

# Merchant Storage Investment in a Restructured Electricity Industry

Afzal Siddiqui<sup>a,b,c,d</sup> Ramteen Sioshansi<sup>e</sup> Antonio J. Conejo<sup>e,f</sup>

<sup>a</sup>Department of Statistical Science, University College London

<sup>b</sup>Department of Computer and Systems Sciences, Stockholm University

<sup>c</sup>Department of Decision Sciences, HEC Montréal

<sup>d</sup>Department of Mathematics and Systems Analysis, Aalto University

<sup>e</sup>Department of Integrated Systems Engineering, The Ohio State University

<sup>f</sup>Department of Electrical and Computer Engineering, The Ohio State University

Electricity Systems of the Future: Incentives, Regulation and Analysis for  
Efficient Investment

Isaac Newton Institute for Mathematical Sciences

University of Cambridge

Cambridge, United Kingdom

19 March, 2019

# Outline

- 1 Introduction
- 2 Mathematical Formulation
  - 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

# Outline

- 1 Introduction
- 2 Mathematical Formulation
  - 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

# Interest in Energy Storage

- Growing interest in energy storage, driven by market and technical changes
  - Novel uses of storage
  - High-cost conventional alternatives
  - Markets provide transparent price signals for *some* storage services
  - Ability to address renewable-integration challenges
- Legislators, policymakers, and regulators are reducing barriers to storage entry
- Actively promoting entry in some cases
- **Question:** Are these policies well guided?

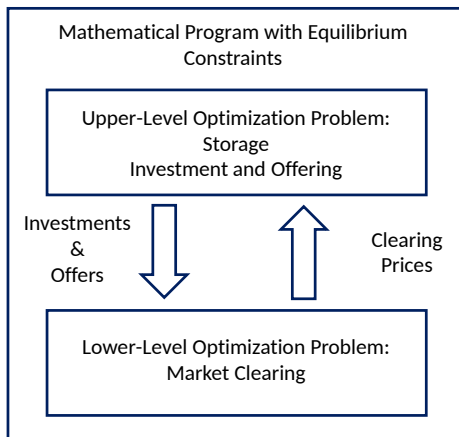
# Market Analysis of Storage

- [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 without transmission constraints: 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?

# Research Question and Approach



- Examine the economic-efficiency impacts of energy storage investment, given market power
- How are energy storage capacity and social welfare affected by the type of storage owner?
- Use a bi-level model: profit-maximising generators and a profit- or welfare-maximising storage investor/operator

# Research 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



# Outline

- 1 Introduction
- 2 **Mathematical Formulation**
  - 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

# 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,  $c(g_{n,t}) = Bg_{n,t}$ ,  $n = 1, \dots, N$ , 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  $\frac{1}{2}lk^2$ , where  $l > 0$

# 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:

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

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

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

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

## Stage-2 Operating Equilibrium

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

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

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

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

$$0 \leq -(p_2(d) - Fp_1(d)) - dp'_2(d) + dFp'_1(d) + \mu \perp d \geq 0 \quad (9)$$

$$0 \leq k - d \perp \mu \geq 0 \quad (10)$$

- 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:

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

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

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

- KKT conditions are:

$$-p_2(k) + Fp_1(k) + lk - kp'_2(k) + Fkp'_1(k) \geq 0 \perp 0 \leq k,$$

which give:

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

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:

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

- The KKT conditions are:

$$\begin{aligned}
 0 \leq & \frac{FZ_1}{(N+1)^2} \left[ \frac{N(A_1 - B)}{Z_1} - Fd \right] - \frac{Z_2}{(N+1)^2} \left[ \frac{N(A_2 - B)}{Z_2} + d \right] \\
 & - \frac{2FZ_1N}{(N+1)^2} \left[ \frac{(A_1 - B)}{Z_1} + Fd \right] + \frac{2Z_2N}{(N+1)^2} \left[ \frac{(A_2 - B)}{Z_1} - d \right] \\
 & - \frac{(A_2 - Z_2d + BN)}{(N+1)} + F \frac{(A_1 - Z_1Fd + BN)}{(N+1)} - (p_2(d) - Fp_1(d)) \\
 & - dp'_2(d) + dFp'_1(d) + \mu \perp d \geq 0 \\
 0 \leq & k - d \perp \mu \geq 0
 \end{aligned}$$

# Stage-2 Operating Equilibrium

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

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

# Stage-1 Investment Equilibrium

- Welfare-maximising storage investor solves:

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

- Which simplifies to:

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

- 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

# Outline

- 1 Introduction
- 2 Mathematical Formulation
  - 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

# 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

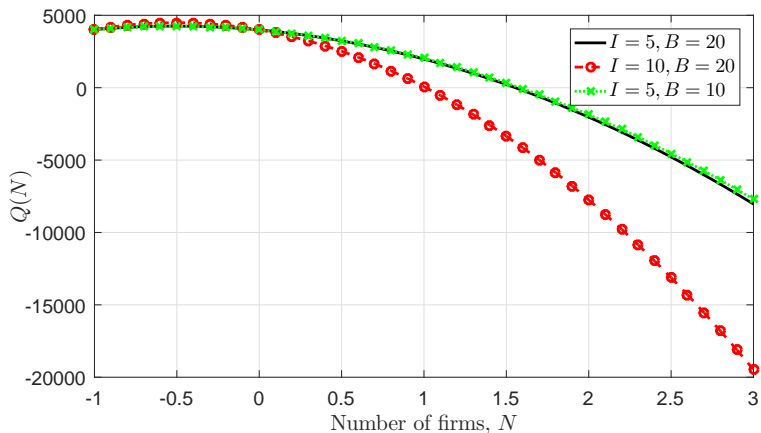
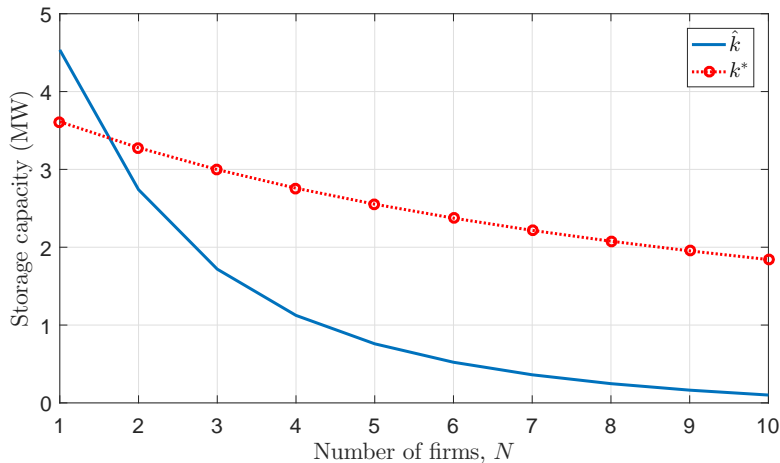


Figure : Positive Root of  $Q(N)$  Gives Threshold Number of Firms

# 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

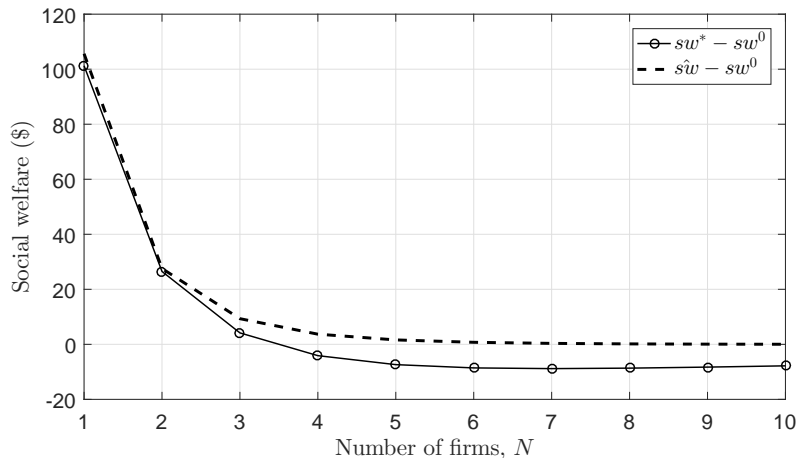


Figure :  $A_1 = 200$ ,  $A_2 = 400$ ,  $Z_1 = 10$ ,  $Z_2 = 10$ ,  $B = 20$ ,  $I = 5$ ,  $E = 0.95$

# Investment Levels and Welfare Impacts

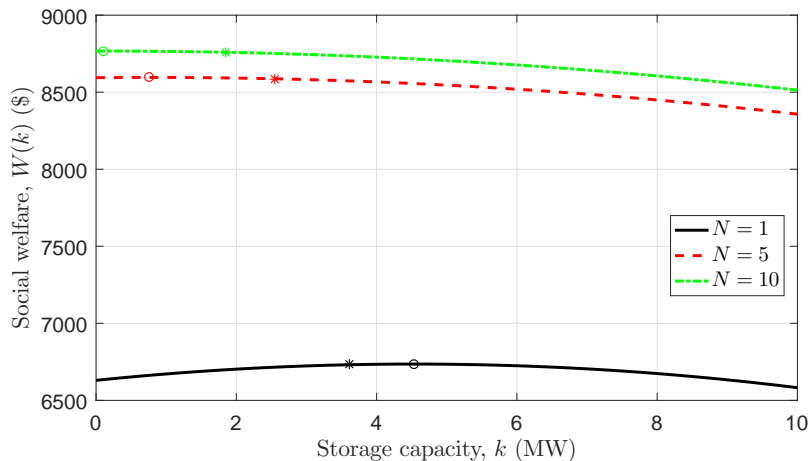


Figure : ○: Welfare-Maximiser's Storage-Investment Level

# Outline

- 1 Introduction
- 2 Mathematical Formulation
  - 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

# 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:

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

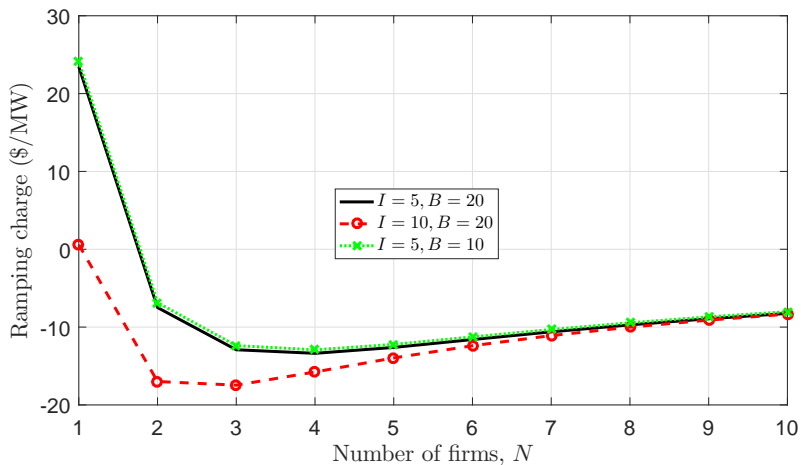
- The socially optimal solution is:

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

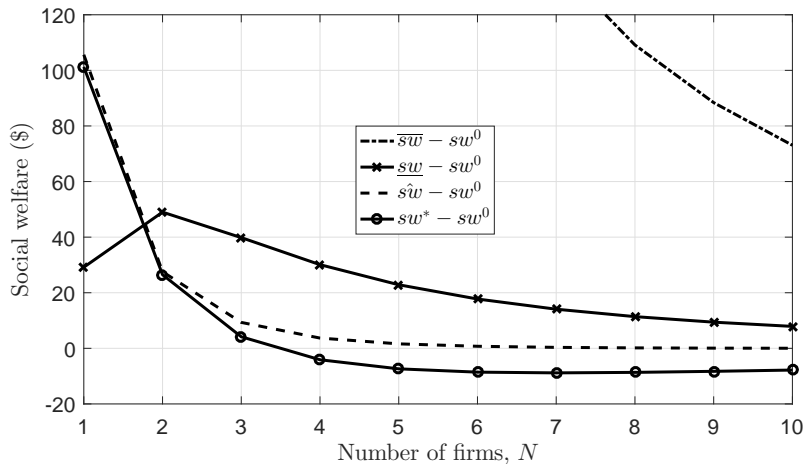
$$\bar{g}_2^G = \frac{A_2 - B}{Z_2}$$

$$\bar{k} = 0$$

# Optimal Ramping Charge Levels



# Welfare Impact of Ramping Charge



# Outline

- 1 Introduction
- 2 Mathematical Formulation
  - 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

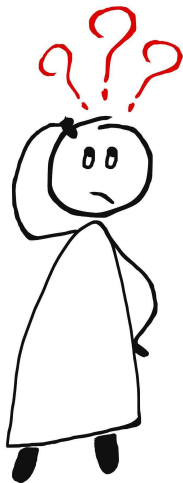
# Summary

- 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





# Future Work

- Stochastic model: how do renewables and renewable-related policies change the picture
- Generator- and/or customer-owned storage
- Transmission constraints
- Multiple storage owners: does competitive entry exacerbate or mitigate welfare impacts of profit-maximising storage investment

# 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.