Auctions with Unknown Capacities

Understanding Competition among Renewables

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The Energy Transition

A challenge for the power sector

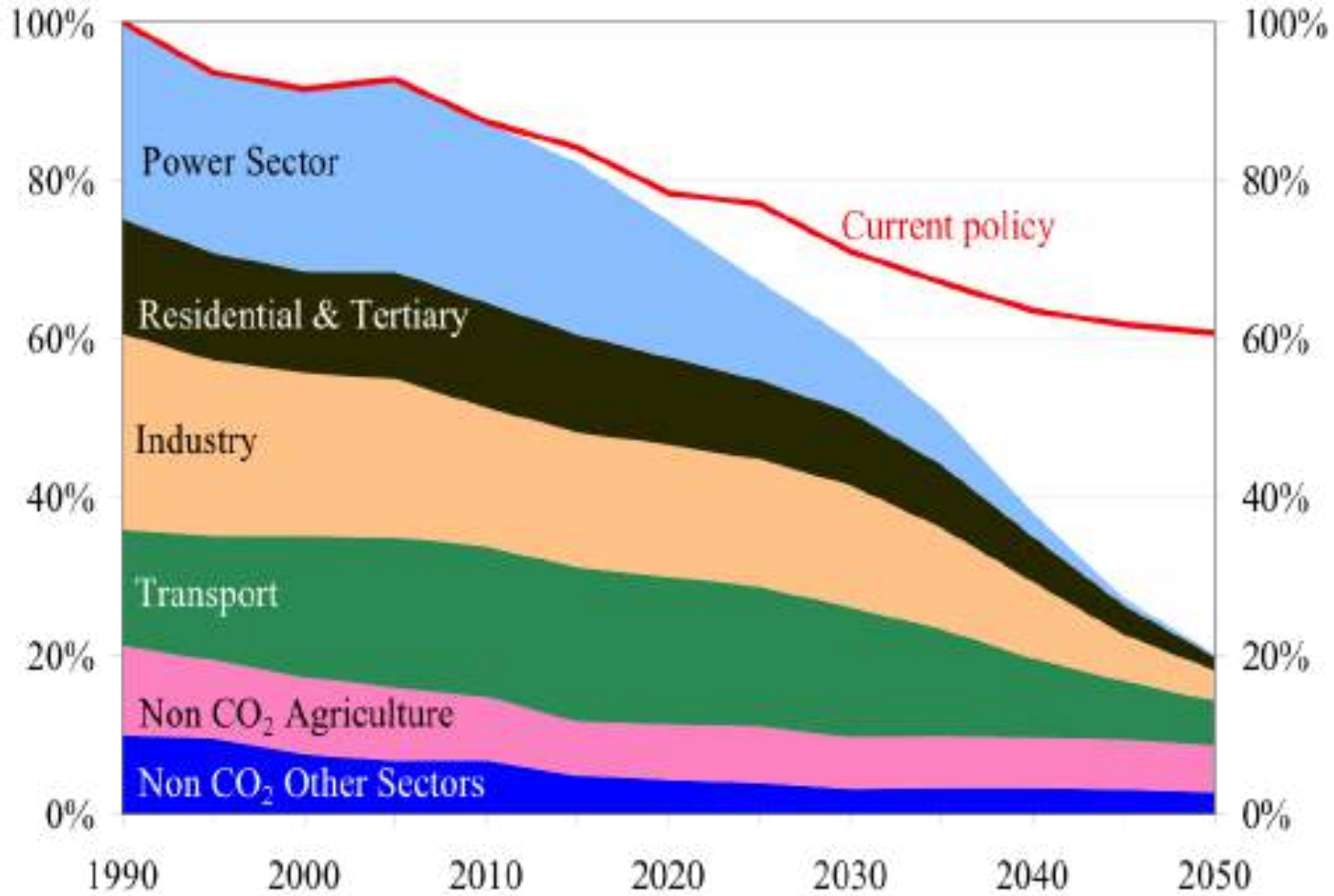

Figure: Emissions reductions in Europe with respect to 1990 levels (Source: EC's 2050 Energy Roadmap)

The Energy Transition

Renewables' key role

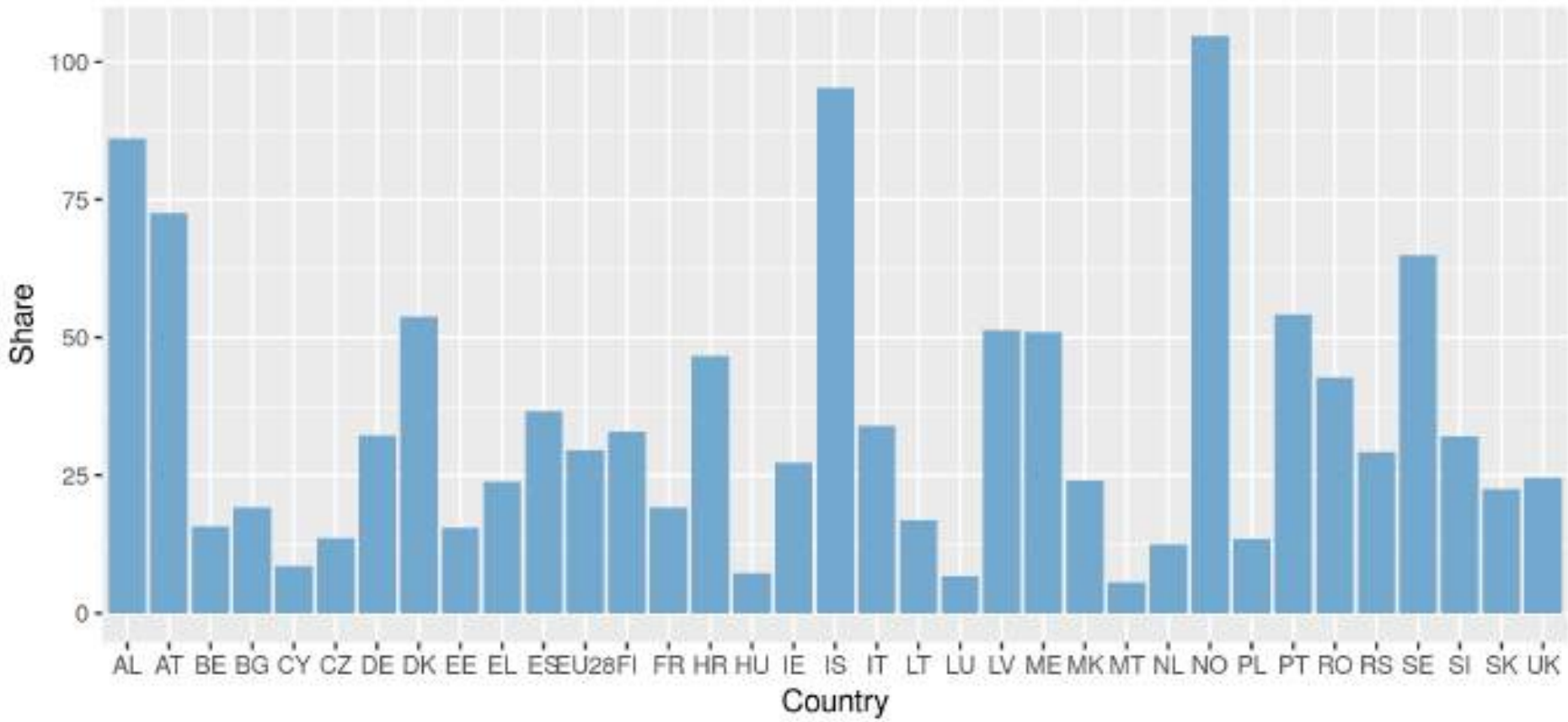

Figure: Share of renewable generation over total electricity consumption (Eurostat)

The Energy Transition

A research agenda

How can we achieve a least-cost energy transition?

Focus on **market design** and **market struture** in **electricity markets**

The Energy Transition

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Renewables:

1. How will renewables-dominated **electricity markets** work?
2. How to promote **renewable investments**?

The Energy Transition

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Renewables:

1. How will renewables-dominated **electricity markets** work?
2. How to promote **renewable investments**?

Coping with renewables' intermittency:

3. How to manage **electricity storage**?
4. What to expect from the **demand response** to dynamic pricing?

New competitive paradigm in electricity

- Shift from fossil fuels to renewables: carbon-free markets
- Competition-wise, two key differences:
  - **Conventional plants**: known capacities, plausibly unknown (heterogeneous) marginal costs
  - **Renewables**: unknown capacities, known (zero) marginal costs

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- Competition-wise, two key differences:
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Renewables fundamentally **change the nature of strategic interaction** among electricity producers.

Forecast Errors in Renewable Production

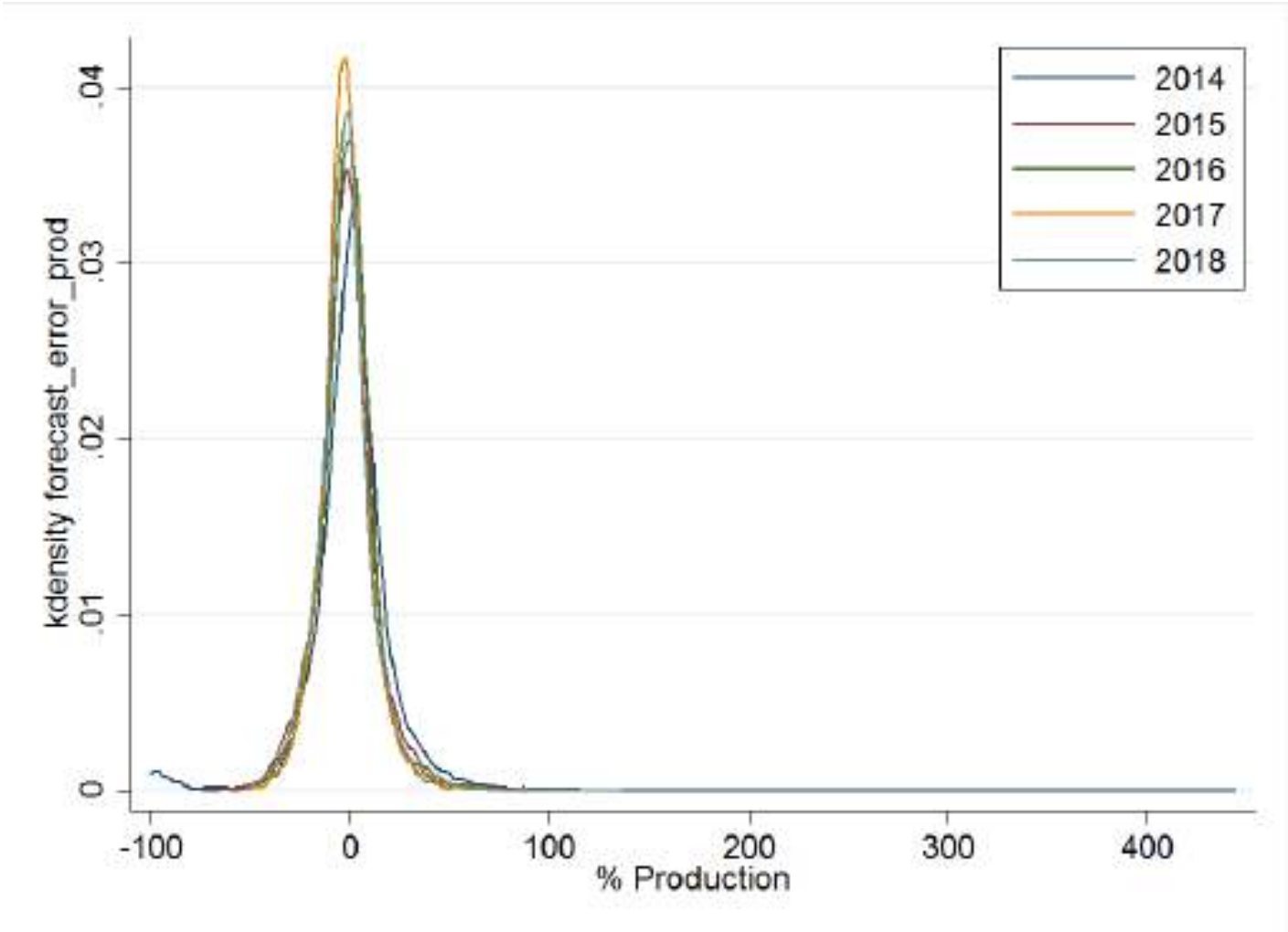

Figure: Distribution of wind forecast errors (Spanish Electricity Market)

Forecast Errors in Renewable Production

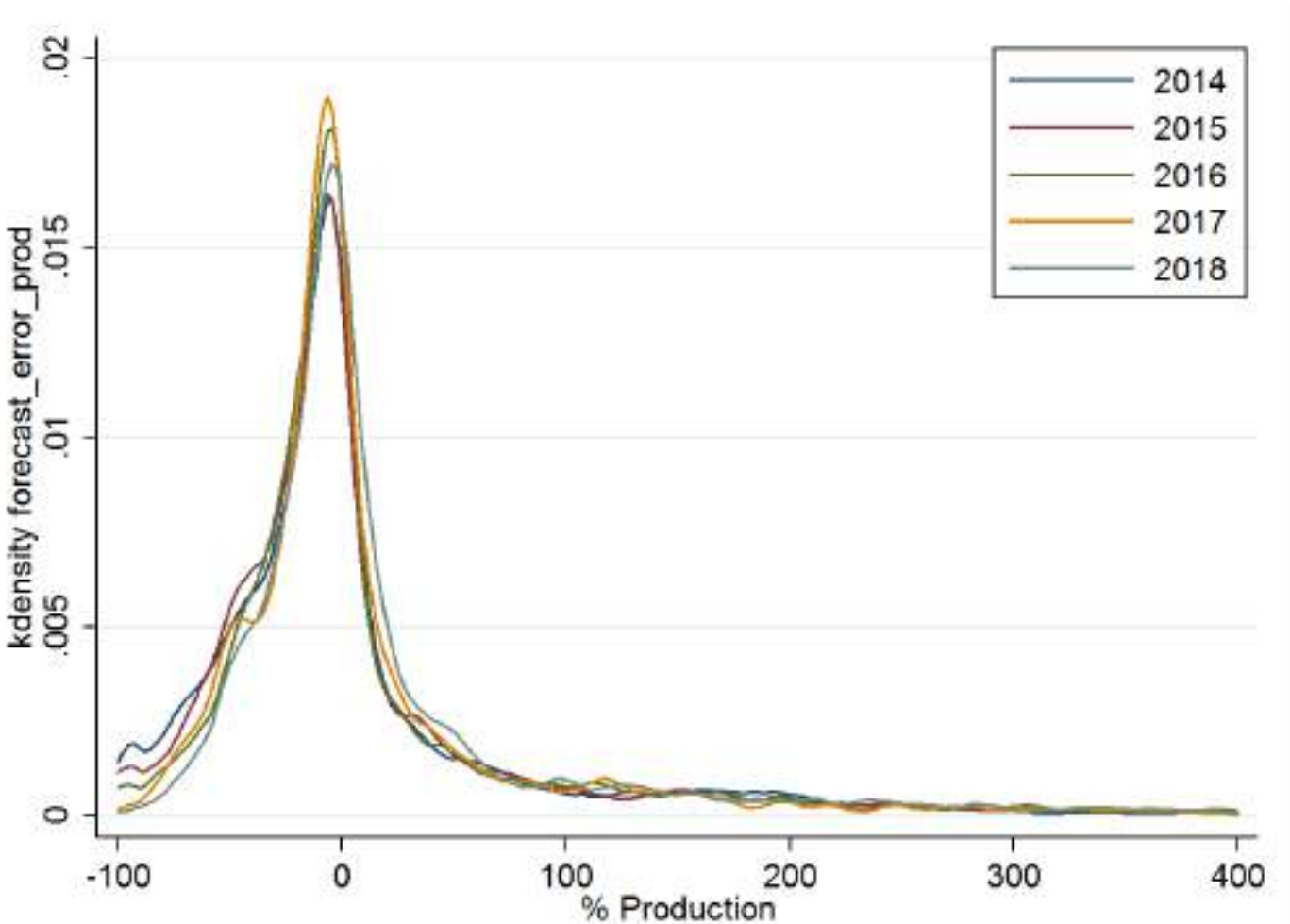

Figure: Distribution of solar forecast errors (Spanish Electricity Market)

Firms have private information on their avalaible capacities

(a) Meteo station (wind)

(b) Meteo station (solar)

Private Information Allows for Better Forecasts

Variables	(1)	(2)
Public forecast	0.582***	0.070***
	(0.035)	(0.021)
Private forecast		0.657***
		(0.008)
Observations	36,671	36,671
R-squared	0.520	0.826
Mean of the error	0	0
Standard deviation of the error	.18	.11

Table: Forecast errors with public versus private information.

Private information allows for better forecasts

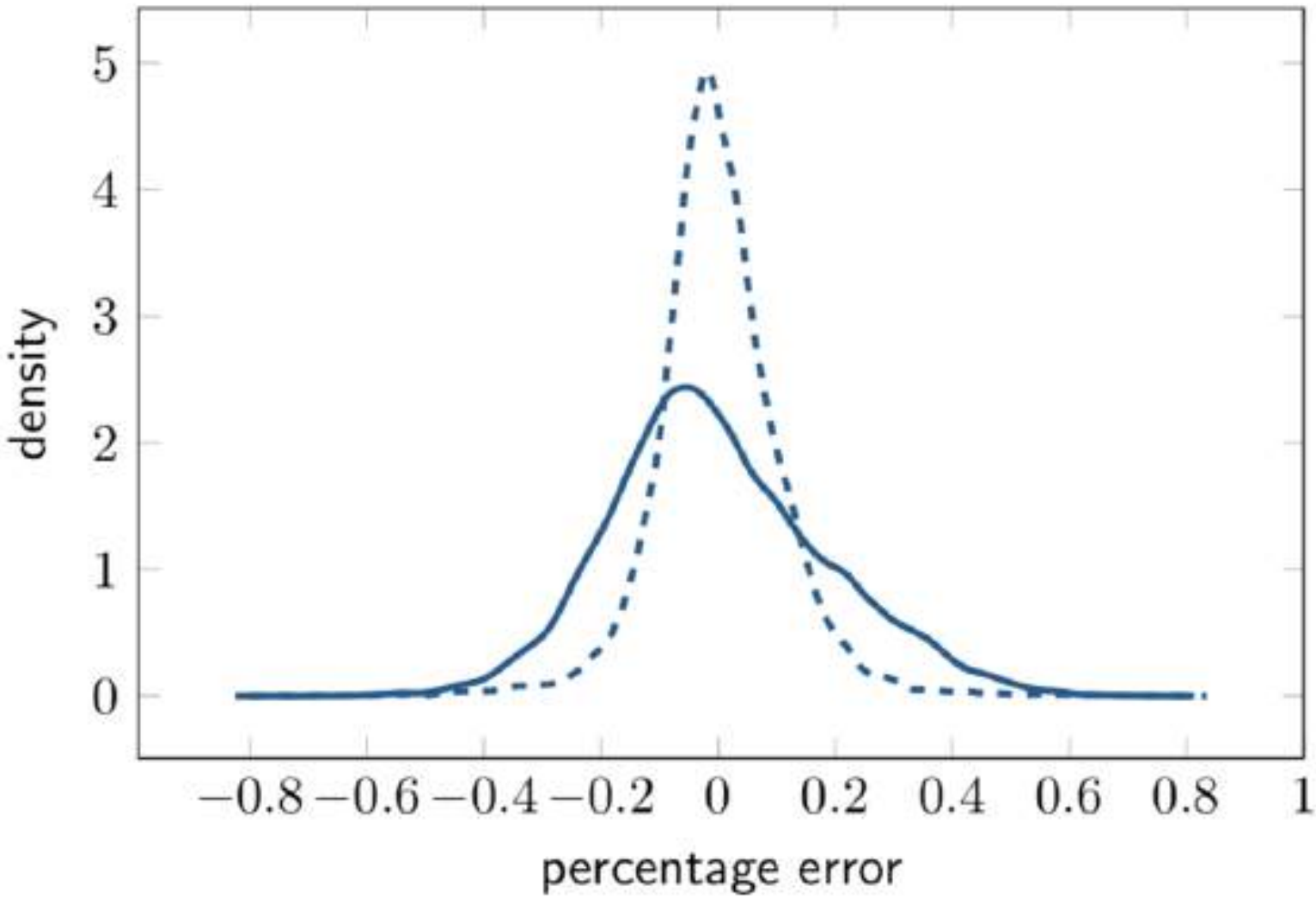

Figure: Kernel distribution of wind forecasts errors at the plant level using private (dashed) vs. plubic (solid) information

Objetives of the Paper

Objectives of the paper:

- Analize multi-unit auctions when capacities are private information
  - Characterize equilibrium bidding
  - Understand whether private information on costs or capacities differ
  - Understand the impact of private information
  - Assess the impact of changes in market structure and market rules

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In the context of electricity markets...

- How will renewables-dominated electricity markets perform?
- How much market power will be exercised?
- How does it all depend on renewables investment?

Beyond electricity....

- Many other goods are bought/sold through multi-unit auctions:
  - Pharmaceuticals, emission permits, toxic assets, T-bills...
  - Hotel bookings, cab services, or product availability in general...

Beyond electricity....

- Many other goods are bought/sold through multi-unit auctions:
  - Pharmaceuticals, emission permits, toxic assets, T-bills...
  - Hotel bookings, cab services, or product availability in general...
- Bidders are **privately informed** about their **costs/valuations**...
- ... and/or about the **maximum quantities** they can sell/buy
  - **Pharmaceuticals**: labs' capacities
  - **Emission permits**: firms' expected emissions
  - **Toxic assets**: banks' amount of toxic assets
  - **Treasury bills**: banks' hedging needs
  - **Hotels/cabs**: rooms/taxis availability

Roadmap

- Related literature
- Model description
- Equilibrium characterization
- The impact of private information
- Extensions:
  - Asymmetric firms
  - N firm oligopoly
  - Capacity withholding not allowed
- Conclusions

Related literature

Multi-unit auctions:

- Wilson (1979)...
- Hortacsu an McAdams (2010), Hortacsu an Puller (2018)...

Electricity auctions:

- von der Fehr and Harbord (1992), Fabra *et al* (2006)
- Private info on costs:
  - Auction approach: Holmberg and Wolak (2018)
  - Supply function approach: Vives (2011)
- Private info on capacities:
  - Cournot competition: Kakhbod *et al* (2018), Acemoglu *et al* (2015)

The Model

- Two (ex-ante) symmetric firms, $i = 1, 2$.
- Marginal costs equal to c.
- Firms' available capacities are uncertain:
  - $k_i = \beta\kappa + \varepsilon_i$
  - $\varepsilon_i \sim \Phi(\varepsilon_i|\kappa)$, with $E(\varepsilon_i) = 0$
  - ε_i is known to firm i but unkown to firm j
  - $k_i \sim \Phi(k_i - \beta\kappa|\kappa) = G(k_i)$ in $k_i \in \left[\underline{k}, \overline{k}\right]$

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- Inelastic and known demand θ.
- Market reserve price $P > c$.

The Model

Bids, Prices and Quantities

1. Firm i observes k_i and submits a bid $(b_i(k_i), q_i(k_i))$
   - with $p_i \leq P$ and $q_i \in [\underline{k}, k_i]$

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2. Firms are called to produce in increasing price order:
   - If $p_i < p_j$: firm i produces $\min\{\theta, q_i\}$
   - If $p_i > p_j$: firm i produces $\max\{0, \min\{\theta - q_j, q_i\}\}$
   - Tie breaking rule is inconsequential for equilibrium outcomes

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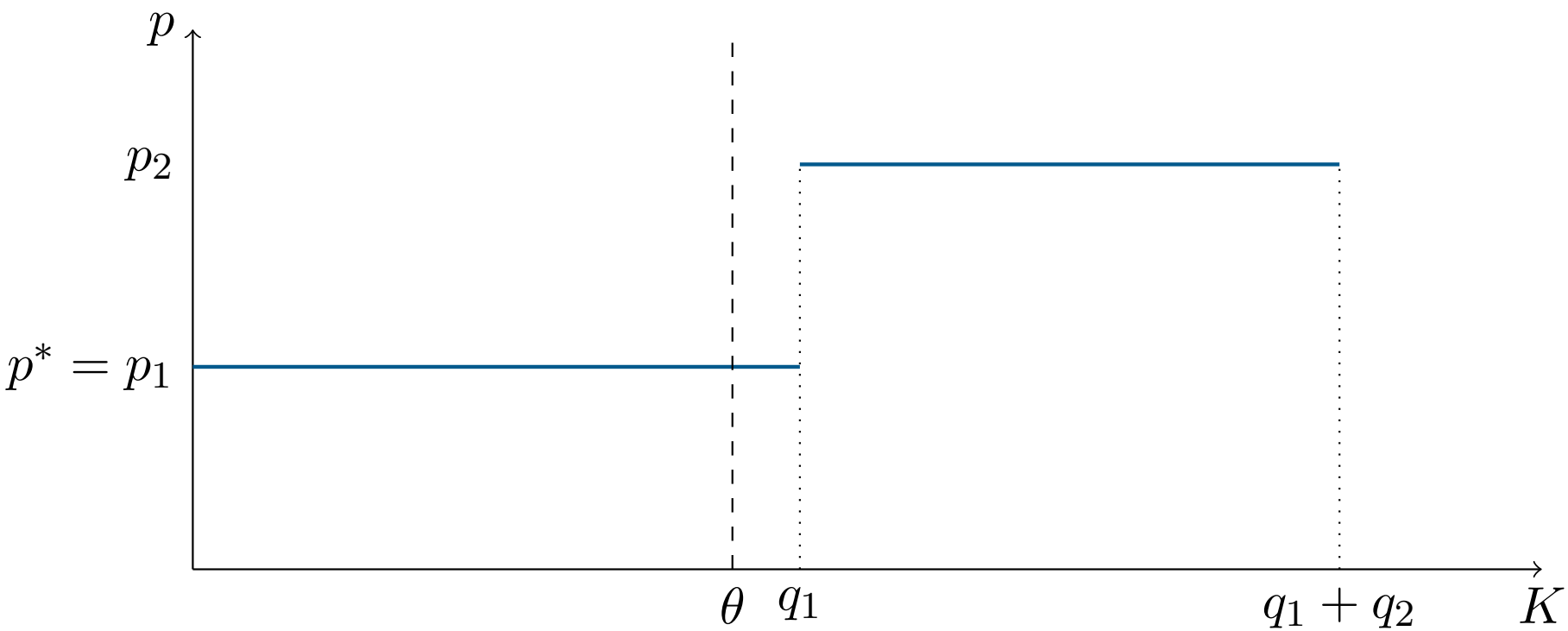
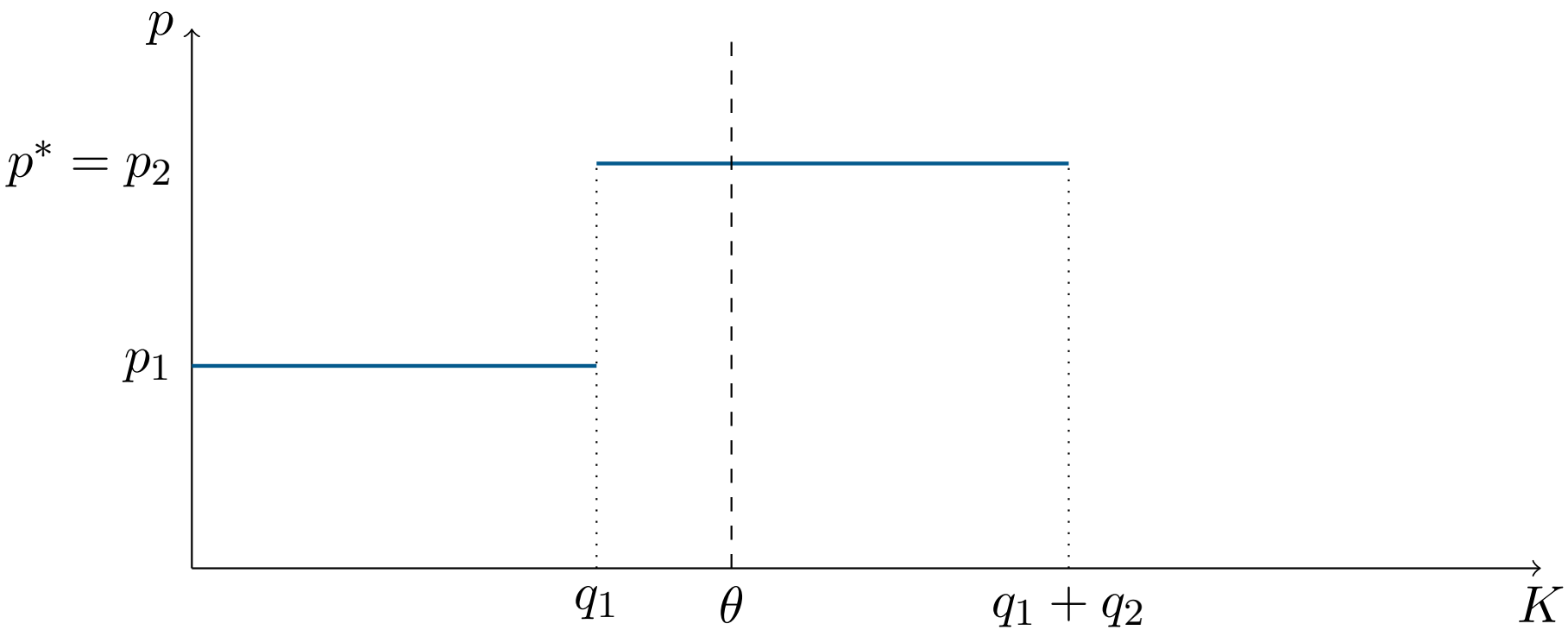
   - Tie breaking rule is inconsequential for equilibrium outcomes
3. All production is paid at the market-clearing price (**uniform-price**).

Market-clearing price



Market-clearing price



Equilibrium Characterization

- We characterize the pure-strategy Bayesian Nash equilibria
- **Ass**: capacity is always enough to cover demand $2\underline{k} \geq \theta$

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Equilibrium Characterization

- We characterize the pure-strategy Bayesian Nash equilibria
- **Ass**: capacity is always enough to cover demand $2\underline{k} \geq \theta$
- Well known case: If $\underline{k} > \theta$: competitive pricing $p^* = c$.
- Two relevant cases:
  1. **Small installed capacities**: $\overline{k} \leq \theta$.
  2. **Large installed capacities**: $\overline{k} > \theta$.

Small Installed Capacities

Equilibrium Properties

Lemma

(i) Withholding is never optimal. Hence, $q_i^* = k_i$.

Capacity withholding is not optimal:

- If $b_i < b_j$, firm i wants to sell as much as possible, $q_i = k_i$.
- If $b_i > b_j$, firm i sells $\theta - q_j$; offering $q_i < k_i$ would either not affect the market price or be unprofitable.

Small Installed Capacities

Equilibrium Properties

Lemma (cont'd)

(ii) All Bayesian Nash Equilibria must be in pure strategies.

The equilibrium cannot involve mixing:

- A firm's profits depend on its realized capacity.
- Without knowing k_j, firm i cannot randomize so as to make firm j indifferent between all the prices in the support.

Small Installed Capacities

Equilibrium Properties

Lemma (cont'd)

(iii) The optimal price offer of firm i, $b_i^*(k_i)$, is weakly decreasing in k_i.

Price offers are weakly decreasing in k_i:

- The profit function is submodular in b_i and k_i.
- Bigger firms are eager to offer low prices to sell all their capacity.

Asymmetric equilibria

Small installed capacities

Asymmetric equilibria allow to sustain highest admissible price P

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Small installed capacities

Asymmetric equilibria allow to sustain highest admissible price P

Proposition

There exist asymmetric pure-strategy Bayesian Nash equilibria, in all of which $p^* = P$. In these equilibria, $p_i^*(k_i) = P$ and $p_j^*(k_j) < \underline{p}$, $i, j = 1, 2$.

Asymmetric bidding:

- One firm bids at P.
- The other firm bids low enough to discourage undercutting.

Asymmetric profits:

- The low bidder makes higher profits.
- Hence, firms face a **coordination problem**.

Small Capacities

Characterizing the symmetric equilibrium

Expected profits can be written as

$$\begin{aligned}\pi_i(b_i; k_i, b_j(k_j)) &= \int_{\underline{k}}^{b_j^{-1}(b_i)} (b_j(k_j) - c) k_i g(k_j) dk_j \\ &\quad + \int_{b_j^{-1}(b_i)}^{\overline{k}} (b_i - c)(\theta - k_j) g(k_j) dk_j\end{aligned}$$

Under symmetry, $b_j(k) = b_i(k)$, the FOC becomes

$$\frac{1}{b_i'(k_i)} g(k_i)(b_i(k_i) - c)(k_i - (\theta - k_i)) + \int_{k_i}^{\bar{k}} (\theta - k_j) g(k_j) dk_j = 0$$

Symmetric equilibrium

Small installed capacities

At the symmetric equilibrium **firms bid below** P, and **price offers are strictly decreasing in** k_i

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Proposition

At the unique symmetric pure-strategy Bayesian Nash Equilibrium, each firm $i = 1, 2$ *offers all its capacity,* $q^*(k_i) = k_i$*, at a price*

$$b^*(k_i) = c + (P - c) \exp\left(-\omega(k_i)\right),$$

where

$$\omega(k_i) = \int_{\underline{k}}^{k_i} \frac{(2k - \theta)g(k)}{\int_k^{\bar{k}} (\theta - k_j)g(k_j)dk_j} dk.$$

Symmetric equilibrium

Small installed capacities

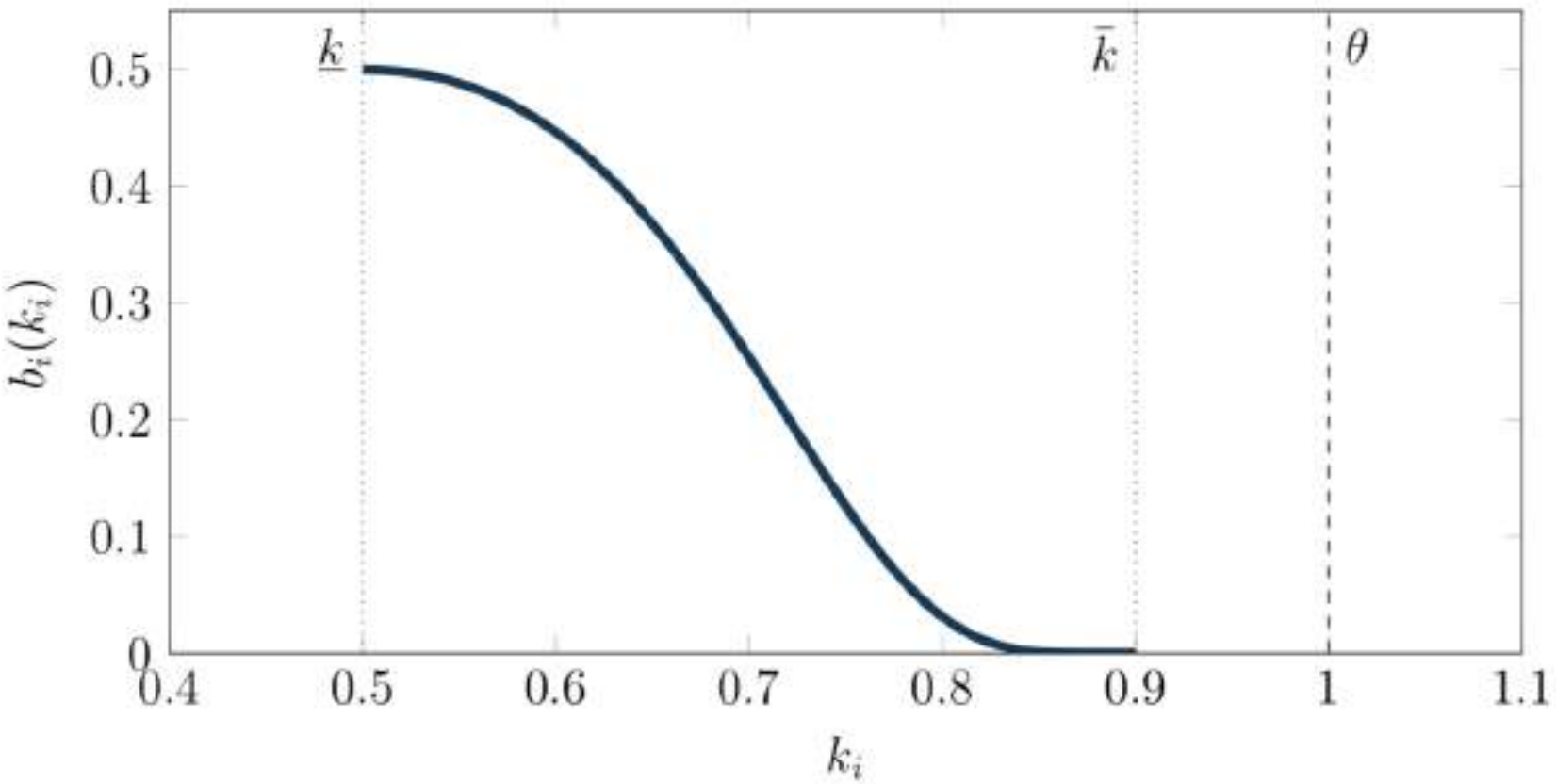


Figure: Equilibrium bids when $k_i \sim U[0.5, 0.9]$, $\theta = 1$, $c = 0$, and $P = 0.5$.

Small Capacities

Interpreting the Symmetric Equilibrium

- Incentives for marginally increasing the price:

$$\frac{b^{*\prime}(k_i)}{b^*(k_i) - c} = -\omega'(k_i) = -\frac{(2k_i - \theta)g(k)}{\int_{k_i}^{\theta}(\theta - k_j)g(k_j)dk_j}.$$

- **Quantity Effect:** If $k_j = k_i = k$ (with prob. $g(k)$), $b_i = b_j$. Marginally increasing b_i implies an *output loss* of $k - (\theta - k) = 2k - \theta$.
- **Price Effect:** If $k_j > k_i = k$, then $p^* = b_i$. Marginally increasing b_i implies a *higher price* which the firm internalizes through its sales, $\theta - k_j$.

Equilibrium with large installed capacities

Proposition

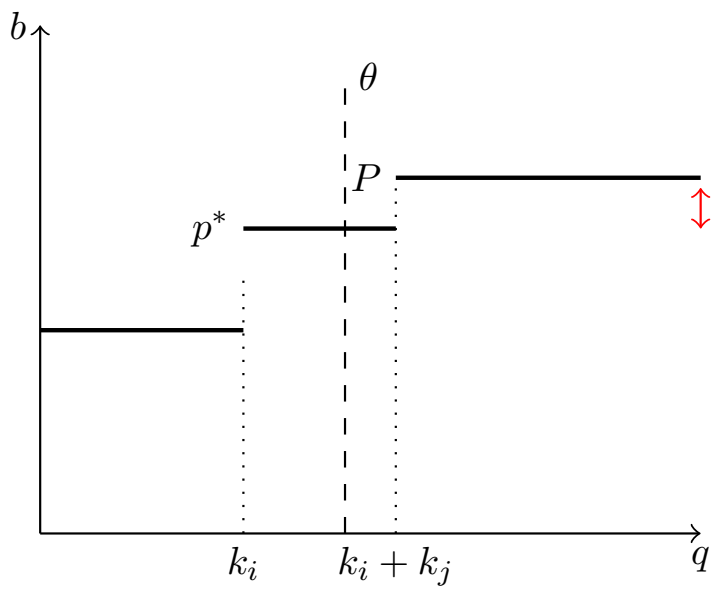
If $\overline{k} > \theta$, in equilibrium, $b_i^*(k_i) = c$ and $q_i^*(k_i) = \theta$ for all $k_i > \theta$, $i = 1, 2$. For $k_i \leq \theta$, the previous Propositions apply with $G(k_i)$ now adjusted to $G(q_i^*(k_i))$, $i = 1, 2$.

- Allowing for $\overline{k} > \theta$ makes **withholding optimal**.
- When $k_i > \theta$, the firm behaves as if k_i was θ.
- The shape of the price function is similar as in the baseline case, with $G(k_i)$ adjusted to accumulate a mass $1 - G(\theta)$ at θ.

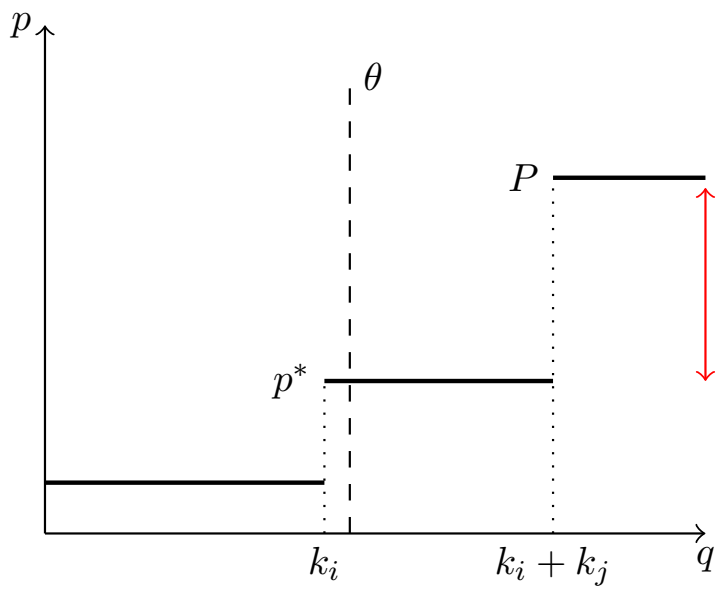
Comparative statics

More available capacity

- When realized capacities are larger relative to demand...
  - Supply functions shift downwards and outwards
  - Market prices fall
- Market power mitigates the price-depressing effects of renewables (different channel than in Acemoglu *et al.* (2015))
- The impact of private information on costs or capacities differ



(a) Small price reduction



(b) Large price reduction

Comparative statics

More installed capacity

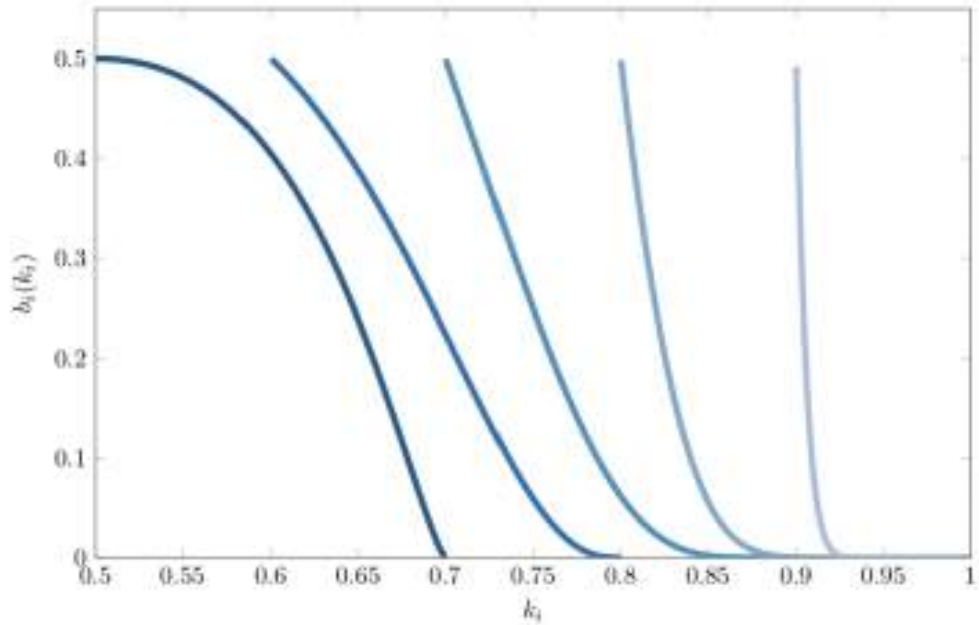


Figure: Equilibrium price offers when $k_i \sim U[\underline{k}, \underline{k} + 0.2]$, for $\underline{k} \in \{0.5, 0.6, 0.7, 0.8, 0.9\}$ with $\theta = 1$, $c = 0$, and $P = 0.5$.

Bid functions shift out with more renewable investments....

1. For a given k_i, the rival is more likely to bid below.
2. However, high capacity realizations are more likely.

Comparative statics

More installed capacity

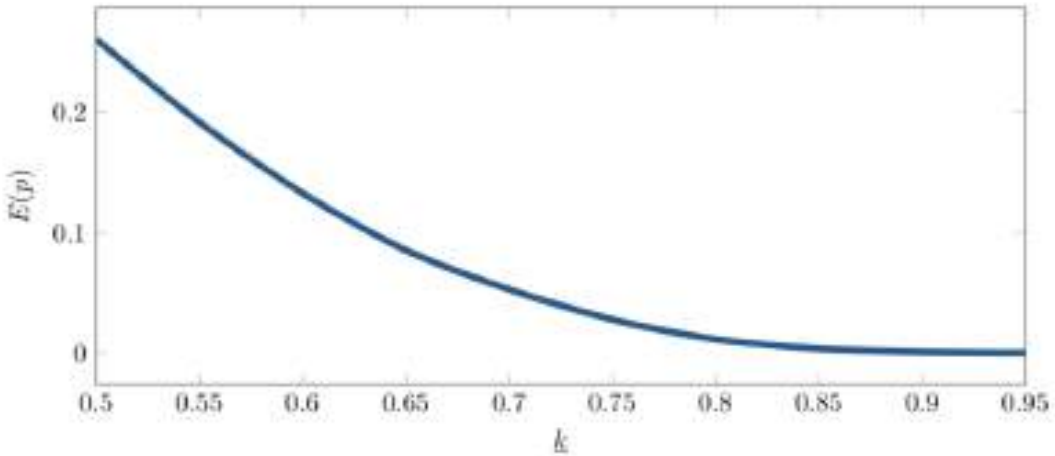


Figure: Average market price when $\theta = 1$, $c = 0$, and $P = 0.5$, and $k_i \sim U[\underline{k}, \underline{k} + 0.2]$, for $\underline{k} \in [0.5, 0.95]$.

Prices smoothly go down with more renewable investments....

1. Large capacities more likely.
2. Probability of a bid at c increases.

The Impact of Private Information

Known versus unknown capacities (symmetric equilibria)

Two benchmarks w/o private information:

1. Capacities are publicly known.
2. Capacities are unknown to both firms prior to bidding.

Lemma

(i) *If realized capacities are* **publicly known**, *all symmetric pure-strategy equilibria result in joint profits* $(P-c)\theta$.

(ii) *If realized capacities are* **unknown** *prior to bidding, the unique symmetric equilibrium involves mixed strategies, with expected equilibrium joint profits* $2(P-c)(\theta - E[k])$.

- Realized capacities are used as a symmetric coordination device. This is not possible with unknown capacities.
- Adding *a bit* of private information around realized capacities does affect outcomes (note that firms are no longer ex-ante symmetric).

The Impact of Private Information

Comparison

Proposition

The comparison of the symmetric equilibria shows that:

(i) *The* **lowest** *expected prices are obtained with* **unknown capacities**.

(ii) *The* **highest** *expected prices are obtained with* **known capacities**.

Private information leads to prices in between the other two:

- With private information, firms avoid the fierce competition that would arise under symmetry (unknown capacities).
- But it falls short of allowing firms to coordinate on high/low bids.

Private information acts as an **imperfect coordination device**.

Extensions

1. **Asymmetric firms**
   - Explicit solution with uniformly distributed capacities.
   - Asymmetric equilibria if capacity intervals do not overlap.
   - Firms choose the same strategy in the range in which they overlap.
   - Equilibrium prices increase with ex-ante capacity asymmetries.
2. N **firms oligopoly**
   - Disentangle the effect of more competition from more information.
3. **Withholding not possible**
   - Equilibrium in pure strategies for $k < \theta$ and in mixed strategies for $k \geq \theta$.

▸ JUMP

Asymmetric Firms

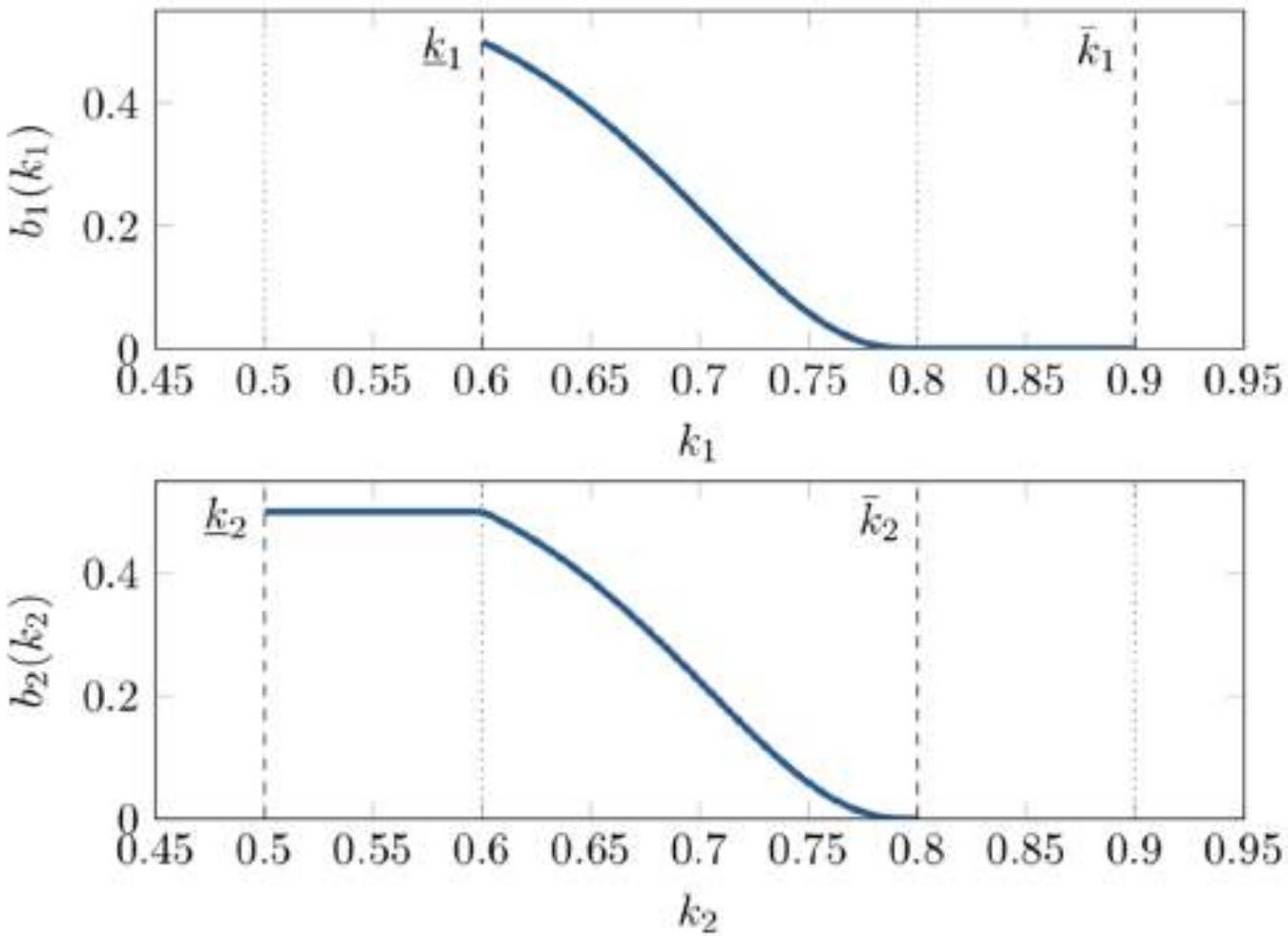


Figure: Equilibrium bids with ex-ante asymmetric firms

Oligopoly

The effects of mergers

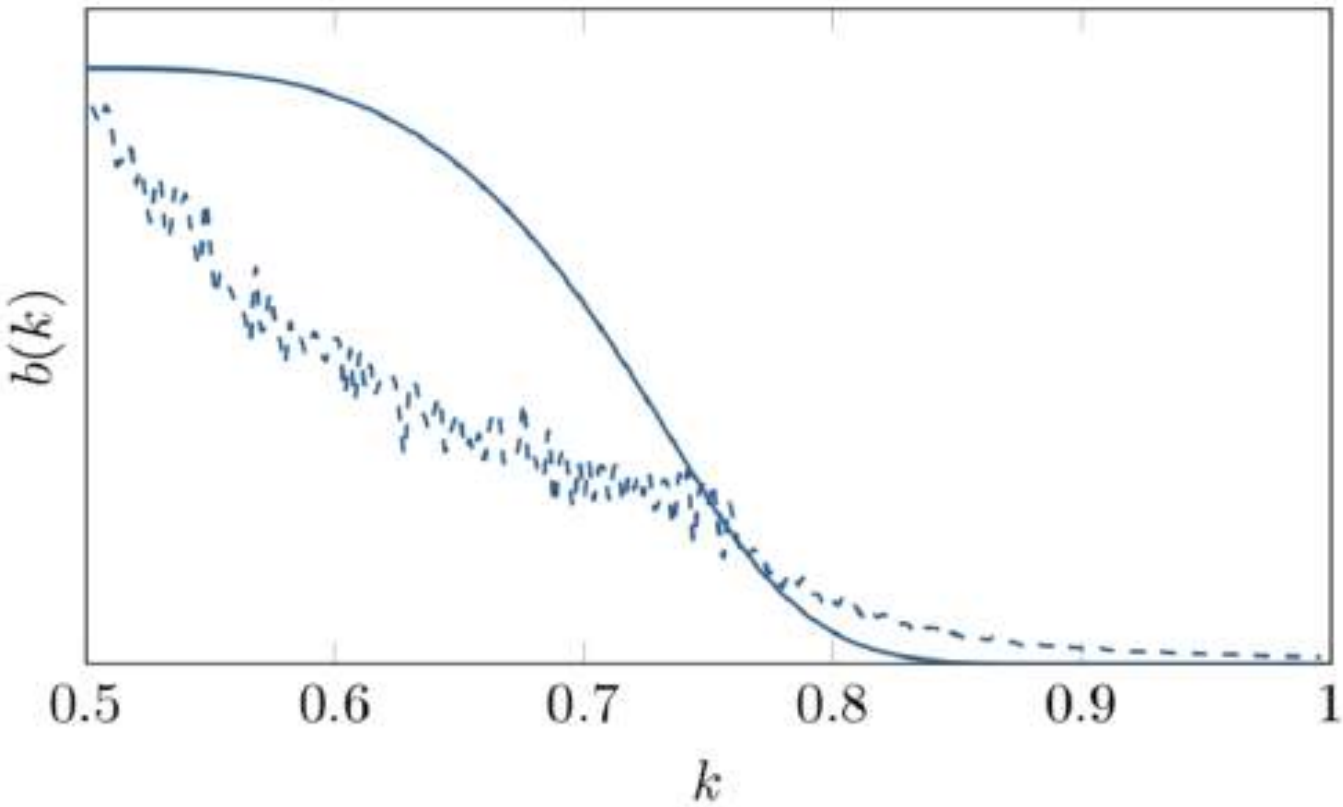


Figure: Equilibrium bids when $N = 2$ (solid line) and $N = 4$ (dashed line)

No capacity withholding allowed

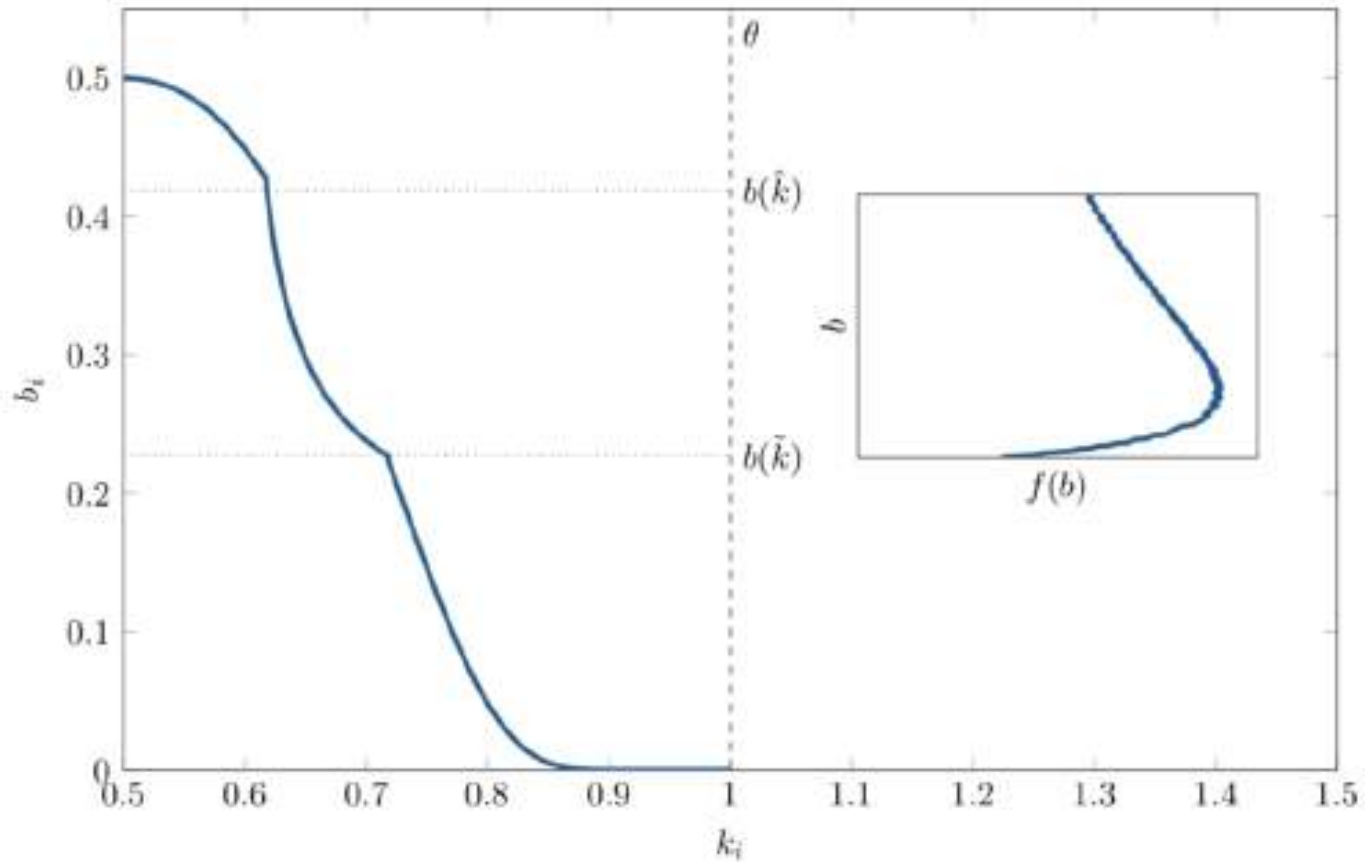


Figure: Equilibrium bids and probability density when $k_i \sim U[0.5, 1.1]$, with $\theta = 1$, $c = 0$, and $P = 0.5$.

No capacity withholding allowed

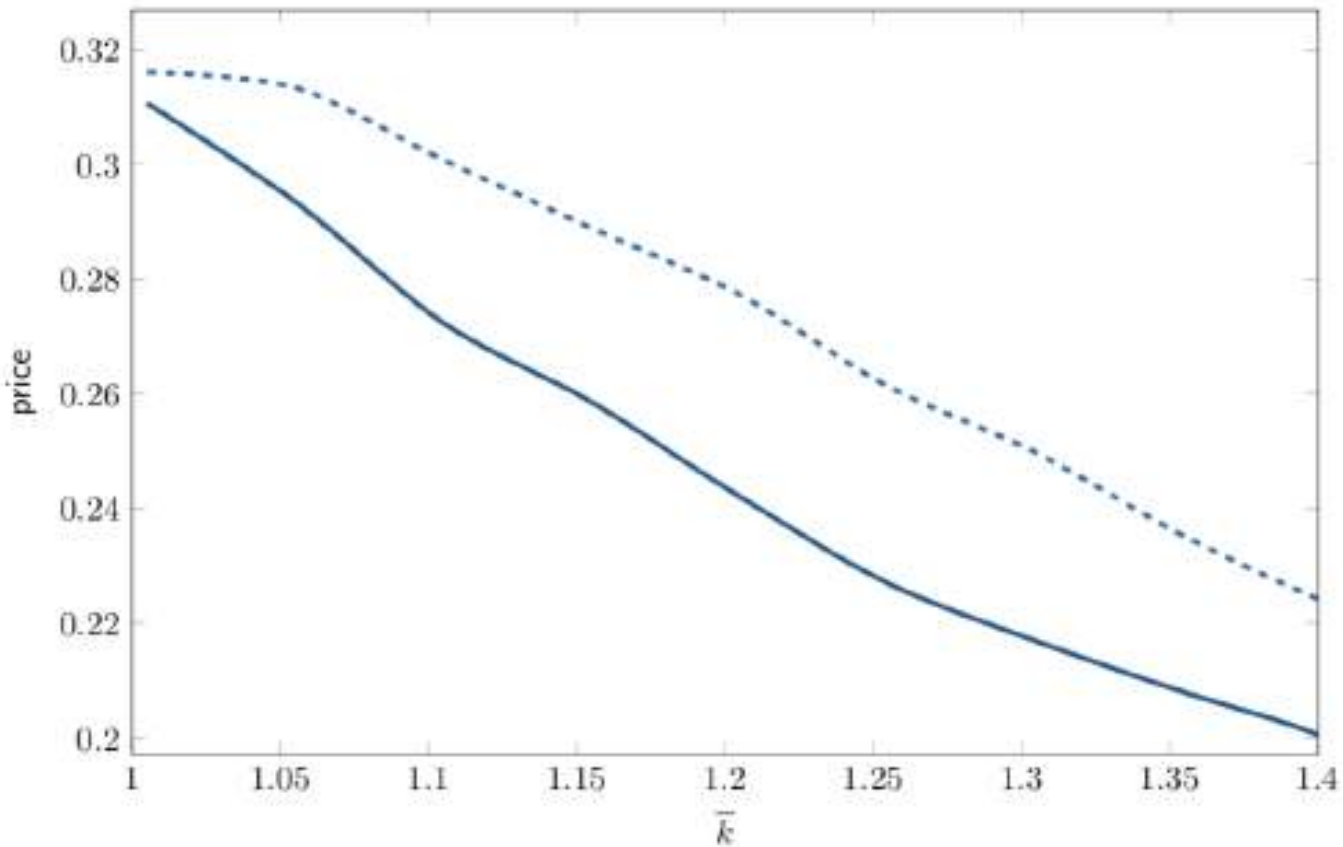


Figure: Equilibrium prices for $\underline{k} = 0.5$ and $\overline{k} > 1$ when withholding is possible (solid line) or not allowed (dashed line)

What have we learnt

Understanding competition among renewables

1. Because of their uncertainty, **renewables mitigate market power**.
2. Still, **market power and price dispersion** will prevail.
3. Market power will involve **above marginal cost pricing when capacities are small**, or **capacity withholding** when large.
4. Lower bids and prices at times with more renewables availability.
5. Investment in renewables will **depress market prices smoothly**.

What have we learnt more broadly

Multi-unit auctions with **private information on capacities**

1. It matters whether private information is on costs or capacities:
   - With private info on capacity....
     - A firm's sales depend on rival's capacity $\rightarrow$ steeper bids.
     - Both prices and quantities respond to capacity shocks.
     - Prices more responsive to private information on capacities.
2. Private information gives rise to higher prices than without, but lower than with known capacities.
3. The mode of competition is endogenous:
   - Bertrand if realized capacity is small.
   - Cournot if realized capacity is large.

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Thank You!

Questions? Comments?

More info at nfabra.uc3m.es

This Project has received funding from the European Reserarch Council (ERC) under the European Unions Horizon 2020 research and innovation programme (grant agreement No 772331)