Merchant Storage Investment in a Restructured Electricity Industry

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   - Assumptions
   - Generator Equilibrium
   - Profit-Maximising Storage Investor
   - Welfare-Maximising Storage Investor
3. Analytical Insights
   - Comparative Statics and Welfare Analysis
   - Numerical Results
4. Welfare Enhancement via Ramping Charges
5. Concluding

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Interest in Energy Storage

- Growing interest in energy storage, driven by market and technical changes
- Legislators, policymakers, and regulators are reducing barriers to storage entry or promoting actively entry
- Question: Are these polices well guided?

Market Analysis of Storage

- [Sioshansi, 2010] analyses the welfare impacts of storage with perfectly competitive generation: merchant- and generation-owned energy storage is underused relative to welfare-maximum, while consumer-owned storage can be welfare diminishing compared to no storage
- [Sioshansi, 2011, Schill and Kemfert, 2011] consider storage in Texas and Germany: adding storage can reduce social welfare relative to a no-storage case
- [Sioshansi, 2014] demonstrates conditions under which storage can reduce social welfare—only with imperfectly competitive generation
- [Virasjoki et al., 2016] take a complementarity approach to assess storage operations under uncertainty and with transmission constraints (with and without market power)
- [Nasrolahpour et al., 2016] use a bi-level model to assess storage investment by a merchant

Market Impacts of Storage

- Existing analyses suggest a mixed picture: in some cases storage can be welfare-diminishing
- These analyses all take an exogenously fixed amount of storage capacity
- Is welfare-diminishing storage-investment optimal for a merchant firm?

Findings

- More market power leads to more storage capacity by the welfare-maximiser relative to the profit-maximiser
- Less market power obviates the need for storage, and welfare-maximiser invests in less capacity
- Under approximately perfect competition, profit-maximising storage investment may actually be welfare-diminishing relative to no storage at all, unlike in [Sioshansi, 2014]
- A ramping charge can improve social welfare above the welfare-maximiser's level

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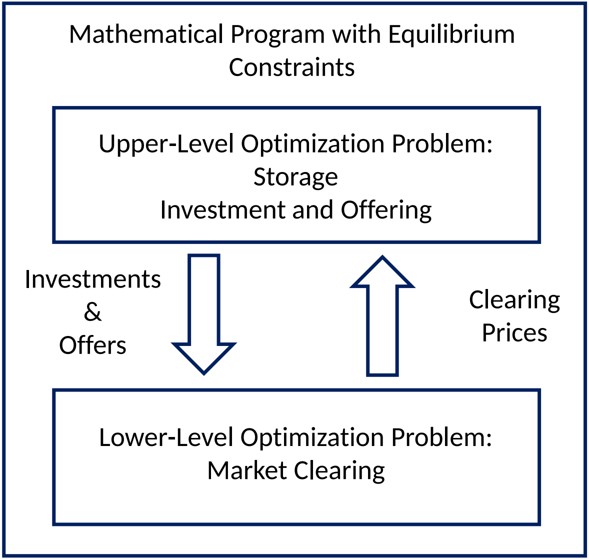
Model Structure



Two-Stage Framework

- Stage 1: Investment by storage investor/operator
- Stage 2: Storage investor/operator determines how much energy to store and discharge during off- and on-peak periods, while generators simultaneously determine production levels
- Stage-2 competition *à la* Nash-Cournot
- No uncertainty or transmission constraints
- Due to sequential nature, we work backwards through the decision stages to find subgame-perfect Nash equilibrium

Stage 2

Operations

- Two periods, $t = 1, 2$, that correspond to off- and on-peak, respectively
- N symmetric profit-maximising firms with linear generation functions, $c(g_{n,t}) = Bg_{n,t}, n = 1, \ldots, N$, where $g_{n,t}$ is generation output (in MW)
- Define total period-t generator output:

$$g_t^G \equiv \sum_{n=1}^{N} g_{n,t}$$

- Period-t inverse demand function (in \$/MW) is $P_t(x) = A_t - Z_t x$, where $A_2 > A_1 > 0$, $Z_t > 0$, $A_2/Z_2 > A_1/Z_1$, and $A_2 > A_1 > B > 0$ (i.e., period-2 demand function always greater than period-1 demand function)
- Storage operations with efficiency $0 < E \leq 1$: charge d/E MW in period 1 and discharge d MW in period 2 (let $F \equiv 1/E$)

Stage 1

Investment

- How much storage capacity, k, to install with investment cost of $\frac{1}{2} I k^2$, where $I > 0$

Generator Profit-Maximisation

- Generator *n*'s profit-maximisation problem:

$$\max_{g_{n,1}\geq 0, g_{n,2}\geq 0} P_1(g_1^G - Fd)g_{n,1} - Bg_{n,1} + P_2(g_2^G + d)g_{n,2} - Bg_{n,2}$$

- The KKT conditions for generator *n*'s problem give:

$$0 \leq -A_1 + Z_1 \cdot (g_1^G - Fd) + Z_1 g_{n,1} + B \perp g_{n,1} \geq 0 \quad (1)$$

$$0 \leq -A_2 + Z_2 \cdot (g_2^G + d) + Z_2 g_{n,2} + B \perp g_{n,2} \geq 0 \quad (2)$$

- By symmetry, we have:

$$g_{n,t} = \frac{g_t^G}{N}, \forall n, t$$

Generator Equilibrium

- Industry output and equilibrium price in each period is:

$$g_1^G(d) = \left(\frac{N}{N+1}\right)\left(\frac{A_1 + Z_1 F d - B}{Z_1}\right) \quad (3)$$

$$g_2^G(d) = \left(\frac{N}{N+1}\right)\left(\frac{A_2 - Z_2 d - B}{Z_2}\right) \quad (4)$$

$$p_1(d) = \frac{A_1 + Z_1 F d + BN}{N+1} \quad (5)$$

$$p_2(d) = \frac{A_2 - Z_2 d + BN}{N+1} \quad (6)$$

Stage-2 Operating Equilibrium

- The storage owner's lower-level operational problem is:

$$\max_{d \geq 0} \; d[p_2(d) - Fp_1(d)] \tag{7}$$

$$\text{s.t.} \; d \leq k; \qquad (\mu) \tag{8}$$

- The KKT conditions for the storage operator's problem are:

$$0 \leq -(p_2(d) - Fp_1(d)) - dp_2'(d) + dFp_1'(d) + \mu \perp d \geq 0 \tag{9}$$

$$0 \leq k - d \perp \mu \geq 0 \tag{10}$$

- There are three possibilities for the solution, $d^*(k)$:

$$d^*(k) = \begin{cases} 0, & \text{if } p_2(0) - Fp_1(0) < 0 \\ k, & \text{if } \frac{p_2(0) - Fp_1(0)}{2[Fp_1'(0) - p_2'(0)]} \geq k \\ \frac{p_2(0) - Fp_1(0)}{2[Fp_1'(0) - p_2'(0)]}, & \text{otherwise} \end{cases}$$

Stage-1 Investment Equilibrium

- Profit-maximising storage investor solves:

$$\max_{k \geq 0} \; [p_2(d^*(k)) - Fp_1(d^*(k))]d^*(k) - \frac{1}{2}Ik^2$$

- Because $d^*(k) = k$ solves (9)–(10) and $p_t(d^*(k))$ solves (1)–(2), $n = 1, \ldots, N, t = 1, 2$ investor's problem simplifies to:

$$\max_{k \geq 0} \; [p_2(k) - Fp_1(k)]k - \frac{1}{2}Ik^2 \qquad (11)$$

- KKT conditions are:

$$-p_2(k) + Fp_1(k) + Ik - kp_2'(k) + Fkp_1'(k) \geq 0 \perp 0 \leq k,$$

which give:

$$k^* = \frac{A_2 - FA_1 - BN(F-1)}{I(N+1) + 2F^2Z_1 + 2Z_2},$$

as profit-maximising investment level

Welfare-Maximising Storage Use

- Generators' problems are unaffected by the change of storage owner, their equilibrium behaviour is still characterised by (3)–(6)
- To characterise welfare-maximising storage operation define:

$$W_1^C(k) = \frac{Z_1}{2(N+1)^2}\left[N\frac{(A_1 - B)}{Z_1} - Fk\right]^2$$

$$W_2^C(k) = \frac{Z_2}{2(N+1)^2}\left[N\frac{(A_2 - B)}{Z_2} + k\right]^2$$

$$W_1^G(k) = \frac{Z_1 N}{(N+1)^2}\left[\frac{A_1 - B}{Z_1} + Fk\right]^2$$

$$W_2^G(k) = \frac{Z_2 N}{(N+1)^2}\left[\frac{A_2 - B}{Z_2} - k\right]^2$$

Stage-2 Operating Equilibrium

- Welfare-maximiser's storage-operation problem:

$$\max_{d \geq 0} \; [W_1^C(d) - W_1^C(0)] + [W_2^C(d) - W_2^C(0)] + [W_1^G(d) - W_1^G(0)]$$
$$+ [W_2^G(d) - W_2^G(0)] + d[p_2(d) - Fp_1(d)]$$
$$\text{s.t. } d \leq k; \qquad (\mu)$$

- The KKT conditions are:

$$0 \leq \frac{FZ_1}{(N+1)^2}\left[\frac{N(A_1 - B)}{Z_1} - Fd\right] - \frac{Z_2}{(N+1)^2}\left[\frac{N(A_2 - B)}{Z_2} + d\right]$$
$$- \frac{2FZ_1N}{(N+1)^2}\left[\frac{(A_1 - B)}{Z_1} + Fd\right] + \frac{2Z_2N}{(N+1)^2}\left[\frac{(A_2 - B)}{Z_1} - d\right]$$
$$- \frac{(A_2 - Z_2 d + BN)}{(N+1)} + F\frac{(A_1 - Z_1 Fd + BN)}{(N+1)} - (p_2(d) - Fp_1(d))$$
$$- dp_2'(d) + dFp_1'(d) + \mu \perp d \geq 0$$
$$0 \leq k - d \perp \mu \geq 0$$

Stage-2 Operating Equilibrium

- There are three possibilities for the solution, $\hat{d}(k)$:

$$\hat{d}(k) = \begin{cases} 0, & \text{if } A_2 - FA_1 - BN(F-1)(N+2) < 0 \\ k, & \text{if } \frac{A_2 - FA_1 - BN(F-1)(N+2)}{F^2 Z_1 + Z_2} \geq k \\ \frac{A_2 - FA_1 - BN(F-1)(N+2)}{F^2 Z_1 + Z_2}, & \text{otherwise} \end{cases}$$

Stage-1 Investment Equilibrium

- Welfare-maximising storage investor solves:

$$\max_{k\geq 0} [W_1^C(\hat{d}(k)) - W_1^C(0)] + [W_2^C(\hat{d}(k)) - W_2^C(0)] + [W_1^G(\hat{d}(k)) - W_1^G(0)]$$
$$+ [W_2^G(\hat{d}(k)) - W_2^G(0)] + [p_2(\hat{d}(k)) - Fp_1(\hat{d}(k))]\hat{d}(k) - \frac{1}{2}Ik^2$$

- Which simplifies to:

$$\max_{k\geq 0} [W_1^C(k) - W_1^C(0)] + [W_2^C(k) - W_2^C(0)] + [W_1^G(k) - W_1^G(0)]$$
$$+ [W_2^G(k) - W_2^G(0)] + [p_2(k) - Fp_1(k)]k - \frac{1}{2}Ik^2$$

- The KKT conditions give:

$$\hat{k} = \frac{A_2 - FA_1 - BN(F-1)(N+2)}{[I(N+1)^2] + F^2Z_1 + Z_2}$$

as the welfare-maximising profit level

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Storage-Investment Levels

Proposition

The welfare maximiser's storage-investment level is larger (smaller) than the profit maximiser's storage-investment level if the number of generating firms is less (greater) than a critical cutoff value, $\bar{N}$.
Moreover, starting from the profit maximiser's storage-investment level, an infinitesimal increase (decrease) in storage capacity is always welfare-enhancing for $N < \bar{N}$ ($N > \bar{N}$).

Proposition

$\bar{N}$ is strictly decreasing in the storage-investment-cost parameter, I, and is strictly decreasing in the generation-cost parameter, B.

Proposition

The profit maximiser's and welfare maximiser's storage-investment levels decrease with more generating firms.

Storage-Investment Levels

Threshold Number of Firms

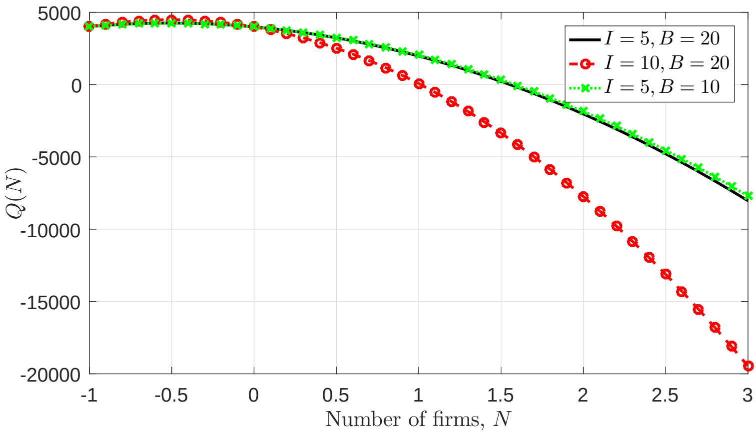
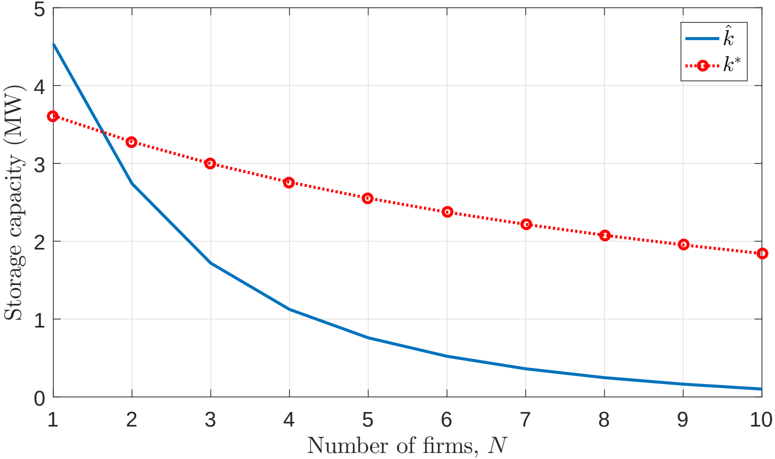


Figure : Positive Root of $Q(N)$ Gives Threshold Number of Firms

Storage-Investment Levels

Investment Levels



Generation-Equilibrium Impact

Proposition

The equilibrium price differential, $p_2(d) - Fp_1(d)$, decreases with storage use. It also decreases with more generating firms.

Social-Welfare Impact

Proposition

The total social welfare that is achieved by the profit maximiser's storage-investment level is strictly greater (less) than the social welfare that is achieved without any storage investment, so long as the number of firms is less (greater) than some critical threshold, $\tilde{N}$, which is strictly greater than $\bar{N}$.

- This result is in contrast to the welfare-impact findings of [Sioshansi, 2011, Schill and Kemfert, 2011, Sioshansi, 2014]

Social-Welfare Impacts of Energy Storage

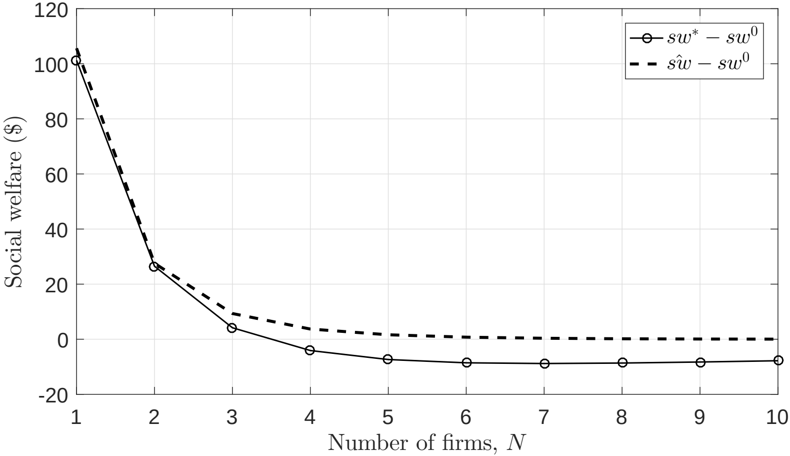


Figure : $A_1 = 200$, $A_2 = 400$, $Z_1 = 10$, $Z_2 = 10$, $B = 20$, $I = 5$, $E = 0.95$

Investment Levels and Welfare Impacts

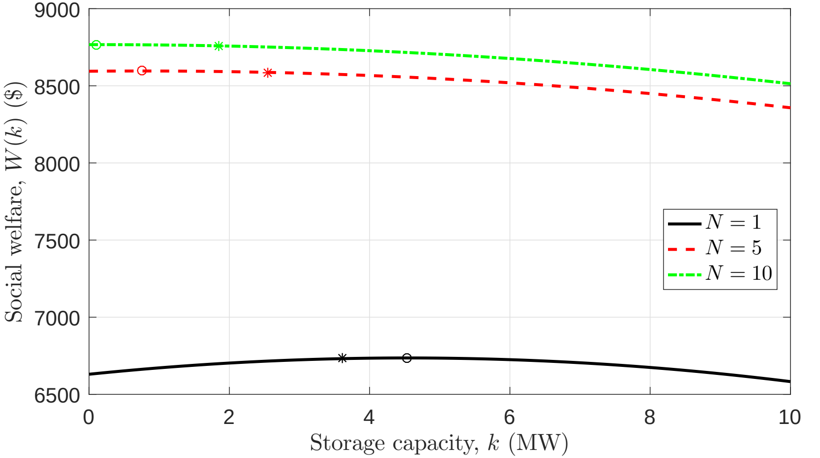


Figure : ○: Welfare-Maximiser's Storage-Investment Level

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Ramping Charge

- Concept: charge or pay generators for differences in their production levels between two periods
- [Zhao et al., 2017]: This is implicitly done today in wholesale markets that include explicit generator-ramping constraints in the dispatch model, by virtue of dual problem
- Depending on its sign, a ramping charge incentivizes bigger or smaller differences in production levels and prices between on- and off-peak periods, with two potential welfare effects:
  1. mitigate/exacerbate exercise of market power by generators
  2. change profit-maximising storage-investment level
- Thus, it can serve to better align incentives of market participants with societal goals

Generator Profit-Maximisation

- Generator *n*'s profit-maximisation problem with ramping charge, *R*:

$$\max_{g_{n,1}\geq 0, g_{n,2}\geq 0} P_1(g_1^G - Fd)g_{n,1} - Bg_{n,1} + P_2(g_2^G + d)g_{n,2} - Bg_{n,2}$$
$$-R \cdot (g_{n,2} - g_{n,1})$$

- New generator equilibrium:

$$\underline{g}_1^G(d) = \left(\frac{N}{N+1}\right)\left(\frac{A_1 + Z_1 Fd - B + R}{Z_1}\right)$$

$$\underline{g}_2^G(d) = \left(\frac{N}{N+1}\right)\left(\frac{A_2 - Z_2 d - B - R}{Z_2}\right)$$

$$\underline{p}_1(d) = \frac{A_1 + Z_1 Fd + (B - R)N}{N+1}$$

$$\underline{p}_2(d) = \frac{A_2 - Z_2 d + (B + R)N}{N+1}$$

Profit-Maximising Storage Investor/Operator

- Profit-maximising storage owner's operational problem is still (7)–(8)
- Investment problem is still (11), but with $\underline{p}_t(k)$ instead of $p_t(k)$
- KKT condition now yields:

$$\underline{k} = \frac{A_2 - FA_1 - BN(F-1) + RN(F+1)}{I(N+1) + 2F^2Z_1 + 2Z_2}$$

- To achieve $\underline{k} = \hat{k}$ need:

$$R = \frac{(A_2 - FA_1)[F^2Z_1 + Z_2 - IN(N+1)]}{N(F+1)[I(N+1)^2 + F^2Z_1 + Z_2]} - \frac{BN(F-1)[I(N+1) + (2N+3)(F^2Z_1 + Z_2)]}{N(F+1)[I(N+1)^2 + F^2Z_1 + Z_2]}$$

Central-Planning Benchmark

- Compare welfare outcomes to a central-planning benchmark
- Assuming that storage capacity is fully utilised, the central planner's problem is:

$$\max_{g_1^G \geq 0, g_2^G \geq 0, k \geq 0} A_1(g_1^G - Fk) - \frac{Z_1}{2}(g_1^G - Fk)^2 + A_2(g_2^G + k) - \frac{Z_2}{2}(g_2^G + k)^2 - B(g_1^G + g_2^G) - \frac{1}{2}Ik^2$$

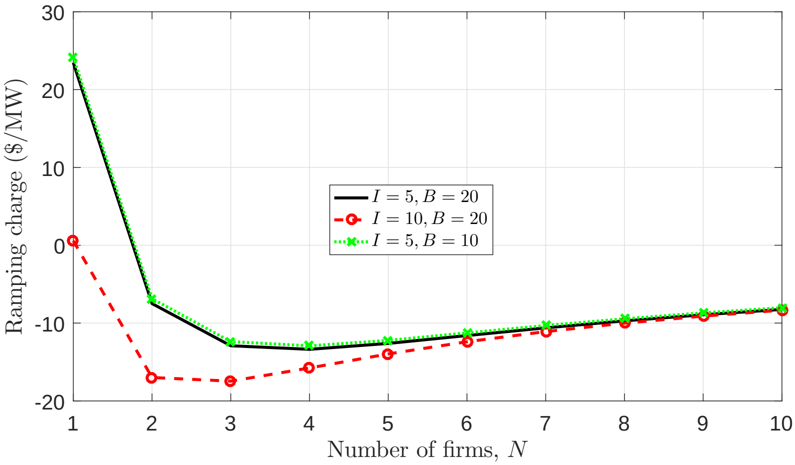
- The socially optimal solution is:

$$\overline{g}_1^G = \frac{A_1 - B}{Z_1}$$

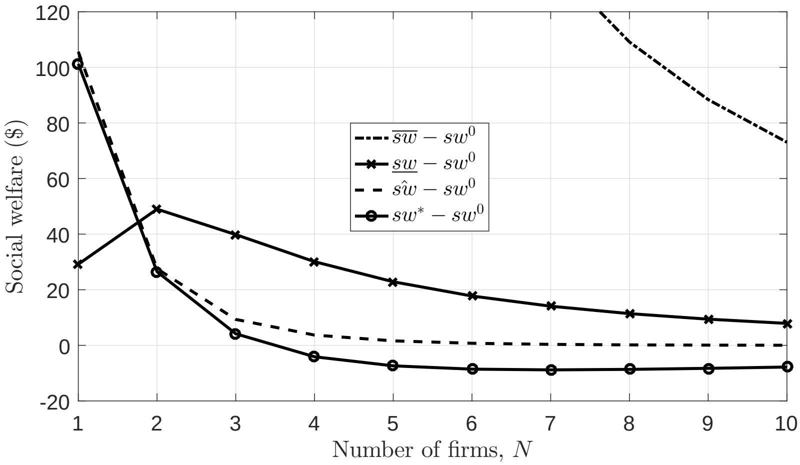
$$\overline{g}_2^G = \frac{A_2 - B}{Z_2}$$

$$\overline{k} = 0$$

Optimal Ramping Charge Levels



Welfare Impact of Ramping Charge



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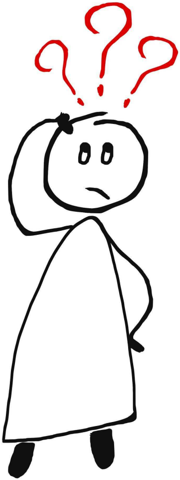
Summary

- Welfare-maximising level of storage investment is less than the profit-maximising level, unless market power is high
- Both higher storage investment cost and generation cost reduce the welfare-maximising investment level (it's more costly to mitigate generation market power with storage)
- With sufficiently competitive generation sector, higher storage capacity benefits a profit-maximising owner through higher volume
- Thus, it may even be beneficial to have no storage built compared to the profit-maximising level
  - ➥ This finding differs from previous analyses, which only show welfare losses from consumer-owned storage or with concentrated generation sector
- A ramping charge allows another degree of freedom to align profit-maximiser's decision with that of society, while also mitigating exercise of market power by generators
- These findings are robust to having linear (instead of constant) marginal generation costs

Questions?



References I

- Nasrolahpour, E., Kazempour, S. J., Zareipour, H., and Rosehart, W. D. (2016).
  Strategic Sizing of Energy Storage Facilities in Electricity Markets.
  IEEE Transactions on Sustainable Energy, 7:1462–1472.

- Schill, W.-P. and Kemfert, C. (2011).
  Modeling Strategic Electricity Storage: The Case of Pumped Hydro Storage in Germany.
  The Energy Journal, 32:59–88.

- Sioshansi, R. (2010).
  Welfare Impacts of Electricity Storage and the Implications of Ownership Structure.
  The Energy Journal, 31:173–198.

- Sioshansi, R. (2011).
  Increasing the Value of Wind with Energy Storage.
  The Energy Journal, 32:1–30.

References II

Sioshansi, R. (2014).
When Energy Storage Reduces Social Welfare.
Energy Economics, 41:106–116.

Virasjoki, V., Rocha, P., Siddiqui, A. S., and Salo, A. (2016).
Market Impacts of Energy Storage in a Transmission-Constrained Power System.
IEEE Transactions on Power Systems, 31:4108–4117.

Zhao, B., Conejo, A. J., and Sioshansi, R. (2017).
Unit Commitment Under Gas-Supply Uncertainty and Gas-Price Variability.
IEEE Transactions on Power Systems, 32:2394–2405.