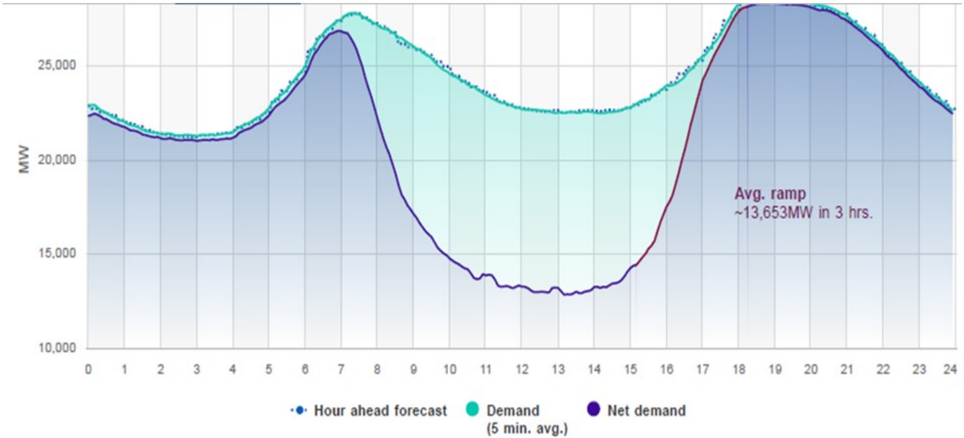
The Economics of Electricity Storage

Natalia Fabra[1]

[1]**Universidad Carlos III de Madrid**

February 22, 2023

The "Duck curve"



The Duck: CAISO Total Demand and Net (of Solar and Wind) Demand for Feb 7, 2019

(source: http://www.caiso.com/TodaysOutlook/Pages/default.aspx)

Introduction

- **Storage** links markets **over time**
- ...just as **transportation** links markets **over space**
- Storage smooths price movements by allowing **arbitrage** over time
  - Predicted demand fluctuations
  - Unpredicted demand fluctuations
  - Temporary production outages
  - Adapting to changes in input or output price changes

Storing electricity

Two types of storage facilities:

- **Hydro generation and storage**
  - Conventional hydro (in reservoir)
  - Pumped storage (bring water uphill; approx. 50% energy loss)
  - Capacity constraints and minimum flows
- **Efficient batteries**

Storing electricity

Two types of storage facilities:

- **Hydro generation and storage**
  - Conventional hydro (in reservoir)
  - Pumped storage (bring water uphill; approx. 50% energy loss)
  - Capacity constraints and minimum flows
- **Efficient batteries**

Potential positive effects of storage (through *peak-shaving*):

- Storage reduces the need to invest in **back-up capacity**
  - It increases the value of renewable and conventional capacity

Storing electricity

Two types of storage facilities:

- **Hydro generation and storage**
  - Conventional hydro (in reservoir)
  - Pumped storage (bring water uphill; approx. 50% energy loss)
  - Capacity constraints and minimum flows
- **Efficient batteries**

Potential positive effects of storage (through *peak-shaving*):

- Storage reduces the need to invest in **back-up capacity**
  - It increases the value of renewable and conventional capacity
- Storage reduces **costs of producing electricity**
  - It increases demand when costs are low and increases supply when costs would otherwise be high

Relevant questions

1. Will **investment** in storage be socially optimal?
2. What are the effects of storage on **costs and prices**?
3. Do storage facilities confer **market power**?
4. Does **ownership** of storage matter?

Relevant questions

1. Will **investment** in storage be socially optimal?
2. What are the effects of storage on **costs and prices**?
3. Do storage facilities confer **market power**?
4. Does **ownership** of storage matter?

David Andrés-Cerezo and Natalia Fabra (2023),

Storing Power: Market Structure Matters

Storing technologies and market structure

- Different types of storage facilities...

Figure: Pumped hydro

Figure: Grid-scale batteries

Figure: Electric vehicle fleet

Storing technologies and market structure

- Different types of storage facilities...

Figure: Pumped hydro

Figure: Grid-scale batteries

Figure: Electric vehicle fleet

- ...that imply different **horizontal and vertical market structures:**
  - Competitive vs. strategic storage
  - Competitive vs. strategic production
  - Different **ownership structures** $\Rightarrow$ stand-alone vs. vertically integrated storage

Relevant questions

1. **Investment in storage capacity** .
   - Will it be socially optimal?
   - Does it depend on market structure?
2. **Productive efficiency and prices.**
   - What are the effects of strategic behavior and the ownership structure?
3. Do storage facilities confer **market power**? Do they mitigate market power in generation?

Modelling set-up

- **Demand**
  - Price- inelastic demand θ; consumers' valuation v.
  - θ is distributed according to a **symmetric** $G(\theta)$ in $\left[\underline{\theta}, \overline{\theta}\right]$.
    - θ can be interpreted as demand net of renewables.
    - Known at the production stage $\rightarrow$ **Focus on seasonal variation.**

Modelling set-up

- **Demand**
  - Price- inelastic demand θ; consumers' valuation v.
  - θ is distributed according to a **symmetric** $G(\theta)$ in $\left[\underline{\theta}, \overline{\theta}\right]$.
    - θ can be interpreted as demand net of renewables.
    - Known at the production stage $\rightarrow$ **Focus on seasonal variation.**
- **Generation**
  - Existing assets allow to produce with costs $\tilde{C}(Q)$ increasing and convex.

Modelling set-up

- **Demand**
  - Price- inelastic demand θ; consumers' valuation v.
  - θ is distributed according to a **symmetric** $G(\theta)$ in $\left[\underline{\theta}, \overline{\theta}\right]$.
    - θ can be interpreted as demand net of renewables.
    - Known at the production stage $\rightarrow$ **Focus on seasonal variation.**
- **Generation**
  - Existing assets allow to produce with costs $\tilde{C}(Q)$ increasing and convex.
- **Storage**
  - Storage capacity K (in MWh); Investment cost $C(K)$ increasing and convex.
  - $q^B(\theta), q^S(\theta)$: quantities bought (B) and sold (S) by the storage facility.

Demand process

Cycle.png

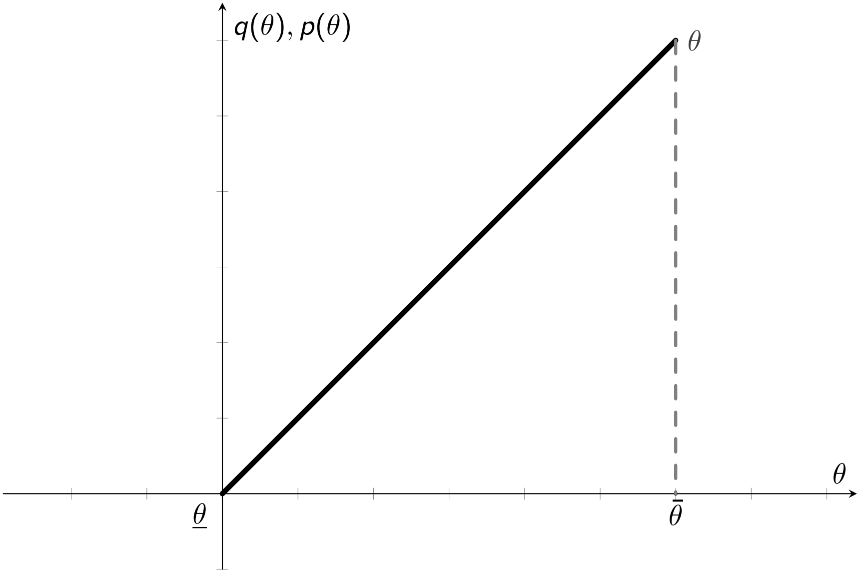
First Best Problem

Welfare is gross consumer surplus minus production and investment costs:

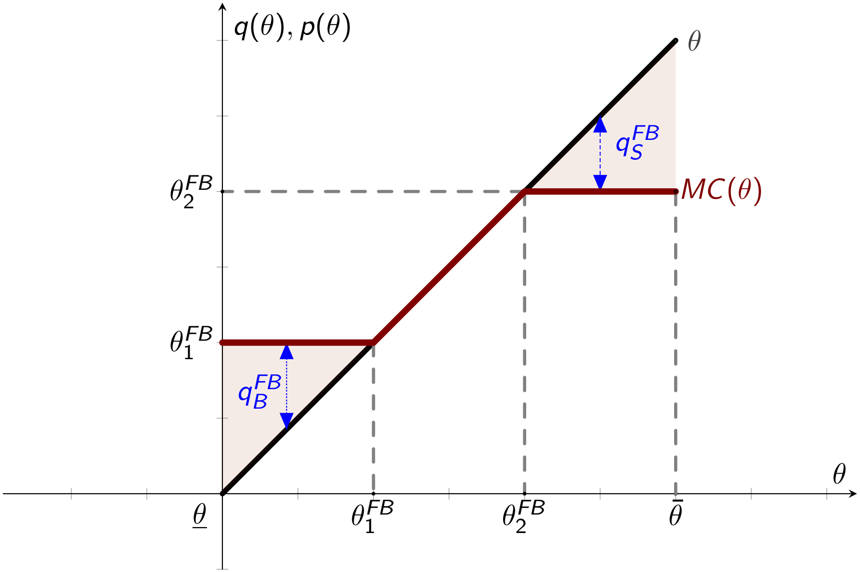
$$\max_{q^B(\theta), q^S(\theta), K} \mathcal{W} = \int_{\underline{\theta}}^{\overline{\theta}} v\theta dG(\theta) - \int_{\underline{\theta}}^{\overline{\theta}} \tilde{C}\big(\theta - q^S(\theta) + q^B(\theta)\big) dG(\theta) - C(K)$$

$$\begin{aligned} \text{s.t. } (\lambda) \quad &: \quad \int_{\underline{\theta}}^{\overline{\theta}} q^B(\theta) dG(\theta) \geq \int_{\underline{\theta}}^{\overline{\theta}} q^S(\theta) dG(\theta) \\ (\mu) \quad &: \quad \int_{\underline{\theta}}^{\overline{\theta}} q^B(\theta) dG(\theta) \leq K \end{aligned}$$

First Best

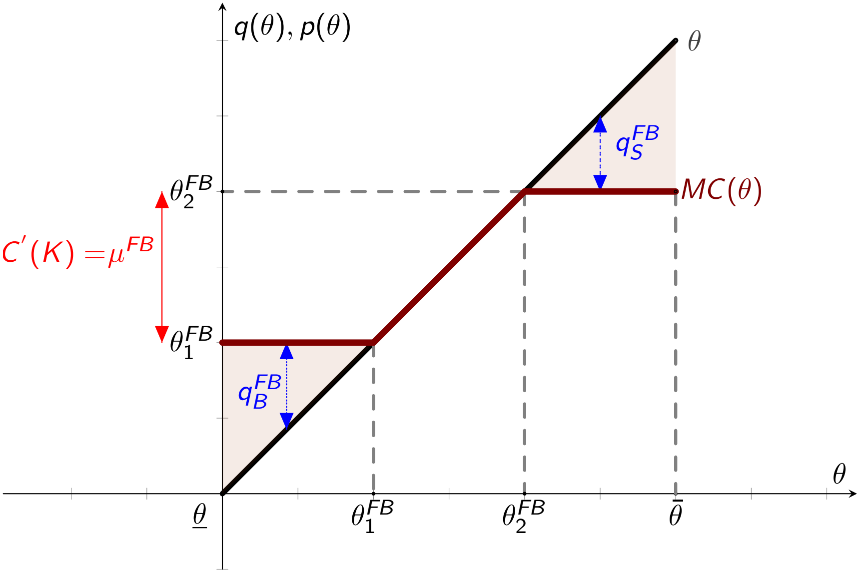


First Best



$q(\theta), p(\theta)$
θ
q_S^{FB}
θ_2^{FB}
$MC(\theta)$
θ_1^{FB}
q_B^{FB}
θ
$\underline{\theta}$
θ_1^{FB}
θ_2^{FB}
$\bar{\theta}$

First Best



$q(\theta), p(\theta)$
θ
q_S^{FB}
θ_2^{FB}
$MC(\theta)$
$C'(K) = \mu^{FB}$
θ_1^{FB}
q_B^{FB}
θ
$\underline{\theta}$
θ_1^{FB}
θ_2^{FB}
$\bar{\theta}$

First Best

- **Optimal storage management:**
  - Store when demand is low and release when demand is high.
  - Equalization of marginal costs within storing and releasing regions.
  - Minimization of total costs of production.
- **Optimal investment in storage:**
  - Marginal benefit $\Rightarrow$ Marginal cost saving from storing one more unit of output.
  - No full marginal cost equalization.

First Best

Horizontal market structure: Production

- Existing assets are owned by:
  - a **dominant firm** (α share), with costs $\tilde{C}_D(q) = \frac{q^2}{2\alpha}$.
  - a **competitive fringe** ($1 - \alpha$ share) with costs $\tilde{C}_F(q) = \frac{q^2}{2(1-\alpha)}$.
  - $\alpha \in (0, 1)$

Horizontal market structure: Production

- Existing assets are owned by:
  - a **dominant firm** (α share), with costs $\tilde{C}_D(q) = \frac{q^2}{2\alpha}$.
  - a **competitive fringe** ($1-\alpha$ share) with costs $\tilde{C}_F(q) = \frac{q^2}{2(1-\alpha)}$.
  - $\alpha \in (0,1)$
- Fringe produces $q_F = (1-\alpha)\,p(\theta)$,
- Dominant firm faces an **elastic residual demand**
  $D(\theta; p(\theta)) = \theta - q_S(\theta) + q_B(\theta) - (1-\alpha)\,p(\theta)$.

Independent storage: Dominant firm

- Maximize profits over the residual demand:

$$\max_{p(\theta)} \pi_D = p(\theta)\, D(\theta; p(\theta)) - \frac{[D(\theta; p(\theta))]^2}{2\alpha}$$

- **Optimal prices:**

$$p(\theta) = \frac{\theta - q^S(\theta) + q^B(\theta)}{1 - \alpha^2}$$

- Constant mark-up equal to α.
- Distorted market shares:
  - Dominant produces $\alpha/(1+\alpha) < \alpha$.
  - Fringe produces $1/(1+\alpha) > 1 - \alpha$

Second Best

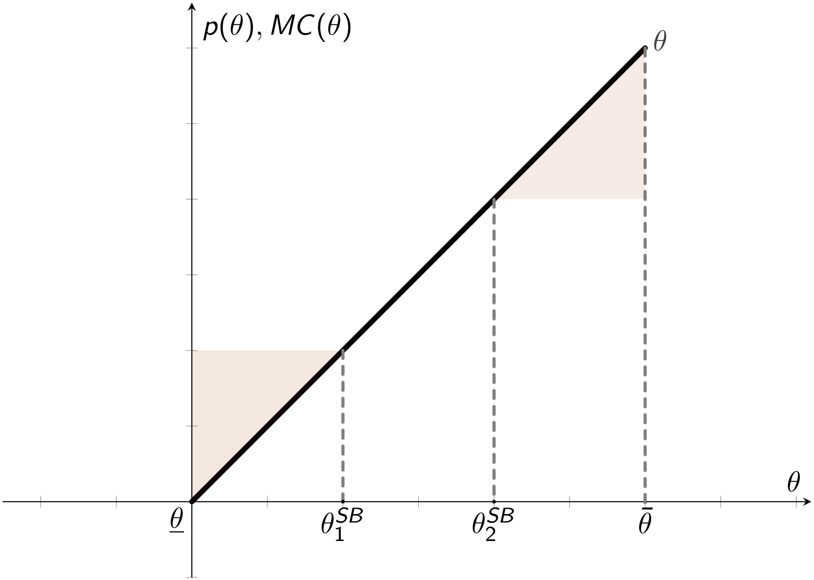
Maximize total welfare taking production decisions as given:

$$\max_{q^B(\theta),q^S(\theta),K} \mathcal{W} = \int_{\underline{\theta}}^{\overline{\theta}} v\theta dG\left(\theta\right) - \int_{\underline{\theta}}^{\overline{\theta}} \left(\frac{q_D^2}{2\alpha} + \frac{q_F^2}{2(1-\alpha)}\right) dG\left(\theta\right) - C\left(K\right)$$

subject to the storage constraints and taking as given that:

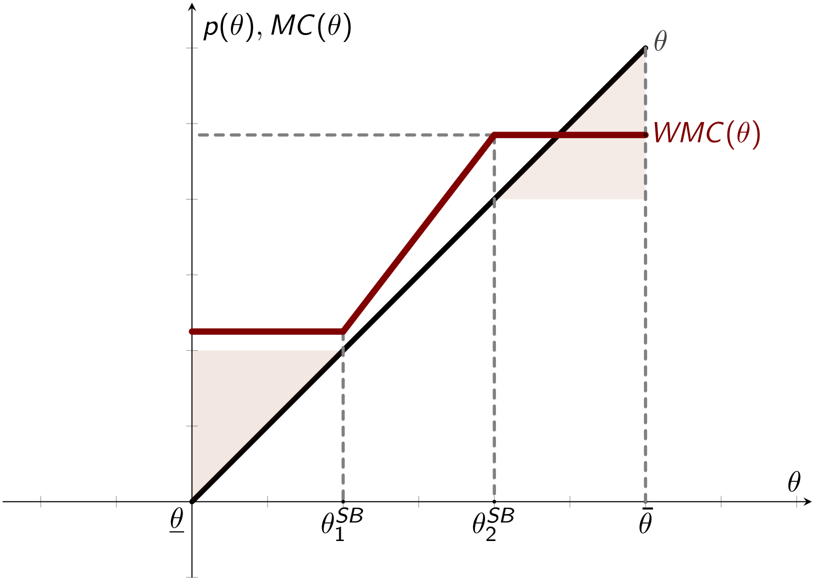
$$q_D = \frac{\alpha}{1+\alpha}\left[\theta - q^S(\theta) + q^B(\theta)\right]$$
$$q_F = \frac{1}{1+\alpha}\left[\theta - q^S(\theta) + q^B(\theta)\right]$$

Second Best



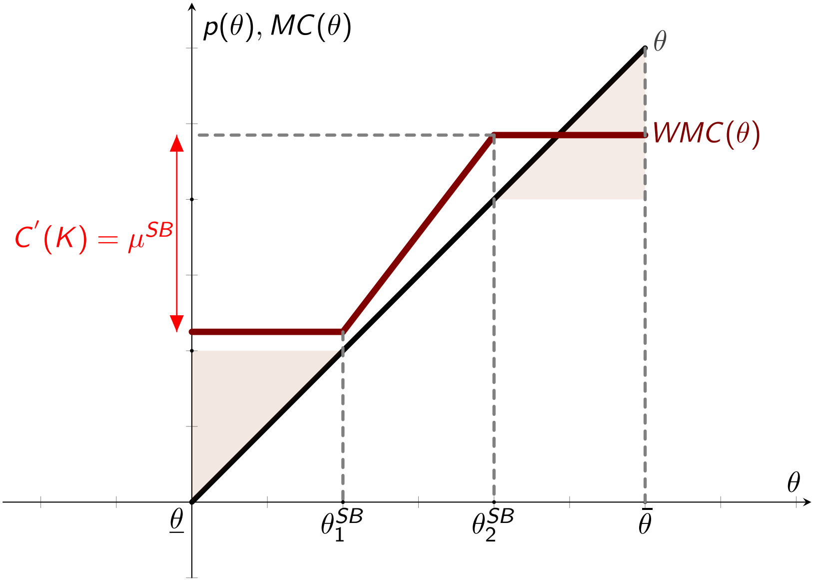
$p(\theta), MC(\theta)$
θ
θ
$\underline{\theta}$
θ_1^{SB}
θ_2^{SB}
$\overline{\theta}$

Second Best



$p(\theta), MC(\theta)$
θ
$WMC(\theta)$
θ
$\underline{\theta}$
θ_1^{SB}
θ_2^{SB}
$\overline{\theta}$

Second Best



$p(\theta), MC(\theta)$
θ
$WMC(\theta)$
$C'(K) = \mu^{SB}$
θ
$\underline{\theta}$
θ_1^{SB}
θ_2^{SB}
$\overline{\theta}$

Second Best

- **Optimal storage management:**
  - Similar to first best.
  - Equalization of *industry (weighted)* marginal costs within storing and releasing regions.
  - **Weighted** marginal cost: sum of the product of each firm's market share and marginal cost.

- **Optimal investment in storage:**
  - Marginal benefit $\Rightarrow$ Marginal cost saving from adding one unit of storage.
  - Market power amplifies differences in industry marginal costs.

▸ Second Best

Problem of competitive storage firms

Perfect competition:

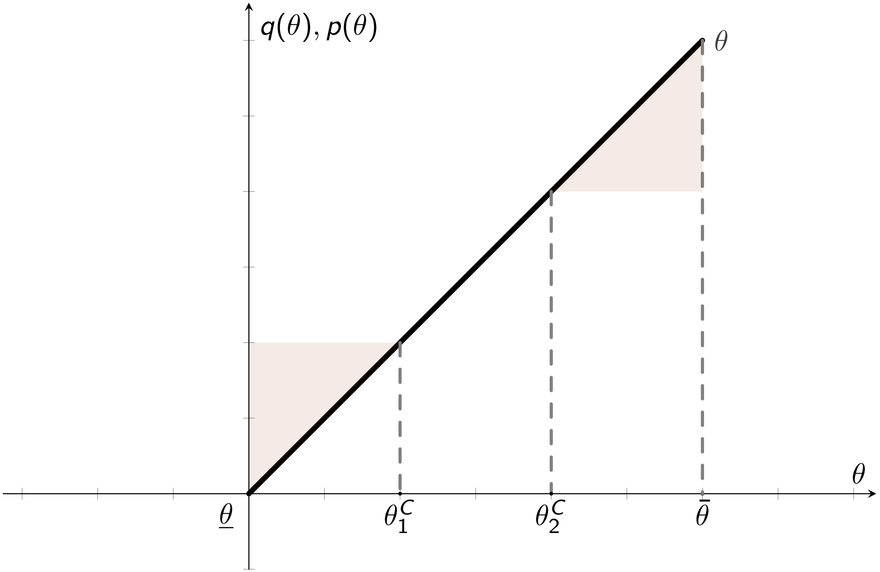
1. Large set of small owners (e.g. electric cars).
2. Take generation prices as given.
3. Free entry in the market $\Rightarrow$ zero-profit condition.

Storage firms maximize:

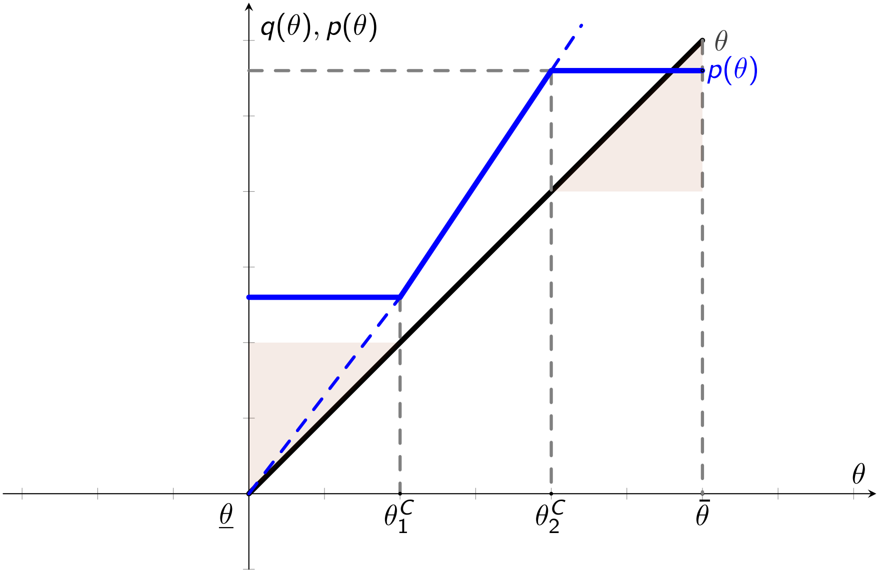
$$\max_{q^S(\theta),q^B(\theta)} \Pi^S = \int_{\underline{\theta}}^{\overline{\theta}} p\left(\theta\right)\left[q^S(\theta) - q^B(\theta)\right] g\left(\theta\right) d\theta - C(K)$$

subject to the storage constraints and the zero-profit condition.

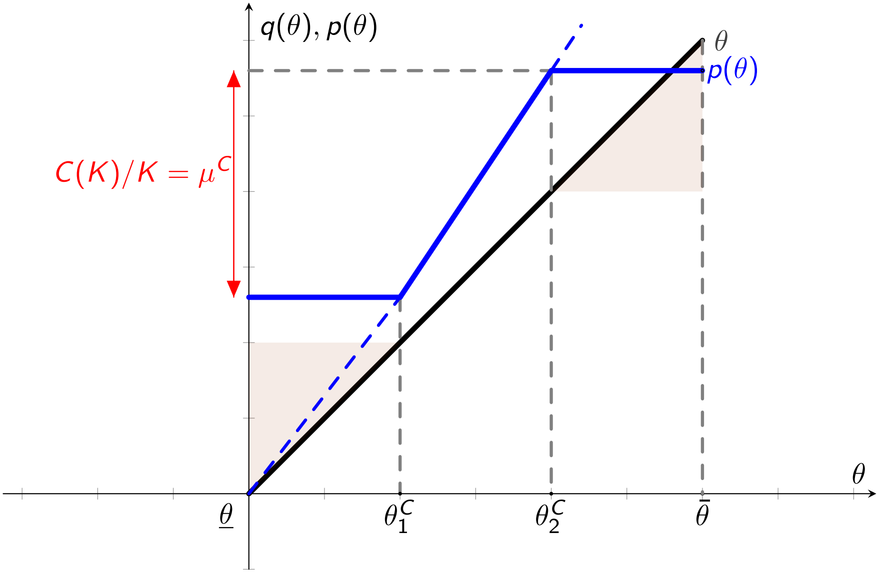
Competitive storage



Competitive storage



Competitive storage

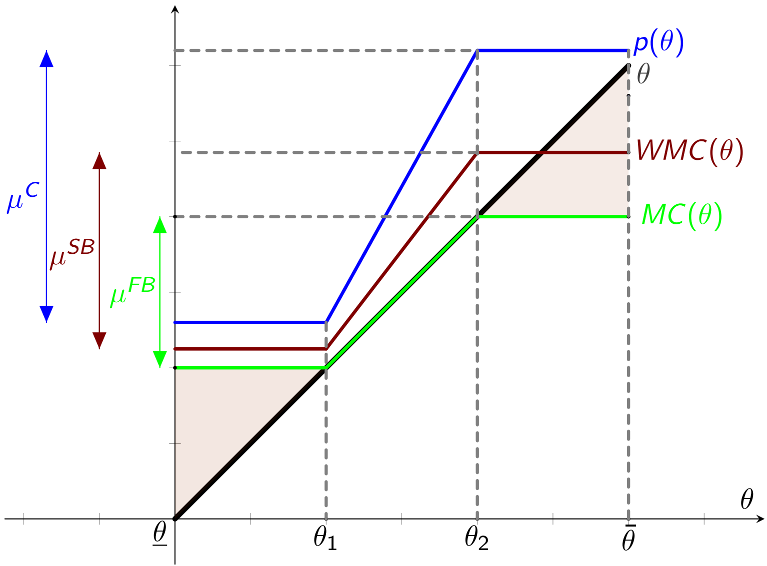


Competitive storage

- **Optimal storage management:**
  - Storage operators exploit arbitrage opportunities.
  - **Prices** (not marginal costs) **equalized** within storage and releasing regions.
- **Equilibrium investment in storage:**
  - Marginal value of storage capacity equals **price differential** that an extra unit of capacity allows to arbitrage.
  - Market power in the product market amplifies arbitrage profits.

▸ Competitive

First Best vs. Second Best vs. Competitive



First Best vs. Second Best vs. Competitive

- Under competitive storage with free-entry in the market, there is **over-investment** and **over-utilization** of storage $\Rightarrow K^C > K^{SB} > K^{FB}$.
  - Price differential higher than marginal cost savings.

$$\underbrace{\frac{\theta_2 - \theta_1}{1-\alpha^2}}_{\mu^C} > \underbrace{\frac{(\theta_2 - \theta_1)(1+\alpha-\alpha^2)}{(1-\alpha^2)(1+\alpha)}}_{\mu^{SB}} > \underbrace{\theta_2 - \theta_1}_{\mu^{FB}}$$

  - Cost convexity $\rightarrow$ Higher infra-marginal profits $\rightarrow C(K)/K < C^{'}(K)$

First Best vs. Second Best vs. Competitive

- Under competitive storage with free-entry in the market, there is **over-investment** and **over-utilization** of storage $\Rightarrow K^C > K^{SB} > K^{FB}$.
  - Price differential higher than marginal cost savings.

$$\underbrace{\frac{\theta_2 - \theta_1}{1-\alpha^2}}_{\mu^C} > \underbrace{\frac{(\theta_2 - \theta_1)(1+\alpha-\alpha^2)}{(1-\alpha^2)(1+\alpha)}}_{\mu^{SB}} > \underbrace{\theta_2 - \theta_1}_{\mu^{FB}}$$

  - Cost convexity $\rightarrow$ Higher infra-marginal profits $\rightarrow C(K)/K < C^{'}(K)$

- $K^{SB} > K^{FB} \rightarrow$ Storage mitigates market power by reducing residual demand at high demand levels.

Vertically Integrated Firm

- Dominant firm **vertically integrated** with storage monopolist.

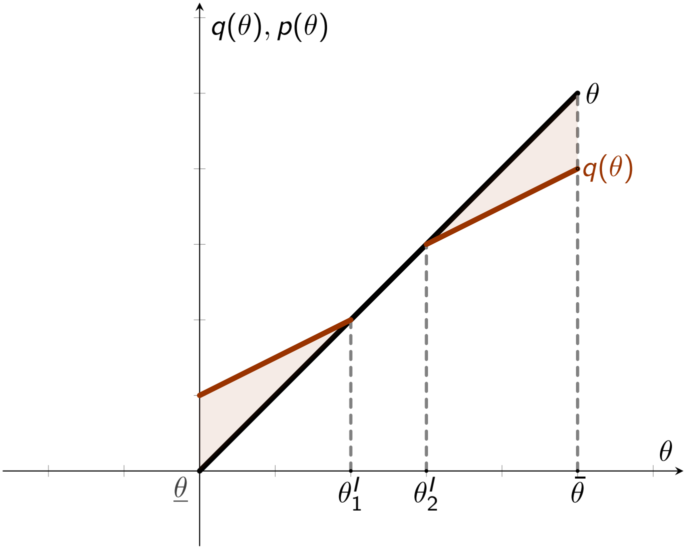
$$\max_{p(\theta), q_B(\theta), q_S(\theta)} \pi_S = \int_{\underline{\theta}}^{\bar{\theta}} \left[p(\theta) D\left(p; \theta\right) - \frac{\left[D\left(p; \theta\right) - q_S(\theta) + q_B(\theta)\right]^2}{2\alpha} \right] g\left(\theta\right) d\theta,$$

subject to the storage constraints.

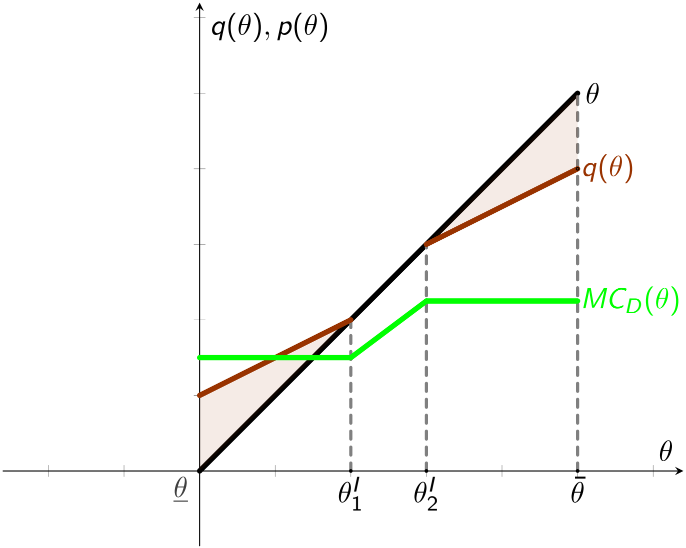
- Higher residual demand (firm controls storage) $\rightarrow D\left(p, \theta\right) = \theta - (1-\alpha) p(\theta)$.

- Storage facilities $\Rightarrow$ Help the dominant producer smooth its production over time.

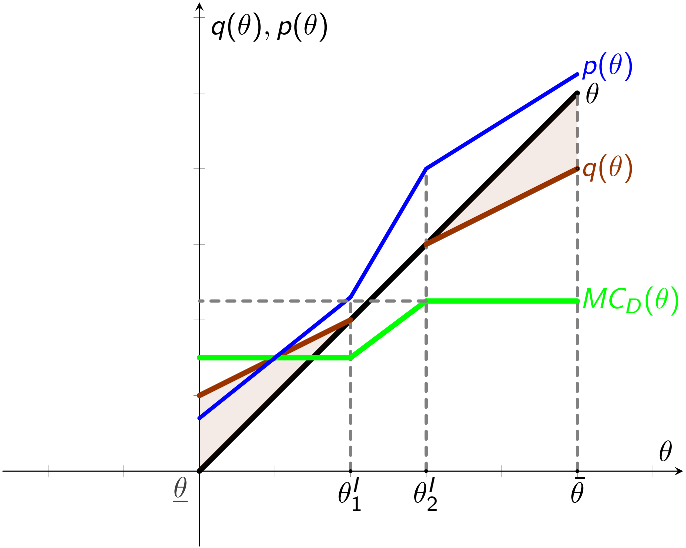
Vertically integrated firm



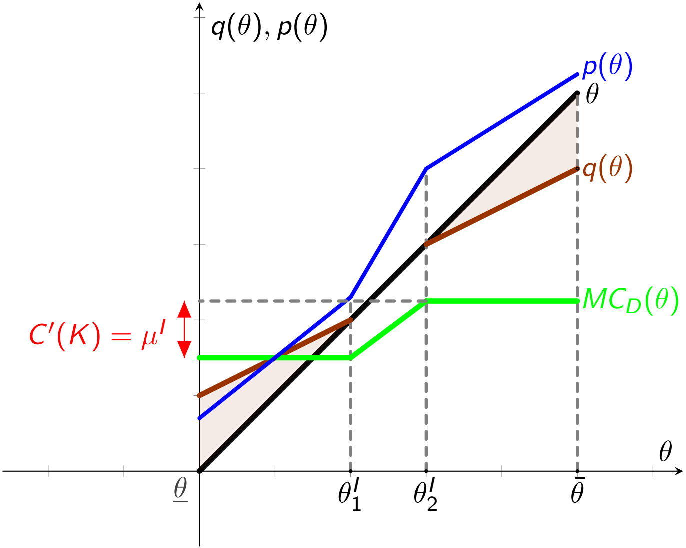
Vertically integrated firm



Vertically integrated firm



Vertically integrated firm



Vertically integrated firm

- **Optimal storage management:**
  - Vertically integrated firm uses storage to **smooth own production**.
  - Under-utilization of given storage capacity with respect to first best.
- **Optimal investment in storage:**
  - Marginal value of storage capacity equals **own marginal cost savings**.
  - Investment decreases in α.

Integrated

First Best vs. Vertically integrated firm

- In a market with a vertically integrated dominant firm, there is **under-investment** in storage, $K^I < K^{FB} < K^{SB}$.
- In contrast to previous cases, K^I is decreasing in α.
  - Efficiency gains from higher α dominate larger arbitrage opportunities

Consumer's surplus

- Consumer's surplus only depends on the price profile (i.e. weighted average price)

$$CS = v\theta - \int_{\underline{\theta}}^{\bar{\theta}} p(\theta)\theta g(\theta) d\theta.$$

- Market power in generation increases the price level.
- Market power in storage increases the variance of the market price.

Consumer's surplus

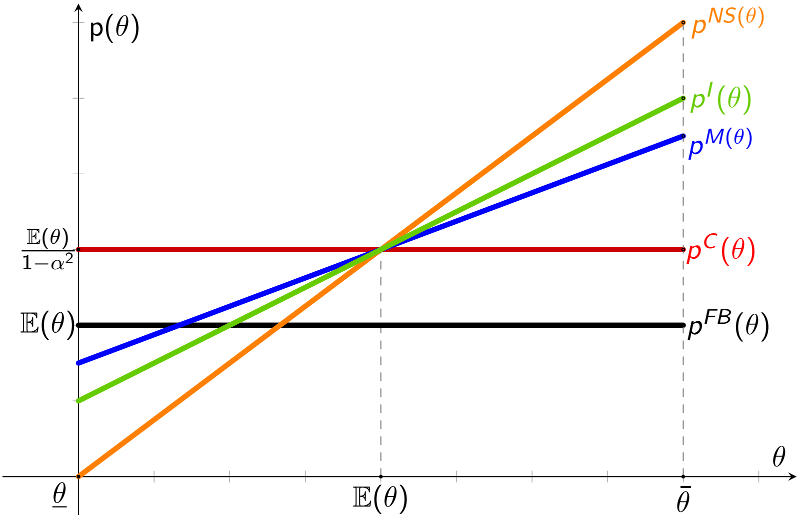
- Consumer's surplus only depends on the price profile (i.e. weighted average price)

$$CS = v\theta - \int_{\underline{\theta}}^{\bar{\theta}} p(\theta)\theta g(\theta) d\theta.$$

- Market power in generation increases the price level.
- Market power in storage increases the variance of the market price.
- The ranking of **consumer surplus** across market structures is

$$CS^{FB} > CS^{C} \geq CS^{SB} > CS^{I} > CS^{NS}.$$

Price profile: no capacity restrictions



Total welfare

- Total welfare is just a function of the **total costs** of production.
- Market power creates static & dynamic productive inefficiencies:
  - Generation (static) $\Rightarrow$ Distorted market shares.
  - Storage (dynamic) $\Rightarrow$ Lower storage usage, production not flatenned.
  - Aggravated with vertical integration $\Rightarrow$ Fringe absorbs demand variations.

Total welfare

- Total welfare is just a function of the **total costs** of production.
- Market power creates static & dynamic productive inefficiencies:
  - Generation (static) $\Rightarrow$ Distorted market shares.
  - Storage (dynamic) $\Rightarrow$ Lower storage usage, production not flatenned.
  - Aggravated with vertical integration $\Rightarrow$ Fringe absorbs demand variations.
- The ranking of **total welfare** across market structures is

$$TW^{FB} > TW^{SB} > TW^{C} > TW^{I} > TW^{NS}.$$

Conclusions

- The market does not provide adequate investment incentives in storage capacity.
  - Market power in generation leads to over-investment.
  - Market power in storage to under-investment.
- Vertical integration between storage and generation yields the most inefficient outcome.
  - Texas regulator: utilities are not permitted to use storage.
- Storage reduces the ability to exercise market power in generation, conditional on being independently owned.
- Storage capacity auctions.
  - Solve investment problem, although inefficient storage operation.

First Best (cont)

Optimal storage management:

For given K, storage decisions are

$$q_B^{FB}(\theta) = \max\left\{\theta_1^{FB} - \theta, 0\right\} \text{ and } q_S^{FB}(\theta) = \max\left\{\theta - \theta_2^{FB}, 0\right\}$$

where

$$\theta_1^{FB} = E[\theta] - \frac{\mu}{2} \leq \theta_2^{FB} = E[\theta] + \frac{\mu}{2},$$

and $\mu = \mu^{FB}(K)$ is the unique solution to

$$\int_{\underline{\theta}}^{\theta_1^{FB}(\mu)} \left[\theta_1^{FB}(\mu) - \theta\right] g(\theta) d\theta = K.$$

Optimal investment in storage:

$$\frac{\partial \mathcal{W}}{\partial K} = 0 \Rightarrow \mu\left(K^{FB}\right) = C'\left(K^{FB}\right) \Rightarrow \theta_2^{FB} - \theta_1^{FB} = C'\left(K^{FB}\right)$$

Back

Second Best (cont)

Optimal storage management:

For given K, storage decisions are

$$q_B^{SB}(\theta) = \max\left\{\theta_1^{SB} - \theta, 0\right\} \text{ and } q_S^{SB}(\theta) = \max\left\{\theta - \theta_2^{SB}, 0\right\}$$

where

$$\theta_1^{SB} = E[\theta] - \frac{\mu}{2}\frac{(1-\alpha^2)(1+\alpha)}{1+\alpha-\alpha^2} \leq \theta_2^{SB} = E[\theta] + \frac{\mu}{2}\frac{(1-\alpha^2)(1+\alpha)}{1+\alpha-\alpha^2},$$

and $\mu = \mu^{FB}(K)$ is the unique solution to

$$\int_{\underline{\theta}}^{\theta_1^{SB}(\mu)} \left[\theta_1^{SB}(\mu) - \theta\right] g(\theta) d\theta = K.$$

Optimal investment in storage: Back

$$\frac{\partial \mathcal{W}}{\partial K} = 0 \Rightarrow \mu\left(K^{SB}\right) = C'\left(K^{SB}\right) \Rightarrow (\theta_2^{SB} - \theta_1^{SB})\frac{1+\alpha-\alpha^2}{(1-\alpha^2)(1+\alpha)} = C'\left(K^{SB}\right)$$

Competitive storage (cont)

Optimal storage management:

For given K, the equilibrium storage decisions are

$$q_B^C(\theta) = \max\left\{\theta_1^C - \theta, 0\right\} \text{ and } q_S^C(\theta) = \max\left\{\theta - \theta_2^C, 0\right\}$$

where

$$\theta_1^C = E[\theta] - \frac{\mu\left(1-\alpha^2\right)}{2} \leq \theta_2^C = E[\theta] + \frac{\mu\left(1-\alpha^2\right)}{2},$$

with $\mu = \mu^C(K)$ implicitly defined by:

$$\int_{\underline{\theta}}^{\theta_1^C(\mu)} \left[\theta_1^C(\mu) - \theta\right] g(\theta) d\theta = K.$$

Investment in storage:

$$\mu^C(K) = (\theta_2^C - \theta_1^C) / \left(1-\alpha^2\right) = C(K)/K < C'(K).$$

▸ Back

Vertically Integrated Firm (cont)

Optimal storage management:

For given K, the equilibrium storage decisions are

$$q_B^I(\theta) = \max\left\{\left(\theta_1^I - \theta\right)/2, 0\right\} \text{ and } q_S^I(\theta) = \max\left\{\left(\theta - \theta_2^I\right)/2, 0\right\},$$

where

$$\theta_1^I = E\left[\theta\right] - \mu(1+\alpha)/2 \leq \theta_2^I = E\left[\theta\right] + \mu(1+\alpha)/2,$$

with $\mu = \mu^I(K)$ is the unique solution to

$$\int_{\underline{\theta}}^{\theta_1^I(\mu)} \frac{\theta_1^I\left(\mu\right) - \theta}{2} g(\theta)d\theta = K.$$

Optimal investment in storage:

$$C'(K) = \mu^I(K) = (\theta_2^I - \theta_1^I)/\left(1+\alpha\right).$$

Back