Cost-Based Recovery Mechanisms in a Duopoly with Non-Convex Costs

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Contents

- Introduction
- Duopoly model setting
- Fixed Cost Recovery (FCR) mechanism
- Loss-Related Profits Recovery (LPR) mechanism
- Comparison and discussion
- Conclusions

Introduction

- Background and Motivation
  - Auction-based day-ahead electricity markets
  - Non-convexities; recovery mechanisms; strategic bidding
- Literature review
  - Few analytical works – convexity assumptions
    - Von der Fehr and Harbord, 1993; **Fabra *et al.*, 2006 (*)**
      - **Nash equilibria for a basic duopoly, asymmetric marginal costs and capacities**
  - Non-convex market designs
    - Sioshansi and Nicholson, 2011; Wang *et al.,* 2012; Wang, 2013
      - Nash equilibria for symmetric capacity duopoly, price-based recovery mechanisms

(*) N. Fabra, N.-H. von der Fehr, D. Harbord, Designing Electricity Auctions, RAND J. Econ, 37(1) 2006, 23-46.

Introduction

- **In this work, we**:
  - enhance the duopoly model employed by Fabra *et al.* (2006), introducing fixed costs;
  - study cost–based recovery mechanisms:
    - Fixed Cost Recovery (FCR) mechanism (simple);
    - Loss-related Profits Recovery (LPR) mechanism (new);
  - identify Nash equilibria;
  - compare the results;
  - discuss the selection of design parameters.

Duopoly Model Setting

- Asymmetric constant marginal costs $c_1, c_2 \quad (0 < c_i < c_I)$
- Asymmetric constant fixed costs $f_1,\ f_2$
- Asymmetric capacities $k_1 < k_2$
- Deterministic, inelastic demand d
  - Low demand: $d \leq k_1$
  - Mid demand: $k_1 < d \leq k_2$
  - High demand: $d > k_2$
- Suppliers submit bids for marginal cost to an auctioneer
  - Bids: $c_1 \leq b_1 \leq P,\ c_2 \leq b_2 \leq P$
  - Price cap: P

Fixed Cost Recovery (FCR) Mechanism

- Suppliers receive the full amount of fixed costs, whenever such costs exist.
- Equilibrium outcomes:

No.	Bids	Conditions	Price	Quantities	Total Payments
1a	$b_i^* = c_I,$	(a) $d \leq k_1$ (or)	c_I	$q_i^* = d,$	$c_I d + f_i$
1b	$b_I^* = c_I$	(b) $k_I < d \leq k_i, d \leq d^{(1)}$		$q_I^* = 0$	
2a	$b_i^* \leq b_I^{(1)},$	(a) $k_i < d \leq k_I$ (or)	P	$q_i^* = k_i,$	$Pd + f_i + f_I$
2b	$b_I^* = P$	(b) $d > k_2$		$q_I^* = d - k_i$	
3a	$b_i^* = P,$	(a) $k_I < d \leq k_i, d \geq d^{(1)}$ (or)	P	$q_i^* = d - k_I,$	$Pd + f_i + f_I$
3b	$b_I^* \leq b_i^{(1)}$	(b) $d > k_2, d \geq d^{(2)}$		$q_I^* = k_I$	

Fixed Cost Recovery (FCR) Mechanism

In any pure strategy equilibrium, the highest accepted price offer is in the set $\{c_I, P\}$.

- Equilibrium outcomes:

No.	Bids	Conditions	Price	Quantities	Total Payments
1a	$b_i^* = c_I,$	(a) $d \leq k_1$ (or)	c_I	$q_i^* = d,$	$c_I d + f_i$
1b	$b_I^* = c_I$	(b) $k_I < d \leq k_i, d \leq d^{(1)}$		$q_I^* = 0$	
2a	$b_i^* \leq b_I^{(1)},$	(a) $k_i < d \leq k_I$ (or)	P	$q_i^* = k_i,$	$Pd + f_i + f_I$
2b	$b_I^* = P$	(b) $d > k_2$		$q_I^* = d - k_i$	
3a	$b_i^* = P,$	(a) $k_I < d \leq k_i, d \geq d^{(1)}$ (or)	P	$q_i^* = d - k_I,$	$Pd + f_i + f_I$
3b	$b_I^* \leq b_i^{(1)}$	(b) $d > k_2, d \geq d^{(2)}$		$q_I^* = k_I$	

Fixed Cost Recovery (FCR) Mechanism

There exists d_P such that…

- Equilibrium outcomes:

No.	Bids	Conditions	Price	Quantities	Total Payments
1a	$b_i^* = c_I,$	$d < d_P$:	c_I	$q_i^* = d,$	$c_I d + f_i$
1b	$b_I^* = c_I$			$q_I^* = 0$	
2a	$b_i^* \leq b_I^{(1)},$	$d > d_P$:	P	$q_i^* = k_i,$	$Pd + f_i + f_I$
2b	$b_I^* = P$			$q_I^* = d - k_i$	
3a	$b_i^* = P,$	(a) (or)	P	$q_i^* = d - k_I,$	$Pd + f_i + f_I$
3b	$b_I^* \leq b_i^{(1)}$			$q_I^* = k_I$	

Fixed Cost Recovery (FCR) Mechanism

Low demand: c_I

Mid demand: c_I or P

High demand: P

If cost asymmetry is higher than the capacity asymmetry, i.e., $\frac{P-c_i}{P-c_I} > \frac{k_i}{k_I}$

the price does not reach the cap for mid demand.

No.	Bids	Conditions	Price	Quantities	Total Payments
1a	$b_i^* = c_I$,	(a) $d \leq k_1$ (or)	c_I	$q_i^* = d$,	$c_I d + f_i$
1b	$b_I^* = c_I$	(b) $k_I < d \leq k_i, d \leq d^{(1)}$		$q_I^* = 0$	
2a	$b_i^* \leq b_I^{(1)}$,	(a) $k_i < d \leq k_I$ (or)	P	$q_i^* = k_i$,	$Pd + f_i + f_I$
2b	$b_I^* = P$	(b) $d > k_2$		$q_I^* = d - k_i$	
3a	$b_i^* = P$,	(a) $k_I < d \leq k_i, d \geq d^{(1)}$ (or)	P	$q_i^* = d - k_I$,	$Pd + f_i + f_I$
3b	$b_I^* \leq b_i^{(1)}$	(b) $d > k_2, d \geq d^{(2)}$		$q_I^* = k_I$	

Loss-related Profits Recovery (LPR) Mechanism

- If a supplier exhibits losses, he will be compensated by (1+α) times the losses, allowing for a positive profit that equals (α) times the losses, α > 0.
- Equilibrium outcomes:

No.	Bids	Conditions	Price	Quantities	Total Payments
1a	$b_i^* = c_i$	(a) $d \le k_1,\ d \le d^{(3)}$ (or)	c_i	$q_i^* = d$	$c_i d + (1+\alpha) f_i$
1b	$b_I^* \le b_i^{(2)}$	(b) $k_I < d \le k_i,\ d \le \min\{d^{(3)}, d_I^{(4)}\}$		$q_I^* = 0$	
2a	$b_i^* = b_I^* = c_I$	(a) $d \le k_1,\ d \ge d^{(3)}$ (or)	c_I	$q_i^* = d$	$c_I d$
2b		(b) $k_I < d \le k_i,\ d^{(3)} \le d < d^{(1)}$		$q_I^* = 0$	
3	$b_i^* \le c_I$ $b_I^* = c_I$	$k_i < d \le k_I,\ d \le d_i^{(4)}$	c_I	$q_i^* = k_i$ $q_I^* = d - k_i$	$c_I d + (1+\alpha)\{f_I +$ $w[f_i - (c_I - c_i)k_i]\}$
4	$b_i^* = b_I^* = p$	$d > k_2,\ p \in \mathrm{B}_3$	p	$q_i^* = k_i$ $q_I^* = d - k_i$	$pk_i + [c_I - \alpha(p - c_I)]$ $\times(d - k_i) + (1+\alpha) f_I$
5	$b_i^* = p$ $b_I^* = p^-$	$d > k_2,\ p \in \mathrm{B}_4$	p	$q_i^* = d - k_I$ $q_I^* = k_I$	$pk_I + [c_i - \alpha(p - c_i)]$ $\times(d - k_I) + (1+\alpha) f_i$
6	$b_i^* \le b_I^{(1)}$ $b_I^* = P$	$k_i < d \le k_I,\ d \ge d_i^{(4)}$	P	$q_i^* = k_i$ $q_I^* = d - k_i$	Pd
7	$b_i^* = P$ $b_I^* \le b_i^{(1)}$	$k_I < d \le k_i,\ d \ge \max\{d^{(1)}, d_I^{(4)}\}$	P	$q_i^* = d - k_I$ $q_I^* = k_I$	Pd
8	$b_i^* \in \mathrm{B}_1$ $b_I^* = P$	$d > k_2,\ d \ge d_i^{(5)}$	P	$q_i^* = k_i$ $q_I^* = d - k_I$	Pd
9	$b_i^* \le c_I$ $b_I^* = P$	$d > k_2,\ d \ge d_i^{(4)}$	P	$q_i^* = k_i$ $q_I^* = d - k_i$	Pd
10	$b_i^* = P$ $b_I^* \in \mathrm{B}_2$	$d > k_2,\ d \ge d_I^{(5)}$	P	$q_i^* = d - k_I$ $q_I^* = k_I$	Pd

Note: $w = 1$, if $c_I < c_i + \frac{f_i}{k_i}$, and $w = 0$, otherwise.

Loss-related Profits Recovery (LPR) Mechanism

- If a supplier exhibits losses, he will be compensated by (1+α) times the losses, allowing for a positive profit that equals (α) times the losses, α > 0.
- Equilibrium outcomes:

Low demand: c_i or c_I

Mid demand: c_i or c_I or P

High demand: <= P

No.	Bids	Conditions	Price	Quantities	Total Payments
1a 1b	$b_i^* = c_i$ $b_I^* \leq b_i^{(2)}$	(a) $d \leq k_1,\ d \leq d^{(3)}$ (or) (b) $k_I < d \leq k_i,\ d \leq \min\{d^{(3)}, d_I^{(4)}\}$	c_i	$q_i^* = d$ $q_I^* = 0$	$c_i d + (1+\alpha) f_i$
2a 2b	$b_i^* = b_I^* = c_I$	(a) $d \leq k_1,\ d \geq d^{(3)}$ (or) (b) $k_I < d \leq k_i,\ d^{(3)} \leq d < d^{(1)}$	c_I	$q_i^* = d$ $q_I^* = 0$	$c_I d$
3	$b_i^* \leq c_I$ $b_I^* = c_I$	$k_i < d \leq k_I,\ d \leq d_i^{(4)}$	c_I	$q_i^* = k_i$ $q_I^* = d - k_i$	$c_I d + (1+\alpha)\{f_I +$ $w[f_i - (c_I - c_i)k_i]\}$
4	$b_i^* = b_I^* = p$	$d > k_2,\ p \in \mathrm{B}_3$	p	$q_i^* = k_i$ $q_I^* = d - k_i$	$pk_i + [c_I - \alpha(p - c_I)]$ $\times (d - k_i) + (1+\alpha) f_I$
5	$b_i^* = p$ $b_I^* = p^-$	$d > k_2,\ p \in \mathrm{B}_4$	p	$q_i^* = d - k_I$ $q_I^* = k_I$	$pk_I + [c_i - \alpha(p - c_i)]$ $\times (d - k_I) + (1+\alpha) f_i$
6	$b_i^* \leq b_I^{(1)}$ $b_I^* = P$	$k_i < d \leq k_I,\ d \geq d_i^{(4)}$	P	$q_i^* = k_i$ $q_I^* = d - k_i$	Pd
7	$b_i^* = P$ $b_I^* \leq b_i^{(1)}$	$k_I < d \leq k_i,\ d \geq \max\{d^{(1)}, d_I^{(4)}\}$	P	$q_i^* = d - k_I$ $q_I^* = k_I$	Pd
8	$b_i^* \in \mathrm{B}_1$ $b_I^* = P$	$d > k_2,\ d \geq d_i^{(5)}$	P	$q_i^* = k_i$ $q_I^* = d - k_I$	Pd
9	$b_i^* \leq c_I$ $b_I^* = P$	$d > k_2,\ d \geq d_i^{(4)}$	P	$q_i^* = k_i$ $q_I^* = d - k_i$	Pd
10	$b_i^* = P$ $b_I^* \in \mathrm{B}_2$	$d > k_2,\ d \geq d_I^{(5)}$	P	$q_i^* = d - k_I$ $q_I^* = k_I$	Pd

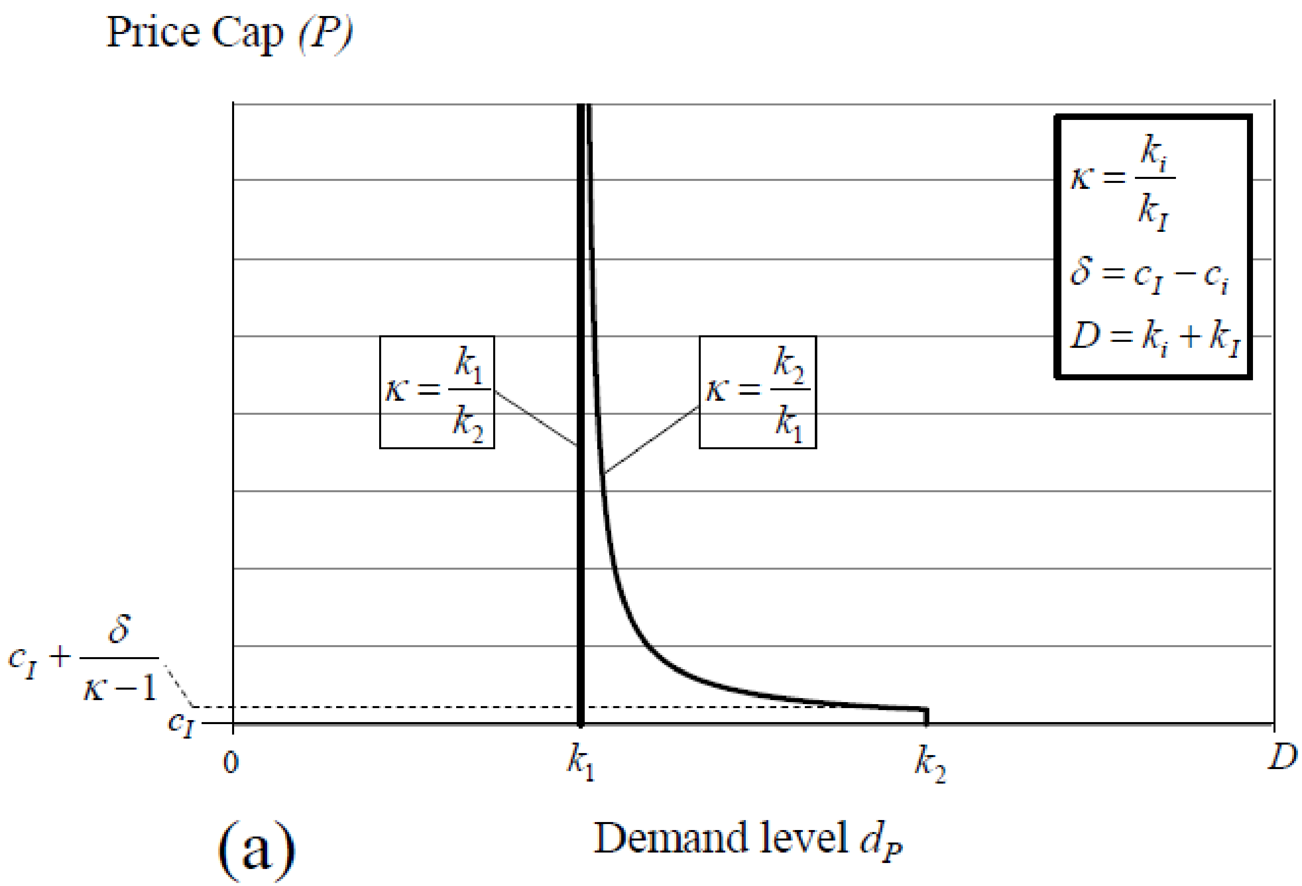
Note: $w = 1$, if $c_I < c_i + \frac{f_i}{k_i}$, and $w = 0$, otherwise.

Comparison and discussion

- For all demand realizations, the price at equilibrium of the **LPR** mechanism is always **less than or equal to** the respective price of the **FCR** mechanism for all $\alpha > 0$.
- There exists $\alpha > 0$, such that for all demand realizations, the total payments of the **LPR** mechanism are **strictly lower than** those of the **FCR** mechanism.
- Design issues:
  - Role of the Price Cap P
  - Role of Loss multiplier α

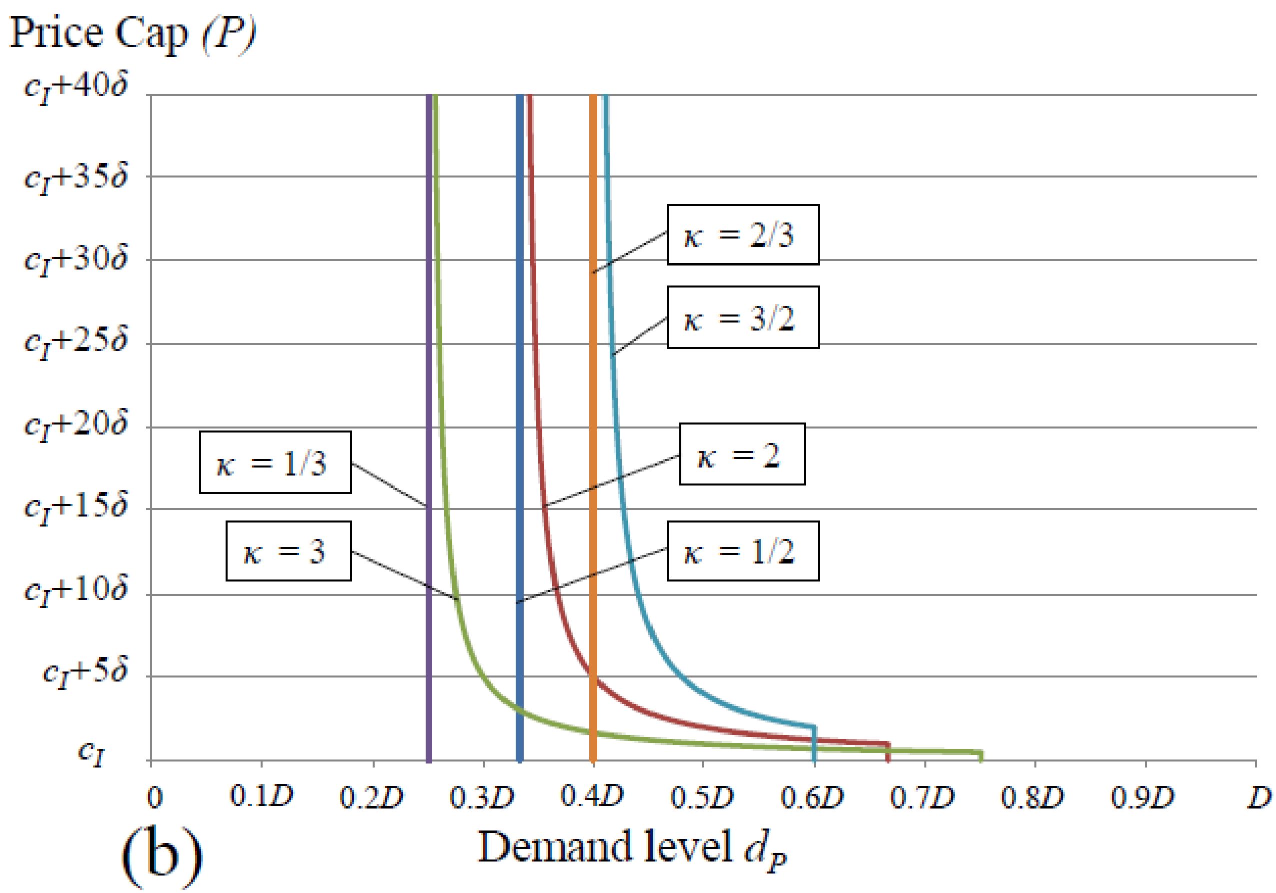
Comparison and discussion

- FCR mechanism



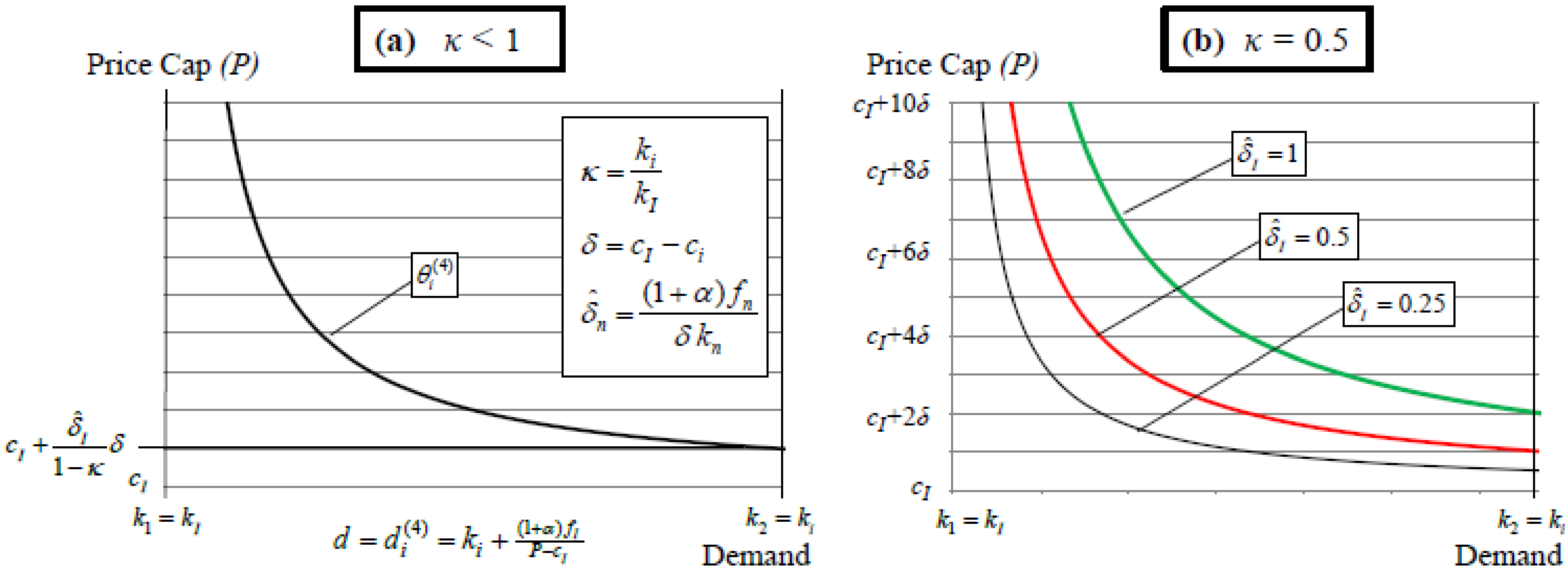
Comparison and discussion

- FCR mechanism



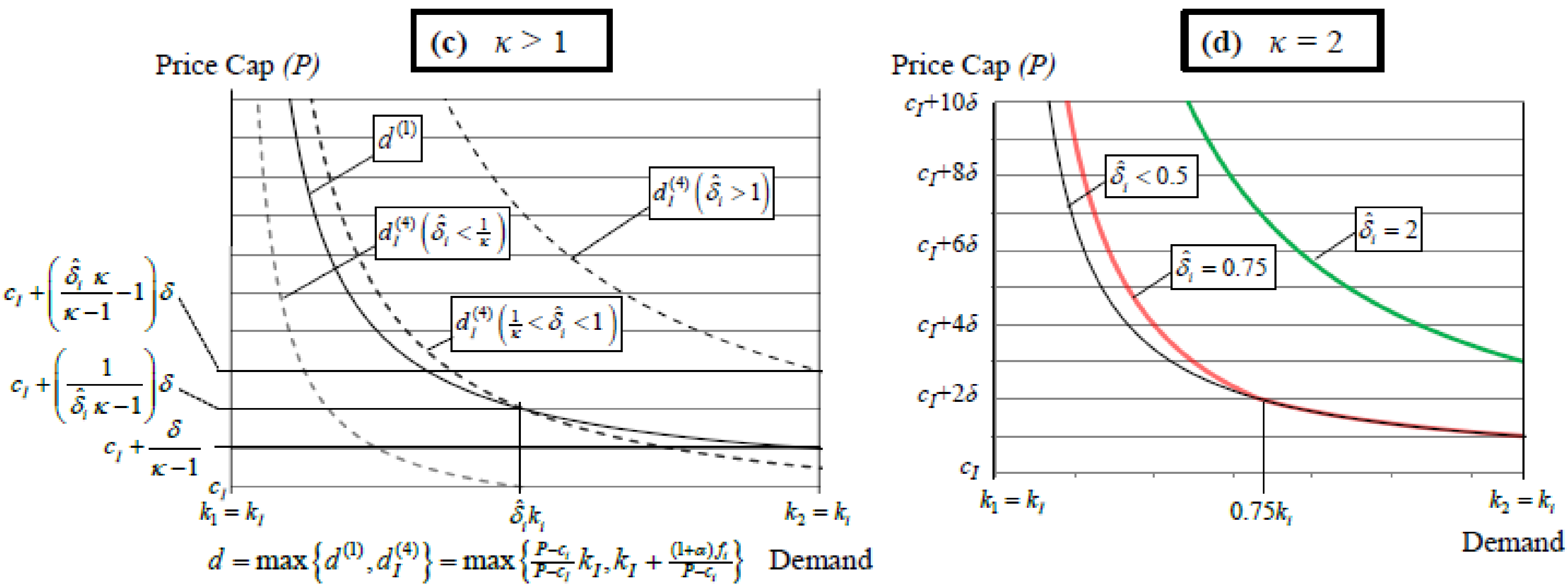
Comparison and discussion

- LPR mechanism



Comparison and discussion

- LPR mechanism



Conclusions

- We identified equilibrium outcomes for the FCR and LPR mechanisms (cost-based recovery mechanisms) for a stylized duopoly
- The LPR mechanism can be designed to outperform the FCR mechanism, in terms of:
  - Equilibrium prices (market signal)
  - Total payments (price for the consumer)
- Appropriate selection of design parameters P (FCR, LPR) and α (LPR) depends on the objective of the regulator
- Insights gained from the stylized example quite encouraging
- LPR concept can be applied to real-sized systems, without the assumption made in the duopoly setting (parallel work)

Questions?

Thank you for your patience!