The Value of Hydropower as a Grid-Scale Storage Resource: A Commodity Market Approach

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Motivation

- Energy storage plays a crucial role in modern power systems, providing services such as grid stability, frequency regulation, and load balancing
- Currently, storage systems earn revenue by offering these grid services and through energy arbitrage—buying electricity when prices are low and selling when prices are high
- However, as storage deployment expands, arbitrage profitability declines due to market saturation and narrowing price differentials (Sioshansi et al., 2009; Li et al., 2024)
- ERCOT, for example, in 2024 saw reduced arbitrage potential due to moderate weather and increased storage capacity

This trend underscores the need for new business models that more fully recognize and compensate the value energy storage provides to the power system

Research Approach

- In this research, we introduce a commodity-market based framework to align compensation with grid benefits
- Our empirical strategy exploits exogenous variation in reservoir storage (as a proxy for grid-scale storage) in the Pacific Northwest to estimate the causal effects on:
  - Real-time prices
  - The distribution of real-time prices
  - And risk premiums
- We employ fixed-effects and lagged dependent variable models to control for unobserved heterogeneity across balancing authorities and capture dynamic price behavior

Findings

- Using reservoir and inflow levels from dams which market hydropower at the mid-Columbia trading hub, we find that a **10% increase in reservoir volume reduces real-time prices by 5%**
- But storage can also affect other market dynamics, such as extreme prices during grid stress events
  - We analyze the distribution of prices, finding that increases in reservoir storage volume reduce prices more at the upper end of the price distribution (~6%)
  - We analyze risk premiums, finding that increases in reservoir storage volume also reduce risk premiums (~5%)

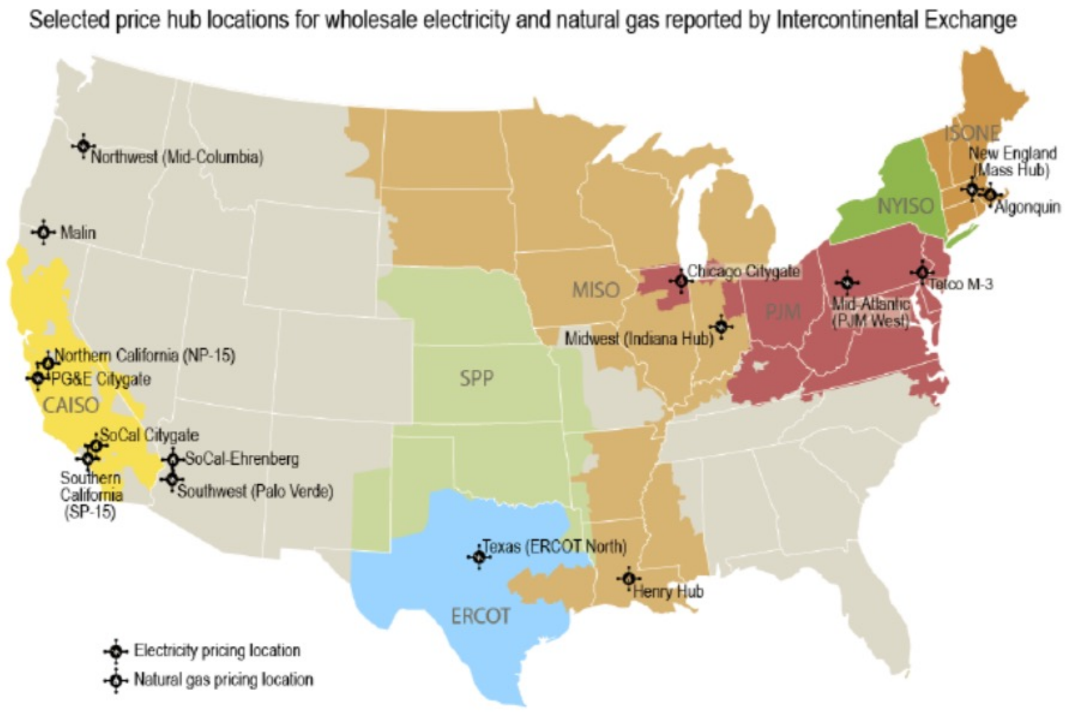
Pacific Northwest Region

- The Pacific Northwest (PNW) is home to a large existing capacity of reservoir storage
  - In 2025, 30% of electric generation in the Northwest Region was hydroelectric (EIA, 2025)
- The PNW is primarily comprised of vertically integrated utilities, which participate in bilateral trading
  - The Western Energy Imbalance Market (WEIM) serves as a real-time balancing market
  - The mid-Columbia trading hub comprises the control areas of Grant PUD, Douglas PUD and Chelan PUD and functions as a day-ahead market
    - Note that this is changing with the EDAM, but was true during our study period

Data

- Day-ahead prices are from the Mid-Columbia Trading Hub (EIA)
- Real-time prices are from the Western EIM (CAISO OASIS)
- Demand data is from the EIA
- Reservoir level, and inflow data is from the Army Corps of Engineers
- Natural gas price data is historical Henry Hub natural gas prices from the EIA
- Natural gas volume data is from EIA's weekly natural gas storage report in the West and Mountain regions
- Data is from May 2022 to November 2024

Mid-Columbia Trading Hub



Source: US Energy Information Administration

Source: U.S. Army Corps of Engineers

Research Question

How does energy storage affect real-time prices in the Pacific Northwest?

Impact of Reservoir Level on Price and Risk Premium

- Several regression models were used to estimate the impact of reservoir level on real-time price and risk premium
  - Fixed effects regression model
  - Fixed effects regression model with lagged price
  - Pooled regression with lagged price
- These models are intended to estimate an upper and lower bound of the impact of reservoir level on real-time price and risk premium
  - A model excluding lagged price may overestimate the impact due to endogeneity between electricity markets and the past decisions of reservoir operators (upper bound)
  - Inclusion of lagged price may underestimate the impact due to dynamic panel bias (lower bound)
- All results presented use Driscoll-Kraay standard errors

Regression Results: Reservoir levels had a negative and statistically significant impact on real-time prices.

	Model (1) BA-level Fixed Effects	Model (2) Fixed Effects & Lagged Price	Model (3) Lagged Price
Reservoir Storage Volume (as a proportion of Max Capacity)	-1.526***	-0.514***	-0.502***
Inflow Deviation (cubic feet per second * 1000)	.0000147	0.000043*	0.00008***
Log Demand (% of GWh)	1.225***	0.274***	0.009**
Gas Volume (Deseasoned) (billions of cubic feet)	-0.002***	-0.0004***	-0.0004***
Log Gas Price (% of $ / million btu)	0.970***	0.302****	0.312***
Daily Solar Generation (GWh)	-0.00000625***	-0.00000193***	−0.00000197***
Daily Wind Generation (GWh)	-0.00000535***	-0.00000152***	-0.00000146***
Lagged Risk Premium	N	Y	0.716***
Balancing Authority Fixed Effects	Y	Y	N
Time Fixed Effects	Y	Y	Y
Constant	-5.331	-0.954	0.826
Observations	229,505	226,796	226,796
R-squared	0.533	0.775	0.775

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Quantile Regression Results

- Quantile regressions enable research on the distributional impact of reservoir level on real-time price
- Results indicate that reservoir level is more impactful during high-price events

	Model (1) 50th Percentile	Model (2) 95th Percentile
Reservoir Storage Volume (as a proportion of Max Capacity)	-0.52***	-0.62***

Research Question

What is the insurance value of energy storage?

Risk Premium Theory

- This theory explains the relationship between spot and forward prices as an expected future spot price (a forecast) and a risk premium.
- The risk premium compensates the agent for taking on risk.

$$F_{T,t} = E_t S_{t+T} e^{-pt}$$

- $F_{T,t}$ = futures price at time t for a delivery at time t+T
- $E_t S_{t+T}$ = expected time t+T spot price from time t
- $-pt$ = risk premium, equivalent to the risk-adjusted discount rate minus risk free interest rate.

Risk Premium Results

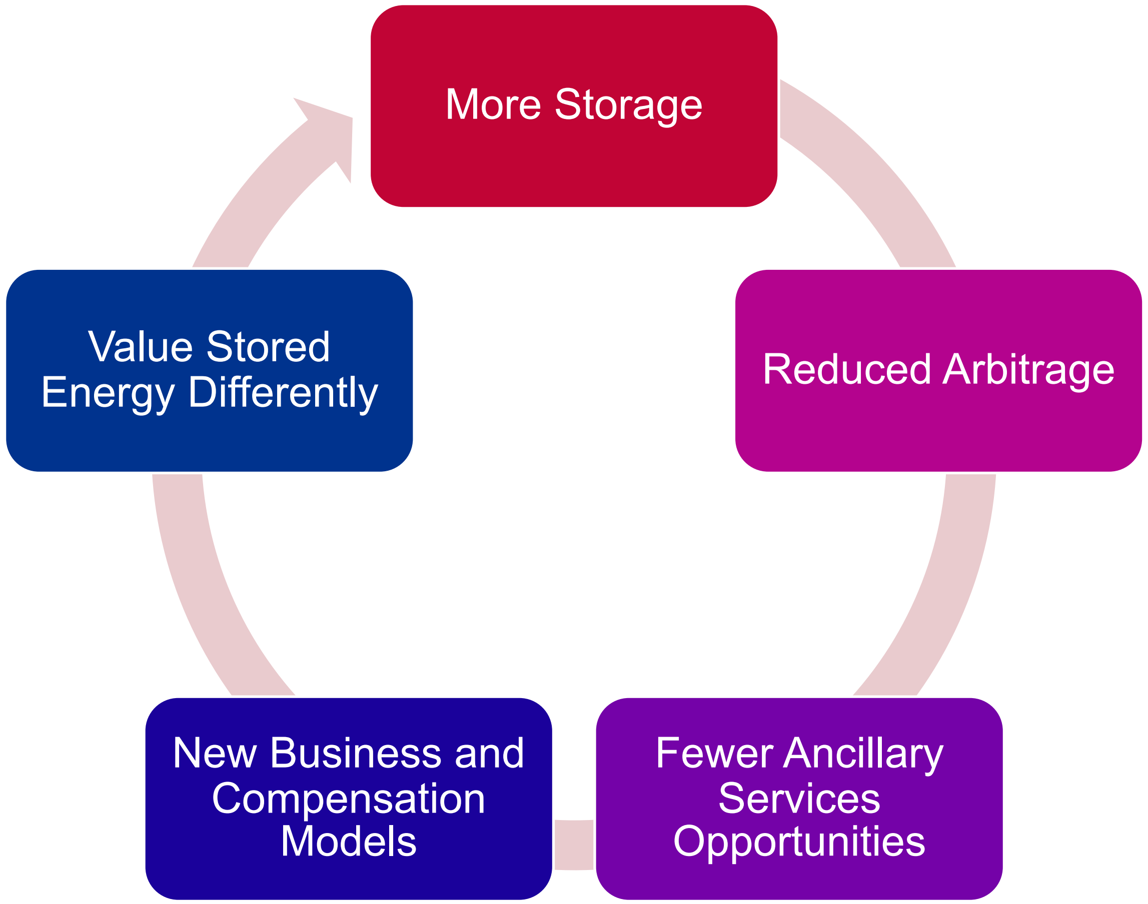
	Model (1) BA-level Fixed Effects	Model (2) Fixed Effects & Lagged Risk Premium	Model (3) Lagged Risk Premium
Hydropower Reservoir Storage Volume (as a proportion of maximum capacity)	-0.6608 (0.2679) **	-0.4622 (0.2313) **	-0.4589 (0.2217) **
Inflow Deviation (cubic feet per second * 1000)	0.0005 (0.0002) **	0.0003 (0.0002) **	0.0003 (0.0002) **
Demand (MWh)	0.0004 (0.0020)	0.0004 (0.0018)	0.0004 (0.0020)
Gas Volume (billions of cubic feet)	0.0008 (0.0009)	0.0003 (0.0007)	0.0003 (0.0007)
Gas Price ($ / million btu)	0.0041 (0.0169)	0.0036 (0.0133)	0.0040 (0.0132)
Daily Solar Generation (MWh)	0.0013 (0.0045)	0.0033 (0.0048)	0.0034 (0.0048)
Daily Wind Generation (MWh)	-0.0030 (0.0008) ***	-0.0023 (0.0008) ***	-0.0014 (0.0004) ***
Lagged Risk Premium		0.2751 (0.0423) ***	0.2781 (0.0419) ***
Balancing Authority Fixed Effects	Y	Y	N
Time Fixed Effects	Y	Y	Y
Constant			0.2580 (0.2217)
Observations	552	552	6072
R-squared	0.266	0.320	0.321

Discussion

- Results show that the reservoir level reduces real-time prices and risk premiums in the Northwestern region
  - A 10% increase in reservoir level results in a 5% decrease in real-time prices
  - A 10% increase in reservoir level results in a ~5% decrease in risk premium

Key Takeaway

- Storage provides value to the system by reducing prices and mitigating risks by acting as the buffer,
- BUT, storage does not get paid to provide the buffer – *storage function*
- INSTEAD, storage gets paid to provide grid services and avail arbitrage opportunities,
- Evidence mounting that revenue opportunity from grid services and arbitrage decrease as more storage is installed,
- HENCE, new business models need to be considered that compensate storage to provide the storage function



Policy Implications: Swiss Winter Reserve

- After recognition of the value of long-duration energy storage, Swissgrid, the Swiss transmission operator, established a winter hydropower reserve in accordance with orders from the Swiss Federal Electricity Commission.
- The winter hydropower reserve compensates storage operators not only for capacity but for energy.
  - 250 GWh of stored energy reserves were acquired at 66.12 Euros/MWh in 2024.
  - The reserve is designed to hold 300 GWh from February to May, with a tolerance of +/- 100 GWh.
- Quantification of hydropower's impacts on price formation can inform the formation and pricing of similar energy reserves.

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Thank you!

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