The Economics of Grid-Scale Electricity Storage: Location Heterogeneity and Business Models

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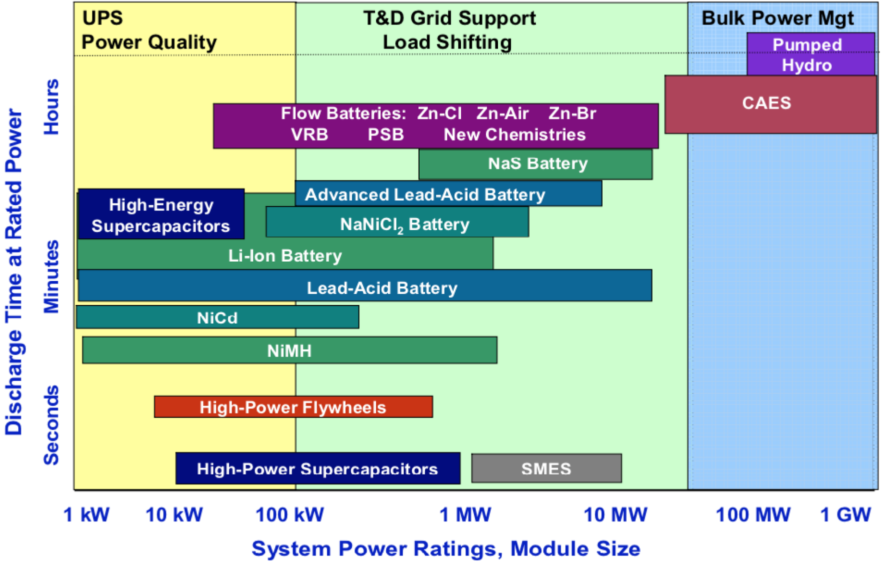
Grid-Scale Batteries Deployed or in Development

- Tesla's Hornsdale project (South Australia):
  100 MW/129 MWh, lithium-ion technology, Dec. 2017
- AES Energy Storage (Escondido, California):
  30 MW/120 MWh, May 2017.
- Rongke Power (Dalian, China):
  200 MW/800 MWh, vanadium flow battery
- Ewe Gasspeicher GmbH (Germany):
  120 MW/700 MWh, flow battery with saltwater & polymers
- Andasol Solar Power Plant (Spain):
  135 MW/1030 MWh, molten salt.
- Solana Solar Power Plant (Arizona, UA):
  280 MW/1680 MWh, molten salt.
- Huntorf Plant (Germany):
  290 MW/870 MWh, compressed air storage.

Grid-Scale Energy Storage Technologies



Storage Batteries: Key Terminology and Metrics

Practical measures:

- Power [MW]: discharge ability
- Energy [MWh]: storage capacity
- Energy-to-power ratio [h]: duration/discharge time

Theoretical measures:

- minimum and maximum capacity ($\underline{s}, \overline{s}$)
- storage decay rate (δ) — technological feature
- (dis-)charge speed (ζ) — power is $\zeta\overline{s}$
- capital cost (per unit of power or energy [LCOS])

Research Questions

Location Heterogeneity and Business Models

1. What are economically-viable business models that support deployment of grid-scale energy storage systems?
2. What are the underlying microeconomic factors that determine optimal size and type of deployment?
3. How do battery characteristics (charging speed, decay rate) influence profitability of storage systems?
4. How important is location? Use Ontario LMP data (zonal prices) to quantify the effect of location heterogeneity.

Business Models

- **Nodal Storage**:
  price arbitrage at congested nodes; buy electricity cheap (or even at negative prices), sell when expensive. Can be used by utilities internally or by independent operators.
  - Focus: network congestion and price variation
- **Demand-Side Storage**:
  electric utilities or distributors trade off (expanding) transmission line capacity against deployment of battery capacity.
  - Focus: stochastic demand variation
- **Supply-Side Storage**:
  deployed by wind farm operators to insure against curtailment risk; electricity is stored on site until it can be sold later.
  - Focus: stochastic supply variation

Nodal Storage & Price Arbitrage

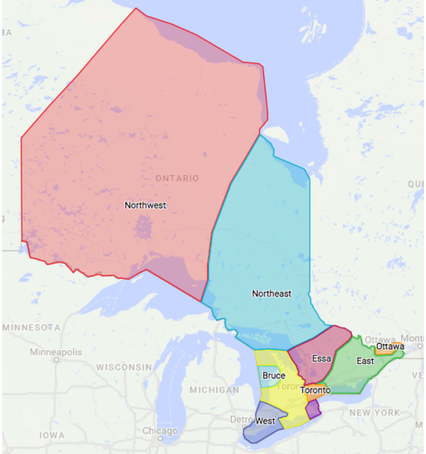
Price Arbitrage Model

- Storage: $s_t \in [\underline{s}, \overline{s}]$ in MWh with min./max. capacity
- Buy electricity $x_t < 0$ or sell electricity $x_t > 0$ at p_t (\$/MWh).
- Limit ζ on (dis-)charge speed: $x_t \in [-\zeta\overline{s}, +\zeta\overline{s}]$
- Storage path: $s_t = (1-\delta)s_{t-1} - x_t$ with decay rate δ
- Maximize profits with quadratic cost for battery

$$\pi_i = \sum_{t=1}^{T} x_{it} p_t - \left[c_i \overline{s}_i + \frac{1}{2} d_i \overline{s}_i^2 \right]$$

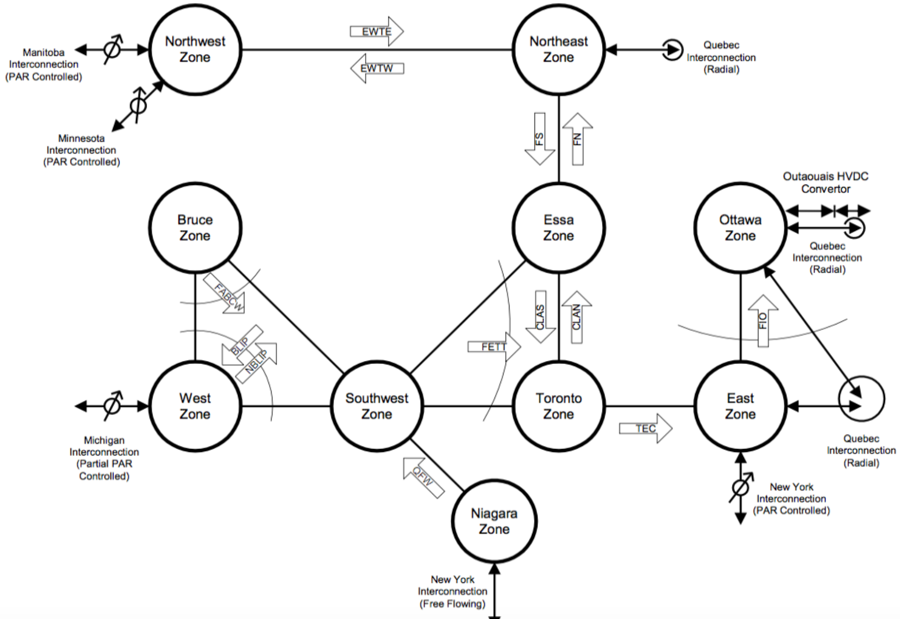
- Find optimal path of x_t given s_0 and s_T, and prices p_t.
- Four shadow prices for constraints: $\mu_t^{\ominus}, \mu_t^{\oplus}, \mu_t^{\circ}, \mu_t^{\bullet}$, and Lagrangean λ_t for charge path. Bang-bang optimal control.
- Numerical solutions: IBM CPLEX with OPL (free)

IESO Electricity Zones



Ontario is divided into ten electricity zones defined by major interfaces (bulk transmission). IESO calculates nodal prices for references nodes (i.e., buses) in each of the nodes. Zones have different mix of generation assets. Several zones have more assets than peak demand. IESO is moving towards a system of Locational Marginal Prices (LMP).

IESO Zones: Interconnections



Electricity Price Dispersion in Ontario (Zonal Prices)

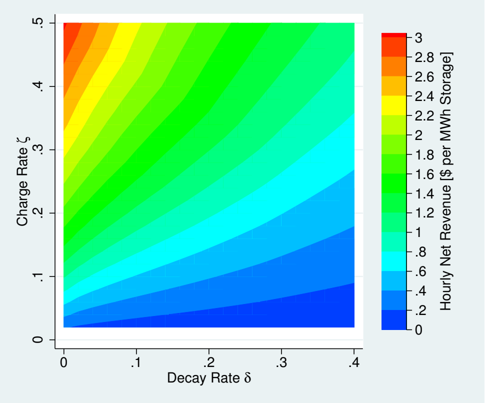
Zone	Node	P5	Q1	Median	Q3	P95	Std	Corr.
IESO HOEP		-3.94	3.21	14.11	28.14	61.35	38.71	
Reference	Richview	-2.77	1.97	11.83	21.66	66.06	53.95	0.613
North West	Atikokan	-471.33	0.00	6.68	14.05	72.97	378.79	-0.048
North West	Pineportage	-1646.54	0.00	4.99	11.78	33.95	481.86	-0.060
North West	Thunderbay	-2.56	1.65	10.14	18.44	57.31	77.31	0.371
North East	Andrews	-130.49	0.00	8.40	16.67	51.08	310.58	-0.011
North East	Canyon	-2.94	1.97	11.39	20.67	64.77	108.20	0.302
North East	NPIroqfalls	-2.86	1.46	10.75	19.96	62.46	135.95	0.234
Ottawa	TAOHSC	-2.77	1.98	11.84	21.66	66.15	57.01	0.602
East	Saunders	-2.74	1.94	11.70	21.38	65.11	53.67	0.604
Toronto	Darlington	-2.77	1.96	11.82	21.60	65.85	53.84	0.613
Essa	Desjoachims	-2.74	1.96	11.73	21.60	66.32	54.02	0.612
Bruce	BruceB	-2.69	1.91	11.48	21.01	63.96	52.90	0.612
South West	GerdauCam	-2.76	1.99	11.84	21.66	66.00	53.86	0.601
Niagara	BECK2	-2.72	1.98	11.70	21.30	65.26	54.56	0.586
West	Greenfield	-2.74	1.96	11.75	21.49	65.35	54.65	0.589

- High price variance in Northwest and Northeast zones, less correlation.
- Prevalence of negative prices in congested zones.

Battery Performance Simulations

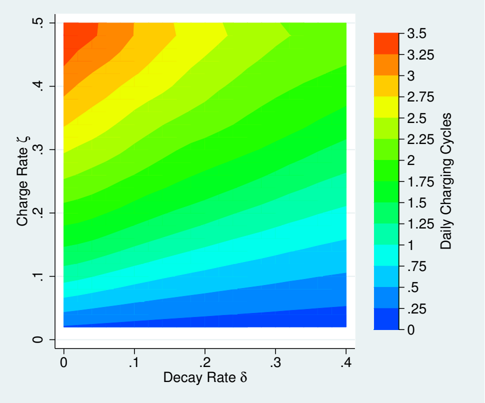
- Data: Ontario Hourly Energy Price (OHEP) and 15 nodal prices
- Time Period: hourly data, 2014–2017
- Optimization periods: 168 hours (1 week) $\times$ 208 weeks
- Computation grid for OHEP: decay rates $\times$ charge speed
  - Decay rate δ: 0.00–0.40, 21 steps
  - Charge speed ζ: 0.02–0.50, 25 steps
- Zonal price simulations: $\delta = 0.02$, $\zeta = 0.25$ (fast charger)
  - Upper bound: perfect foresight using actual prices
  - Lower bound: use (simplistic) day-ahead price forecasts

Simulation Results: Hourly Revenue per MWh



- Simulations based on HOEP.
- Average hourly revenue (sales minus purchases) for each MWh of battery storage
- Fast-charging low-loss batteries can achieve CAD 3/MWh.
- Insufficient to be profitable at current costs.

Simulation Results: Utilization Rate

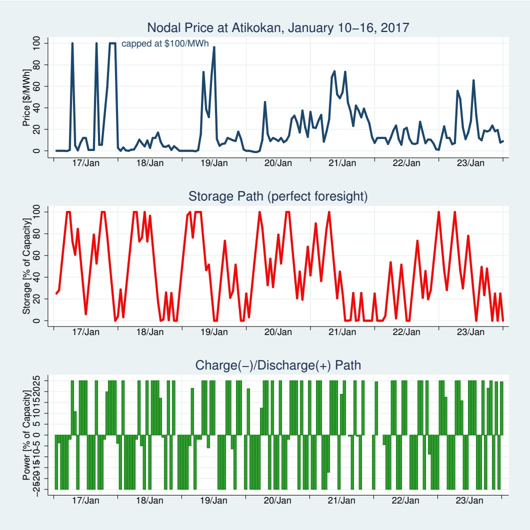


- Metric: charge-discharge cycles per day
- With perfect foresight, storage systems can achieve thee full cycles.
- Usefulness of storage is underestimated when only a single diurnal cycle is assumed!

Simulation Results: Actual/Hindsight Nodal Prices

Zone	Node	Revenue per MWh Storage	Revenue per MWh Sold	Charge Cycles
IESO	HOEP	1.855	21.28	2.184
North West	Atikokan	20.397	210.40	2.458
North West	Pineportage	23.981	256.85	2.430
North West	Thunderbay	2.878	30.32	2.405
North East	Andrews	10.582	112.78	2.429
North East	Canyon	3.424	36.31	2.400
North East	NPIroqfalls	4.037	42.96	2.405
Ottawa	TAOHSC	2.803	29.28	2.404
East	Saunders	2.703	28.21	2.404
Toronto	Darlington	2.717	28.36	2.404
Essa	Desjoachims	2.720	28.39	2.403
Bruce	BruceB	2.651	27.67	2.404
South West	GerdauCam	2.718	28.35	2.403
Niagara	BECK2	2.728	28.47	2.404
West	Greenfield	2.719	28.41	2.403

Simulation Example: Actual/Hindsight Nodal Prices



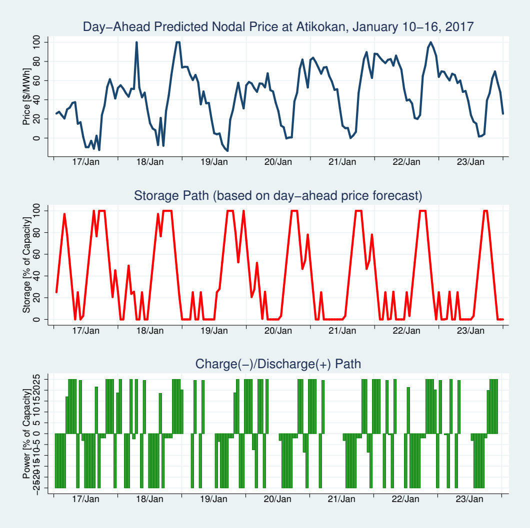
- "Typical" week in January 2017
- Significant short-term "pumping" allows for more than two charge cycles per day.

Simulation Results with Day-Ahead Forecast Prices

Zone	Node	Revenue per MWh Storage	Revenue per MWh Sold	Charge Cycles
IESO	HOEP	0.937	11.59	2.059
North West	Atikokan	3.777	44.38	2.142
North West	Pineportage	6.056	76.20	2.126
North West	Thunderbay	0.878	10.41	2.131
North East	Andrews	3.287	40.96	1.999
North East	Canyon	0.983	11.93	2.135
North East	NPIroqfalls	1.064	13.14	2.111
Ottawa	TAOHSC	1.077	12.94	2.129
East	Saunders	0.947	11.21	2.133
Toronto	Darlington	1.036	12.90	2.061
Essa	Desjoachims	1.018	12.54	2.074
Bruce	BruceB	0.935	11.01	2.140
South West	GerdauCam	0.984	12.10	2.083
Niagara	BECK2	1.060	13.24	2.091
West	Greenfield	1.041	13.09	2.059

- Revenue from MWh stored falls 50%, but 2 charge cycles per day still feasible.

Simulation Example: Day-Ahead Forecasts



- Same "typical" week in January 2017 as in perfect foresight example.
- Reduced short-term "pumping", but still close to two full charging cycles per day.
- Conventional assumption that grid-scale batteries provide only one diurnal charge cycle underestimate the full potential of such systems.

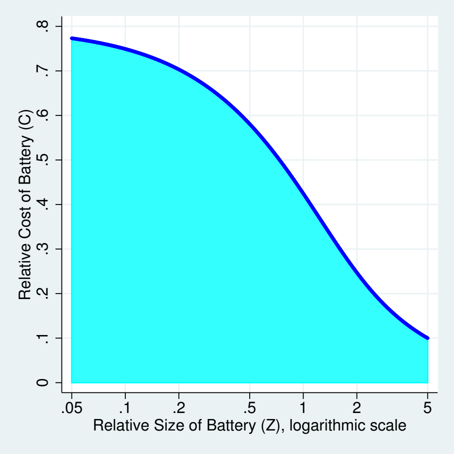
Are Batteries Cost-Effective yet?

- Convert hourly revenue per MWh storage into lifetime revenue discounted to present using conversion factors in table, assuming discount rate and lifetime of storage system.

Discount Rate [%]	Time Horizon (Years)		
	10	15	20
3.5	73.275	101.476	125.221
5.0	68.528	92.117	110.599
8.0	60.404	77.052	88.382

- Example: Net revenue of CAD 2.0 per MWh and hour. At 5% discount rate and with 15-year life, lifetime revenue is 184 CAD/kWh of storage (=146 USD/kWh).
- Current capital costs for lithium-ion batteries are in the 335-425 USD/kWh range.
- To make battery storage economical, need at least 4-5 CAD/MWh.

Limits to the Price Arbitrage Model



- Price arbitrage is self-limiting. Increase in grid-scale battery capacity reduces potential for price arbitrage.
- Relationship between relative size (Z, capacity to standard deviation of 'net demand') and relative cost (C, fixed cost relative to 'one-sigma price lift')
- From marginal use of storage to absorbing all variation through storage ($Z \to 5$), batteries need to become about 4–7 times more profitable than at the outset.

- Key economic variable: marginal cost of supply determines how much equilibrium price increases for 1-σ shift in demand; determines C.

Demand-Side Storage

Remote communities at the end of long transmission lines

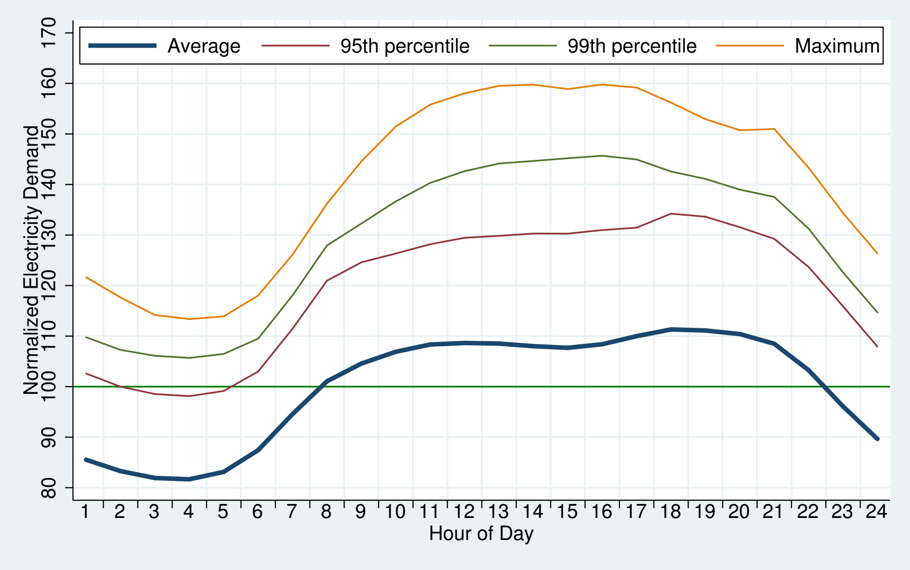
Demand-Side Storage: Transmission v. Storage

- Maximum transmission capacity ($\bar{z}$) and storage capacity ($\bar{s}$)
- Cost factor g per length L of line
- Battery cost depends on size $\bar{s}$ and speed ζ (i.e, energy & power)
- Minimize sum of transmission and storage cost.
  $C = C_z + C_s = gL\bar{z}(\bar{s}) + (h_1 + h_2\zeta)\bar{s}$
- Optimal solution for battery size is

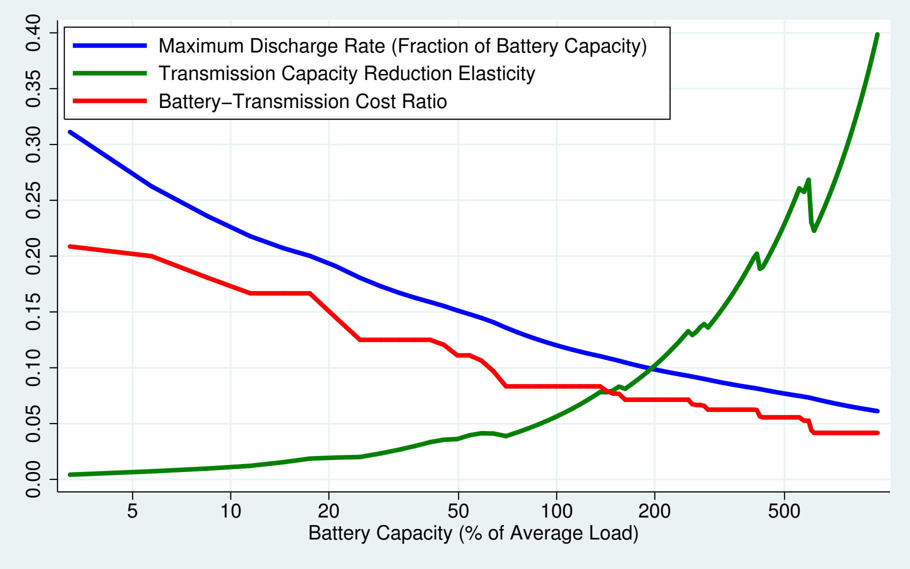
$$\bar{s}^* = [-\bar{z}'(\bar{s})]^{-1} \left(\frac{h_1 + h_2\zeta}{gL} \right)$$

- Requires knowledge of peak demand path q_t to determine trade-off function $\bar{z}(\bar{s})$ and marginal trade-off $\bar{z}'(\bar{s})$.
- Maximum possible gain: shave off all peaks and troughs so that transmission line use equals average demand.

Demand-Side Storage: Diurnal Profile



Demand-Side Storage: Simulation Results



Demand-Side Storage: Simulation Results

- Blue Curve: as battery capacity (energy) increases, battery requires less discharge speed (power); energy-to-power ratio increases.
- Green Curve: battery capacity that is less than average load reduces transmission capacity very little: elasticity is 5% or less. Elasticity also equals cost ratio of battery to transmission line.
- Red Curve: the ratio of marginal battery cost to marginal transmission line cost (equal to $-\bar{z}'(\bar{s})$) must be less than 20%. If cost ratio is above, battery is not economical. As cost ratio falls, optimal battery size gets larger.

Supply-Side Storage

Acciona Energy installed a 1.7MW peak-power lithium-ion battery experimental facility in September 2017 at its 15MW Barasoain wind plant in the Navarre region, Spain

Supply-Side Storage: Mitigating Curtailment Risk

- Stochastic output $y(t) \in [0, 1]$ per unit of generating capacity K.
- Battery path $x(t) \in [-1, +1]$ per unit of storage capacity S.
- Feed-in-tariff $\bar{p}$ fixed, so no price arbitrage here.
- Curtailment risk is binary $\omega(t) \in \{0, 1\}$.
- Maximize profits of independent power producer deploying windfarm with nominal capacity K and storage S.

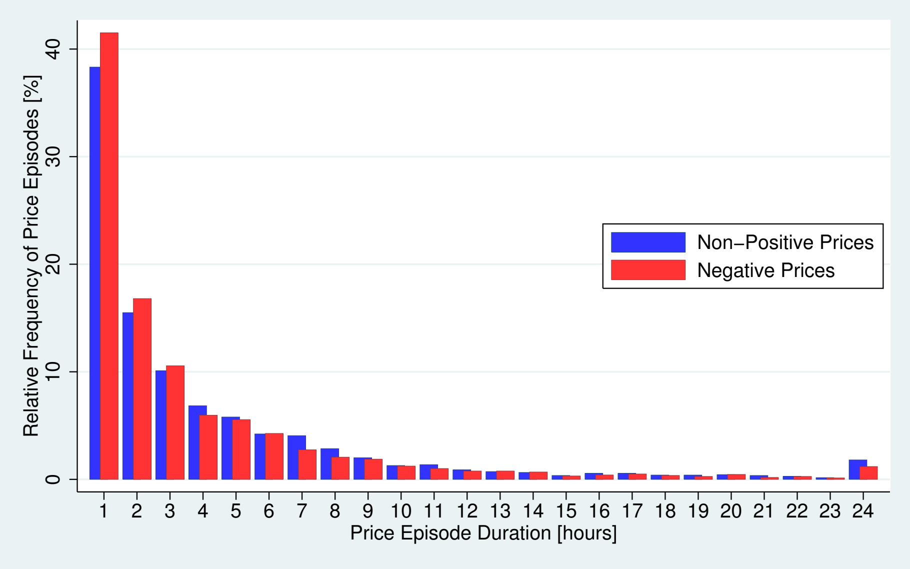
$$\pi = \int_0^T \bar{p}(1 - \omega(t))(x(t)S + y(t)K)dt - [f_1 K + (f_2/2)K^2 + hS]$$

- Correlation of $\omega(t)$ and $y(t)$ can become positive at high rates of renewables penetration or locational clustering; this effect reduces generation capacity but increases battery capacity.
- Battery utilization function $u(\kappa \equiv K/S) = \int_0^T \frac{1}{2}x(t)\mathrm{d}t$ depends on y and ω so that optimal $\kappa^* = [u'(\kappa)]^{-1}(h/\bar{p}\bar{y}\bar{\omega})$

Negative/Non-Positive Electricity Prices in Ontario

Zone	Node	Negative Prices ($p < 0$) Event Freq. [%]	Negative Prices ($p < 0$) Mean Dura. [hours]	Negative Prices ($p < 0$) Lapse Time [hours]	Non-Positive Prices ($p \leq 0$) Event Freq. [%]	Non-Positive Prices ($p \leq 0$) Mean Dura. [hours]	Non-Positive Prices ($p \leq 0$) Lapse Time [hours]
IESO HOEP		12.51	4.82	38.49	19.27	5.32	27.61
Reference	Richview	11.96	3.03	25.35	20.19	3.98	19.73
North West	Atikokan	19.20	3.26	17.00	25.47	3.68	14.47
North West	Pineportage	25.18	4.05	16.10	32.21	4.55	14.12
North West	Thunderbay	12.15	3.03	24.96	20.37	3.97	19.48
North East	Andrews	18.96	3.55	18.74	26.42	4.21	15.93
North East	Canyon	12.19	3.02	24.82	20.09	3.93	19.57
North East	NPIroqfalls	13.10	3.12	23.84	21.02	3.99	18.97
Ottawa	TAOHSC	11.97	3.02	25.19	20.16	3.95	19.61
East	Saunders	12.00	3.02	25.15	20.23	3.97	19.63
Toronto	Darlington	11.98	3.03	25.28	20.20	3.98	19.70
Essa	Desjoachims	11.95	3.03	25.39	20.17	3.99	19.78
Bruce	BruceB	11.98	3.03	25.26	20.21	3.98	19.70
South West	GerdauCam	11.89	3.02	25.43	20.07	3.97	19.75
Niagara	BECK2	11.85	3.02	25.46	20.03	3.96	19.78
West	Greenfield	11.94	3.03	25.37	20.12	3.97	19.72

Curtailment Risk: Duration of Negative+Zero Prices



Supply-Side Storage: Key Results

- Curtailment risk can be decomposed into frequency of curtailment events and duration of curtailment events.
  - Frequency of events helps with utilization of batteries.
  - Duration of events (and distribution) determines optimal battery size.
- Curtailment risk can be proxied by episodes of negative or non-positive prices. Curtailments tend to be short in duration (less than 4 hours) and frequent (more than daily). Requires high charging/discharging speeds to be viable.
- Correlation of curtailment risk and output matters: batteries are more useful when curtailments occur when output is high; this effect will increase with high rate of renewables penetration and clustering of generator locations.

Conclusions

- **Business Models**
  - With current state of technology, grid-scale energy storage is not economical in most locations. Require net revenue of at least CAD $4-5 per MWh storage per hour, or
  - Batteries can be useful to improve utilization of transmission lines with high marginal cost that serve remote communities.
  - Batteries for intermittent electricity producers useful only with high frequency and long duration of curtailments.

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- **Location Heterogeneity**
  - Battery deployment can be economical to relieve significant grid congestion in specific locations: in Ontario, in the Northwest and Northeast electricity zones.
  - Curtailment risk is geographically clustered.

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  - Battery deployment can be economical to relieve significant grid congestion in specific locations: in Ontario, in the Northwest and Northeast electricity zones.
  - Curtailment risk is geographically clustered.
- **Policy Implications**
  - Nodal (locational marginal) pricing is needed to provide appropriate incentives for deployment in the right location. Ontario's IESO is moving in this direction.

THANK YOU