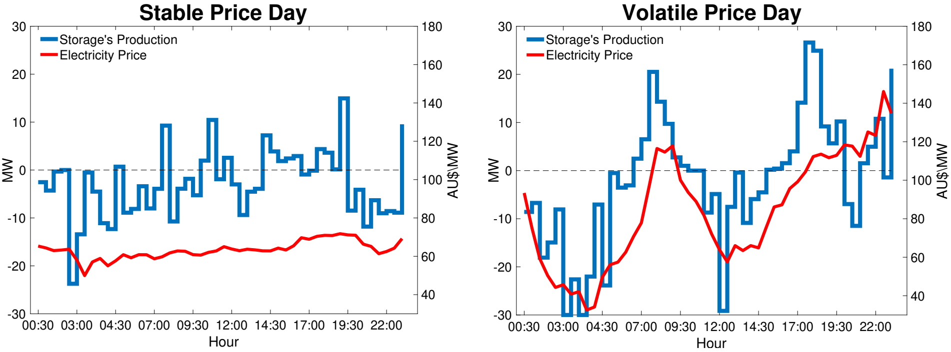
Two technical challenges

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

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

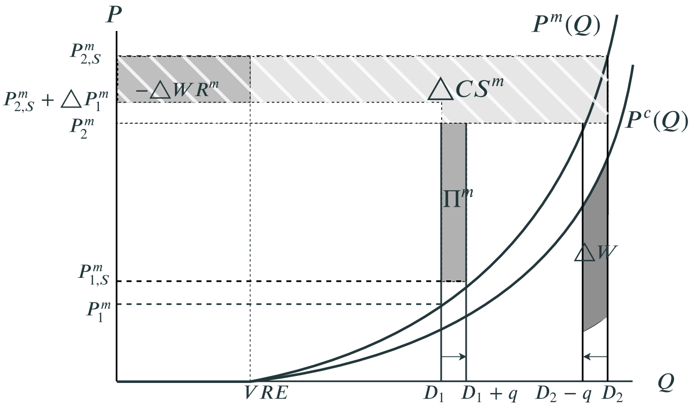
Simulate a grid-scale energy storage in **South Australia**

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

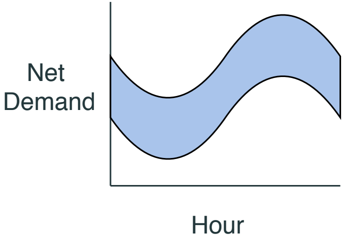


Market power, $P^m(Q) > P^C(Q), \forall Q$

Arbitrage, Energy Storage shifts demand

Consumer surplus increases, price variation decreases

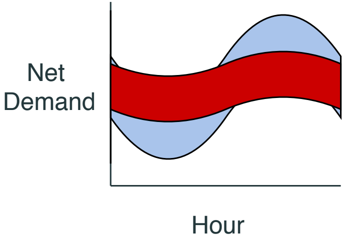
$$f_D(D_d|X_k)$$



Observed variation of demand in data conditional on X_k

Picture for the Algorithm

$$f_{D'}^{\sigma_i}(D'_d | X_k^{\sigma_i})$$

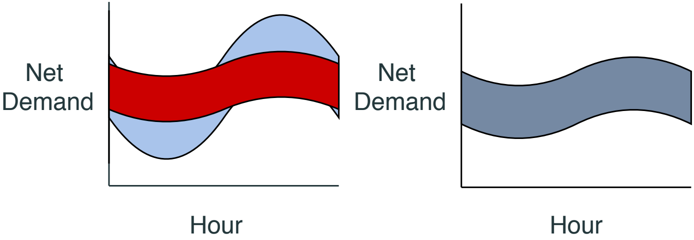


+ Storage's Production
σ_i

Storage smooths demand

Picture for the Algorithm

$$f^{\sigma_i}_{D'}(D'_d | X^{\sigma_i}_k) \quad \approx \quad f_D(D_d | X_m)$$



Look for a similar observed variation of demand

Use firms strategies conditional on X_m as a best response to storage

Australia's National Electricity Market (NEM)

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

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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

Road Map for Price Impact

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

Model Comparison

Table 1: Yearly Returns Per 1 MWh Under Alternative Modeling Assumptions

	(1)	(2)	(3)	(4)
Revenue (1000 AU$ per MWh)	46.66	23.31	12.38	11.18
Cost (1000 AU$ per MWh)	25.27	25.27	25.27	25.27
Profit (1000 AU$ per MWh)	21.39	-1.96	-12.89	-14.09
Production (MWh)	845	716	511	450
Δ CS (1000 AU$ per MWh)	-	-	24.56	27.08
<u>Model Assumptions</u>				
Price Uncertainty	×	✓	✓	✓
Price Effect	×	×	✓	✓
Firms' Response	×	×	×	✓

- Price Effect has significant impact on profit
- Allowing firms' response affects profit

Price Paths

Road Map for Ownership

3 Ownership structures

- Monopoly Storage
- Load-Owned Storage
- Perfectly Competitive Storage Market

Private Incentives are not Socially Optimal

Table 2: Storage's Private and Social Returns Under Different Ownerships

	Per Year					
	Million AU$					Thousand MWh
	Storage's			Δ in Market's		
Ownership	Revenue	Cost	Profit	Consumer Surplus	Cost	Production
Monopoly	1.34	3.03	-1.69	3.25	-1.54	54
Load-Owned	0.59	3.03	-2.44	5.45	-2.21	114
Competitive	1.06	3.03	-1.97	3.56	-1.77	84

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

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Two distortions in prices

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

Price Paths

Renewables and Storage

Table 3: Under Different Renewable Penetration Levels

	Per Year								
	Million AU$							Thousand Ton	Thousand MWH
	Storage's			Δ in Market's					
	Revenue	Cost	Profit	Consumer Surplus	Cost	Wind Revenue	Solar PV Save	Δ in CO_2 Emissions	Curtailment
Baseline	1.34	3.03	-1.69	3.25	-1.54	-1.70	-0.44	-3.12	-
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

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Two drivers for the impact

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

CO_2 Impact | Effect on Other Incumbents

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
  Capacity Markets

- *Under-utilization*: Prices are not right incentives for efficiency
  Ownership Discussion

An independent energy storage **does not** seems support renewables when there is **no curtailment**

Thank you very much

Other comments

- 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.

CAISO MIX

CAISO Future Power Plant Capacity

Fuel Type	*2020*	*2021*	*2022*	*2023*	*2024*
Biomass	1,068.7	1,072.9	1,122.8	1,122.8	1,122.8
Coal	531.5	531.5	531.5	531.5	531.5
Geothermal	1,798.2	1,866.6	1,901.6	1,901.6	1,901.6
Natural Gas	31,761.1	30,923.3	31,323.3	28,454.5	28,654.5
Other Fuel	954.4	2,207.4	2,424.7	2,619.7	2,689.7
Solar	14,023.2	17,044.3	21,913.9	23,255.2	24,055.2
Uranium	2,978.6	2,978.6	2,978.6	2,978.6	1,856.6
Water	9,088.4	9,092.8	9,092.8	9,092.8	9,092.8
Wind	8,796.1	9,069.4	9,230.4	9,522.8	9,538.3

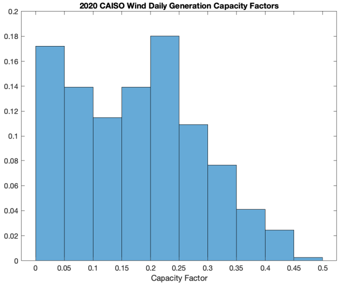
– 4 GW Pump Hydro in 2020, contracted or announced 2.3 GW

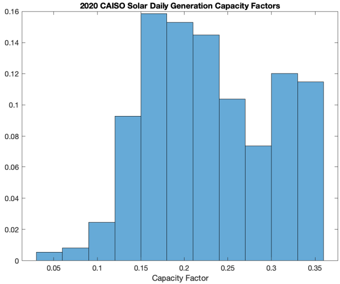
– 250 MW Battery in 2020, contracted or announced 1.5 GW

Curtailment in CAISO

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.

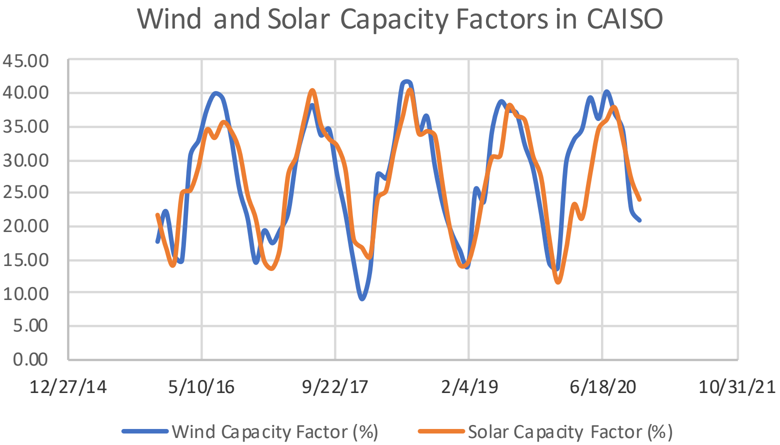




There are days with almost no wind or solar in the whole system

Need for **200-300 GWh** storage to maintain the short-run balance

Simple Exercise Cont.

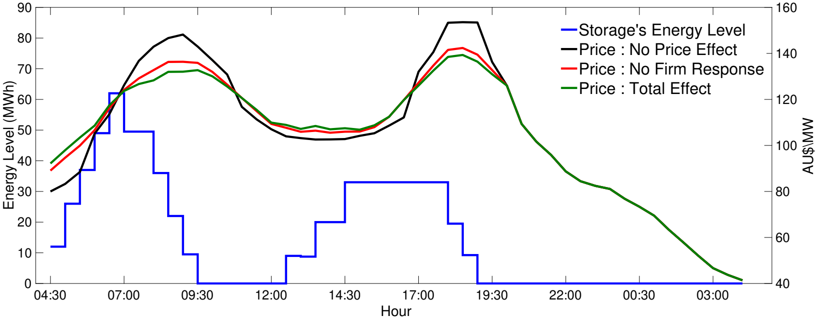


Seasonal variation is around 50-60%

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

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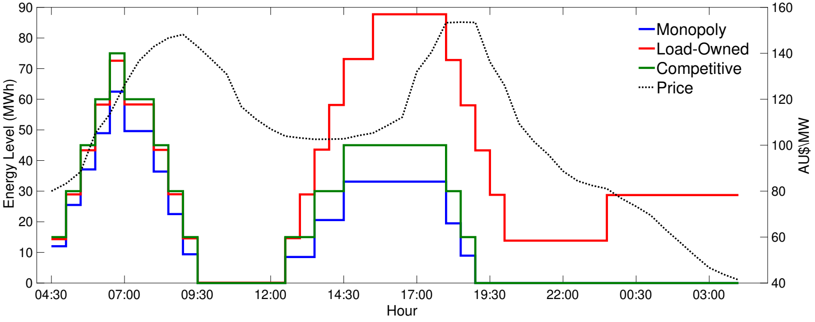
Ownership's Impact on Operation

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

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Storage's CO_2 Impact

Table 4: Storage's CO_2 Impact Under Different Ownerships

	Per Year				
	Million AU$			Thousand Ton	Thousand MWh
	Storage's			Δ in CO_2 Emissions	Production
Ownership	Revenue	Cost	Profit		
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Two drivers for CO_2 impact

- Round-trip efficiency
- CO_2 efficiency differences of marginal units

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Storage's Impact on Incumbents

Table 5: Storage's Production and Revenue Impact on Incumbent Generators

	Per Year				
	Thousand MWh		Million AU$		
	Δ in Production of		Δ in Revenue of		
Ownership	Natural Gas Generators	Diesel-Oil Generators	Natural Gas Generators	Diesel-Oil Generators	Renewables
Monopoly	6.70	-4.31	-0.90	-1.02	-1.70
Load Owned	21.92	-8.34	-1.86	-1.55	-1.43
Competitive	14.38	-6.34	-0.93	-1.18	-1.62

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

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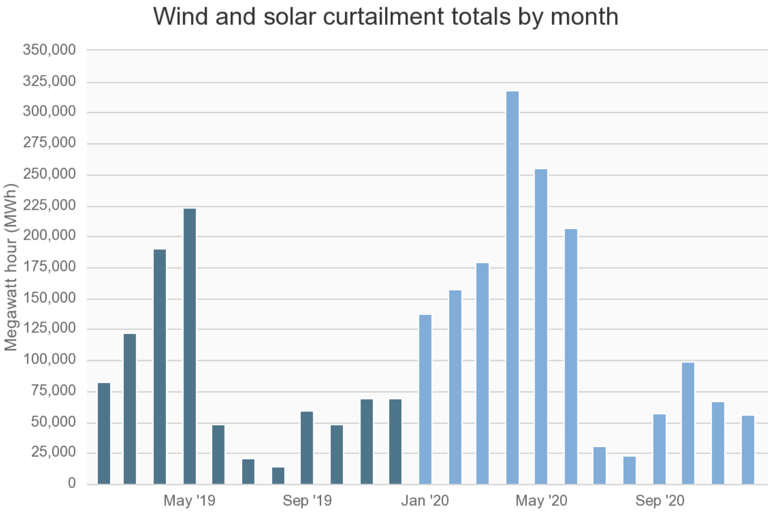
CAISO Curtailment



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