Firms' Bidding Behavior in a New Market: Evidence from Renewable Energy Auctions

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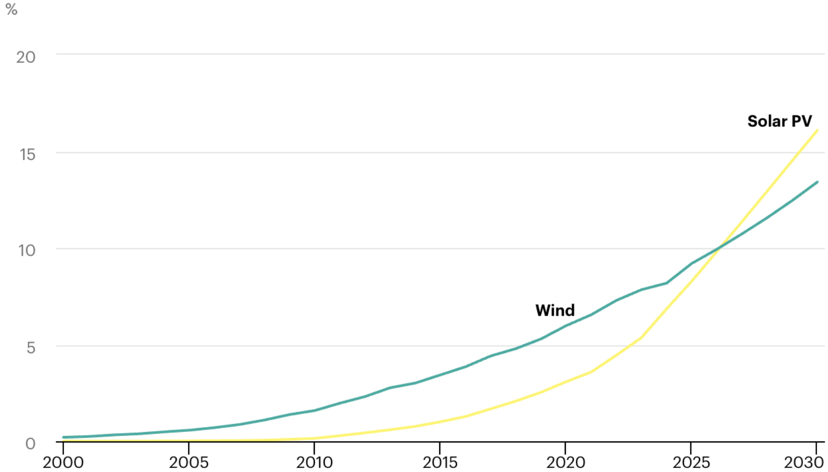
Renewables' share of generation more than tripled since 2015 worlwide

Share of renewable electricity generation by technology, 2000-2030, worlwide



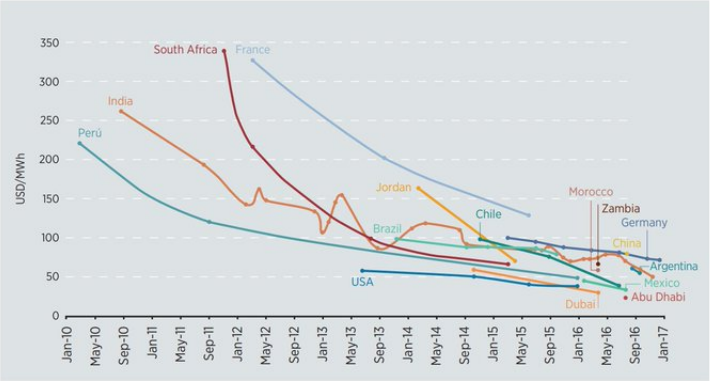
Introduction

- Climate change mitigation policies envision large investment in Renewable Energy (RE) technologies
- Governments are looking for most effective ways to increase RE shares:
  - Fixed subsidy schemes mostly replaced by market-based support mechanisms: *RE auctions* ($>$ 100 countries, Dec. 2018)
- Yet, determinants of the market participants' bidding behavior has not been widely studied empirically
  - Importance for total deployment cost of technologies and for successful auction implementation

Solar auctions have been implemented in numerous countries

Downward trend in average auction prices

Figure 2.3 Evolution of average auction prices for solar PV, January 2010-February 2017



Notes: Prices are averages. On the rare occasion when multiple auctions occurred within the same month, the average price of those auctions is shown. In case of ambiguity regarding the auction's date, the date when the winning bids were selected and announced was taken as the main reference.

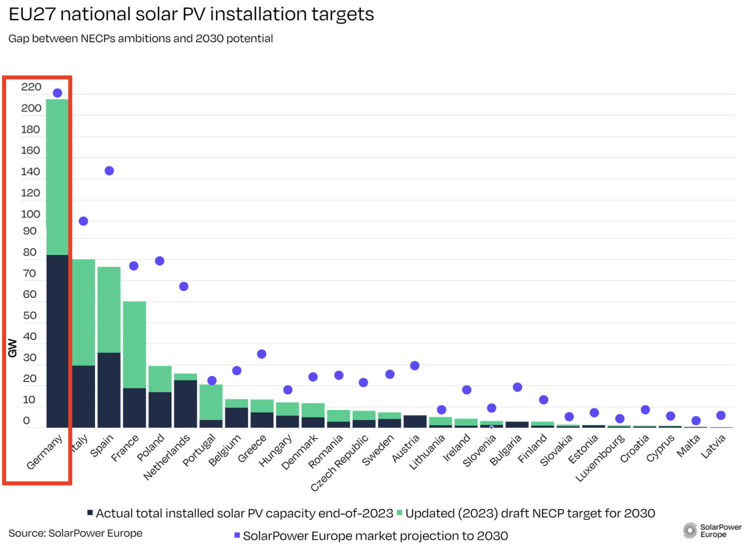
Sources: Based on data from BNEF (2016 a, b,c), ANEEL (2016), BnetzA (2017a), Bridge to India (2017a), Coordinador Eléctrico Nacional (2016), Eberhard and Kåberger (2016), Elizondo-Azuela, Barroso et al. (2014), IFC (2016), Mahapatra (2016 a,b), MINEM (2016a, b), MNRE (2010), MNRE (2012), Ola (2016), Osinergmin (2016), Santiago and Sinclair (2017a, b), Shahan (2016).

Research questions

- How does auction design impact market outcomes?
  - Focus on **pricing rule** (uniform vs. pay-as-bid (PAB) pricing) in setting where outcome of auction determines level of in-feed price (production subsidy)

- What is the role of cost and market factors in observed price developments in RE auctions?

The case of Germany: Largest solar PV capacity installed in the EU



Source: SolarPower Europe

This paper

- Uses unique bid-level data for German RE auctions (2015-2019) - with focus on utility scale solar photovoltaic plants
- Uses quasi-experimental data: uniform and PAB formats observed
- Recovers bidders' costs by estimating a structural model of multi-unit auctions under uniform and PAB pricing rules accounting for future cash flows from subsidies
- Documents correlations of bidders' cost/market factors on bid prices and markups under the different pricing rules
- Studies counterfactual outcomes from **uniform auction design**: prices, subsidies, & cost efficiency

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Findings:

- Pricing rule matters for prices and markups in German solar auctions
- Bid prices and costs are strongly correlated with bidders' size
- Adopting Uniform format ⇒ lower subsidy expenses and market power

Contributions

1. **Methodology:** Multi-unit auctions with future payments
   - Extend standard framework for multi-unit auctions commonly used in treasury auctions to account for discounted value of future payments
   - New application in context where auction equilibrium determines future subsidy payments taking into account common market price uncertainty
2. **Policy:** Discussion on effective auction design
   - First paper to empirically study ranking pay-as-bid vs. uniform auction in renewable energy auctions

Relations to literature (selected)

- We add to empirical literature on Bidding in Energy Auctions

  Wholesale Electricity Market: Hortacsu and Puller (2008); Hortacsu et al. (2019); Reguant (2014); Wolak (2003, 2007)
  RE Procurement: Hara (2024); Ryan (2021)

- We extend literature on Auction Design and Market Outcomes

  Ausubel et al. (2014); Fabra et al. (2011); Fabra and Montero (2023); Holmberg and Wolak (2018); Kang and Puller (2008); Willems and Yu (2023)

- We build on literature on Empirical Analysis of Multi-Unit Auctions

  Methods: Hortacsu and McAdams (2010, 2018); Kastl (2011, 2012)
  Applications: e.g., Cassola et al. (2013); Elsinger et al. (2019); Gupta and Lamba (2023); Kim (2022); Reguant (2014); Wolak (2007)

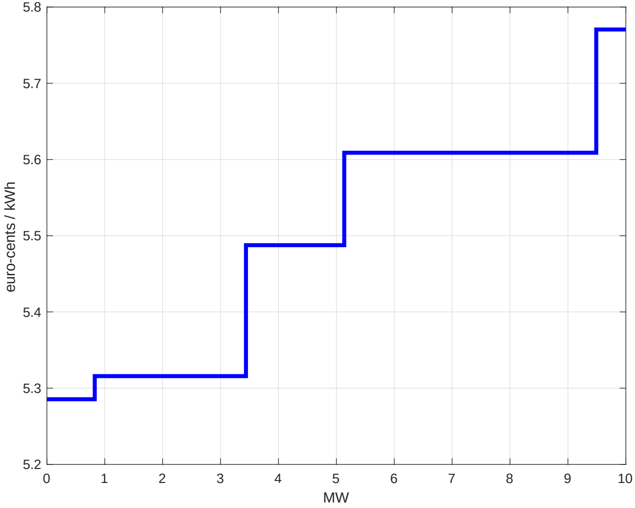
RE Auctions - Germany

- Introduction of auctions in 2015 for 'large' solar, wind, and biomass installations
  - Focus on utility-scale solar ($>$ 750 kW and $\leq$ 20 MW)
- Multi-unit auctions: total demand (auction volume) set by government, bidders submit multiple quantity-price pairs (projects)
- Pay-as-bid pricing rule (except two early rounds w/ uniform pricing)
- 20 year payment guarantee (one-sided 'Contract for Difference', CfD)
- Last successful bid is fully awarded: no rationing

Additional auction details

An example of a bid curve

Data from one single firm in a specific auction round



Subsidy payments

One-sided CfD

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$$\text{subsidy}_{it} = \begin{cases} b_i - cp_t & \text{if } b_i > cp_t \\ 0 & \text{if } b_i \leq cp_t \end{cases}$$

Uniform auction

$$\text{subsidy}_{it} = \begin{cases} p^* - cp_t & \text{if } b_i > cp_t \\ 0 & \text{if } b_i \leq cp_t \end{cases}$$

cp_t: ("**c**apture **p**rice") avg mkt price of solar at the EPEX spot mkt

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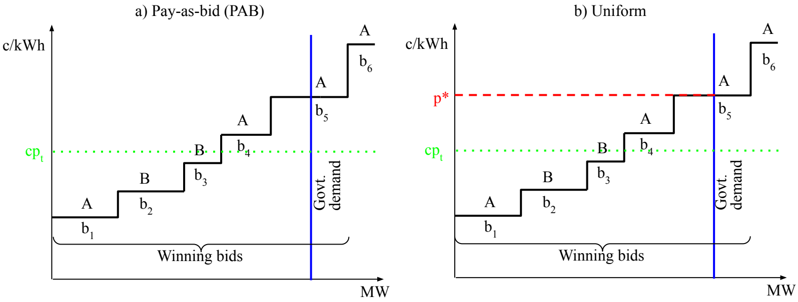

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- b_i & p^*: determined at time 0: the time of the auction
- cp_t: calculated for the entire solar portfolio in Germany on a monthly basis
- Support mechanism guarantees generators receive at least their bid
- Insurance against low capture prices. Eliminates long-term risk

Data

RE auctions:

- **All individual bids (winners + losers)** from 18 auction rounds (2015-2019), anonymized
- Focus on two uniform-price auctions in 2015 and pay-as-bid auctions between April 2016 and June 2019 (16 rounds)
- **For winning bids:** information on project realization and annual production

Auction rounds Summary statistics

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Auction rounds | Summary statistics

Additional data:

- Aggregate cost development: solar panel and system cost (industry data)
- Average solar irradiation (German Weather Service)
- Access nodes of high-voltage electricity network

Location of bids and network | Evolution of competition

Reduced form evidence: Uniform pricing vs Pay-as-bid

$$b_{ik\tau} = \beta_0 + \beta_1 \mathbb{1}(\text{uniform pricing}) + \beta \mathbf{X}_{ik\tau} + \mu_i + \zeta_\tau + \varepsilon_{ik\tau},$$

	(1)	(2)	(3)	(4)	(5)
$\mathbb{1}$(uniform pricing)	-1.501***	-1.396***	-1.220***	-1.313***	-1.165***
	(0.133)	(0.133)	(0.191)	(0.132)	(0.130)
$\mathbb{1}$(large bidder)	-0.277*	-0.308***	-0.052		
	(0.147)	(0.106)	(0.095)		
Auction volume (100 MW)	-1.150**	-1.028**	-2.286***	-0.660	-2.182
	(0.448)	(0.499)	(0.699)	(0.499)	(1.733)
Auction volume^2	0.164**	0.146*	0.385***	0.094	0.328
	(0.069)	(0.076)	(0.105)	(0.075)	(0.537)
Distance to network (100 km)	0.475*	0.439*	0.318	0.415	0.335
	(0.258)	(0.262)	(0.245)	(0.337)	(0.397)
Solar irradiation (MWh/m^2)	-1.915**	3.075*	1.271	2.893	3.674
	(0.871)	(1.660)	(1.869)	(2.273)	(2.747)
Avg. system cost (€/kWh)		0.679**	0.339	0.832**	0.748**
		(0.315)	(0.215)	(0.356)	(0.305)
N	1,573	1,573	598	1,573	583
Adjusted R^2	0.72	0.75	0.70	0.83	0.82
Mean DV	6.89	6.89	6.14	6.89	8.51
Land-type FE	No	Yes	Yes	Yes	Yes
State FE	No	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes
Bidder FE	No	No	No	Yes	Yes

Notes: DV: bid values. Sample: All RE auctions from April 2015 - June 2019. Col 3: winning bids only. Col 5: 2015-2016 only. Standard errors clustered at the bidder level. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Model of multi-unit auctions, set-up

- Building on Hortacsu & McAdams (2010), Kastl (2011, 2012): empirically estimate costs taking into account discreteness of bids
  - Our contribution: **stream of future subsidy payments**
- R auction rounds, indexed by τ: discriminatory auction (PAB) of Q_τ divisible units (government demand for solar capacity)
- In each round: N_τ bidders, risk-neutral with independent private values (IPV)
  - IPV: idiosyncratic shocks to project cost (planning, financing, land)
  - Additionally model common market component from expected capture prices

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  - IPV: idiosyncratic shocks to project cost (planning, financing, land)
  - Additionally model common market component from expected capture prices
- **Allow for heterogeneous groups:** bidders assumed to be symmetric conditional on belonging to group g, defined by bidder size (average project size)

Expected payoffs

- Each firm has a cost of developing solar (per unit cost of production) $c_i(q_{ik}; s_i) \equiv c_{ik}$, increasing in private signal s_i and project capacity q_{ik} in MW (omitting the time subscript)
- Firm i submits a non-decreasing supply schedule

$$y_i(p; s_i) = \sum_k q_{ik} \mathbb{1}[p \in (b_{ik}, b_{ik+1}]]$$

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to maximize

$$E\Pi_i = E_{Q,s_i|s_{-i};cp_t} \int_0^{Q_i(\boldsymbol{y}(\cdot;\boldsymbol{s}))} \pi_i \, dq$$

where

$$\pi_i = \sum_{k=1}^{K} \left[\sum_{t=13}^{T=252} \underbrace{\delta^t \left[\mathbb{1}(b_{ik} > cp_t)(b_{ik} - c_{ik}) + \mathbb{1}(b_{ik} \leq cp_t)(cp_t - c_{ik})\right]}_{\text{Discounted future profits}} \right] \mathbb{1}(q_k \leq q < q_{k+1}).$$

and $Q(\cdot)$ is the quantity firm i gets awarded when all firms' supply schedules are $\boldsymbol{y}(\boldsymbol{p}; \boldsymbol{s})$

Equilibrium Price and Bids

- We assume common market price expectations for the evolution of capture price: $E[cp_t] = cp_0 \times \gamma_1 \phi_t \times \gamma_2 \sigma_t$ Capture price

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- Set of all supply schedules in $\boldsymbol{y}(\boldsymbol{p}; \boldsymbol{s})$ is a Bayesian Nash equilibrium if each firm i maximizes $E\Pi_i$
- Horizontal sum of other bidders' supply curves ($\sum_{j \neq i} y_j(p; s_j)$) and the total demand for solar installations (Q) determine residual demand RD_i faced by firm i:

$$RD_i(p; s_i) = Q - \sum_{j \neq i} y_j(p; s_i)$$

- Intersection of $RD_i(p; s_i)$ with $y_i(p; s_i)$ for each i determines an equilibrium price p_c

Recovering Costs

- Consider **profits from step k** of bidding curve

$$\pi_{i,k} \equiv \underbrace{\sum_{t \mid b_{i,k} > cp_t} \delta^t (b_{i,k} - c_{i,k})}_{\text{subsidy active}} + \underbrace{\sum_{t \mid b_{i,k} \leq cp_t} \delta^t (cp_t - c_{i,k})}_{\text{no subsidy}}$$

$$= b_{i,k} \sum_{t \mid b_{i,k} > cp_t} \delta^t - c_{i,k} \sum_{t=13}^{T=252} \delta^t + \sum_{t \mid b_{i,k} \leq cp_t} \delta^t cp_t$$

$$= L_{1,k}(cp_t, b_{i,k}) b_{i,k} - L_2 c_{i,k} + L_{3,k}(cp_t, b_{i,k})$$

- **Perturbation argument** building on Kastl (2011, 2012):

$$\underbrace{\Pr(b_{i,k} < p_c < b_{i,k+1})}_{\equiv M_1} \pi_{i,k} = \underbrace{\Pr(b_{i,k+1} \leq p_c)}_{\equiv M_2} (L_1(cp_t, b_{i,k+1}) b_{i,k+1} - L_1(cp_t, b_{i,k}) b_{i,k}$$
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$$+ L_3(cp_t, b_{i,k+1}) - L_3(cp_t, b_{i,k})),$$

- **Gives expression for cost:**

$$c_{i,k} = \frac{1}{L_2} \left(L_{1k} b_{ik} + L_{3k} - \frac{M_2}{M_1} (L_{1,k+1} b_{i,k+1} - L_{1k} b_{i,k} + L_{3,k+1} - L_{3,k}) \right)$$

Estimating the cost of production

Resampling of competitors bids to construct simulated residual demand curves

- **Goal:**
  - Estimate $c_{i,k}$ using expression above. Challenge: Estimation of M_1 and M_2
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- **Robustness:** estimate 'standard' version in which everything depends on auction payoff $(y_i^{-1}(q; s_i) - c_{ik})$ ▸▸ No future payoffs

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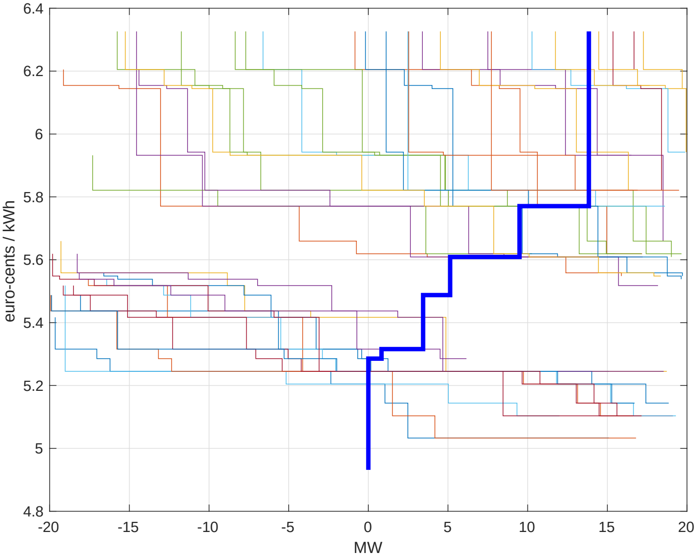
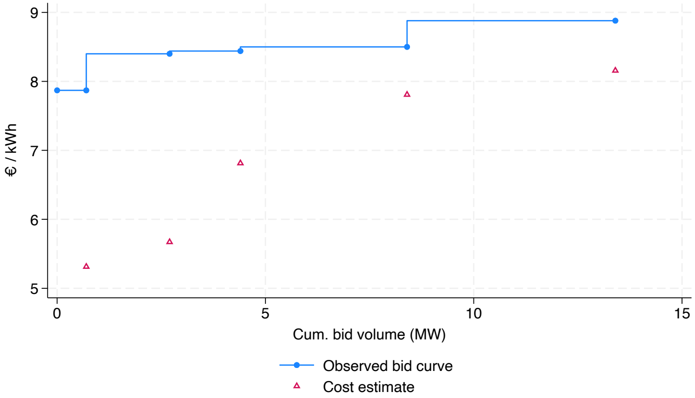
3. Repeat previous step for the other group $h \in G \setminus \{g\}$, drawing n_h bid vectors, assigning weight of $1/n_h$.
4. Construct bidder i's realized residual demand $RD_i(p; s_{-i})$ to **determine the realized market-clearing price.**

Simulated market clearing prices, example



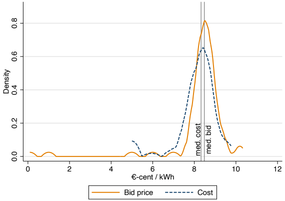
Bid curve and cost estimates



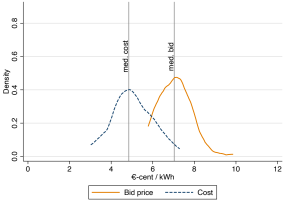
Notes: Example of bid curve and cost estimates for one bidder under PAB pricing. We omit the bidder indicator as well as the round number in order to comply with the anonymization of the data. In this case, there are five different quantity-price pairs (bids) submitted by this bidder.

Estimated costs and observed bids densities

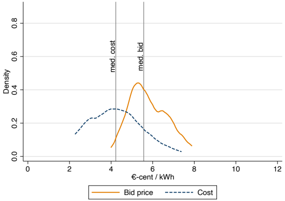
Qty-weighted avg. bids, UP and PAB, Lerner index



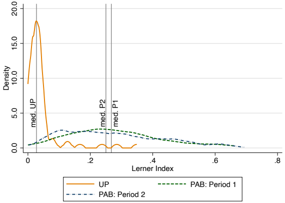
(a) UP: Auction rounds 2-3



(b) PAB, Period 1: Auction rounds 4-8



(c) PAB, Period 2: Auction rounds 9-18



(d) Lerner Index, all three periods

No future payoffs

Goodness-of-fit

- Our estimates: median cost of 5.33 €-cents/kWh
- Industry data: median average system cost of 5.05 €-cents/kWh
- Remarkable result: no cost information was provided to the structural model
- Estimated costs recovered by inverting the optimality condition using only the observed bids as inputs

Correlation between MCs, bids, and market factors

Set of linear regressions:

- Accounting for land type, state, year (and bidder) FEs
- **DV:** markups, prob. of winning, bid values (pass-through)

Main findings:

- Large bidders have lower markups under PAB compared to small bidders and the initial UP rounds
- Auction generally selects low cost bids
- Evidence of heterogeneous cost pass-through over **time** and by **bidder size** Results

Robustness

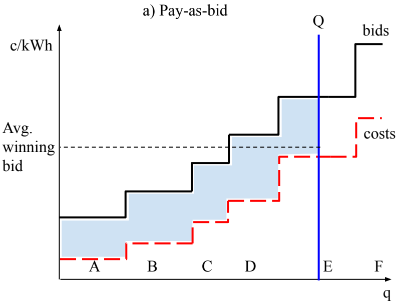
- Regression
  - Drop single step bidders
  - Keep only last appearance of each bid
  - Omit interpolated observations (zero margin)
  - Alternative definition of large bidders (number of steps)
- Model
  - Assume symmetric bidders
  - Treat auction rounds independently vs. pool multiple auction rounds (4-dimensional kernel)
  - **IPV assumption:** regression of bid prices on publicly available data (t-1), pairwise correlation test of residuals (Bajari and Ye, 2003)

Multi-unit Auctions and Pricing Rules

- Bidders' strategies can be different under different auction formats
- No theoretical ranking for revenue in mult-unit auctions (Ausubel et al., 2014)

Revenue in Pay-as-bid Auction (assuming monotonicity of costs)

Revenue in Uniform Auction (firms might bid differently ⇒ non-monotonic costs)

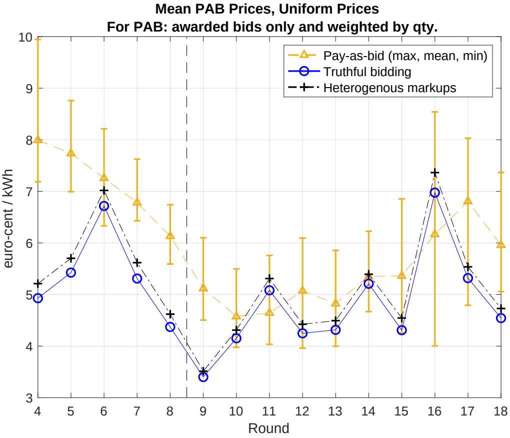


Counterfactual: Pay-as-bid (PAB) vs. uniform price auction

- Focus on PAB rounds 4-18 and **consider two 'extreme' cases:**
  - Truthful bidding: Assume bidders bid *truthfully* ($b = c$) (common in the literature)
  - Heterogenous markups: use uniform auction rounds to estimate qty-weighted mean markup of 6% for small bidders and 2% for large bidders
    Regression UP
  - More complex CFs difficult: Wilson (1979), LiCalzi and Pavan (2005), McAdams (2006) have found multiplicity of equilibria in multi-unit UP
- For each round, pool all estimated costs in increasing order: supply curve under uniform auction format
- Find intersection with volume demanded by regulator $\Rightarrow$ single market clearing price
- All bidders with inframarginal costs receive market clearing price
- No clear theoretical ranking between PAB and uniform pricing rule: empirical question

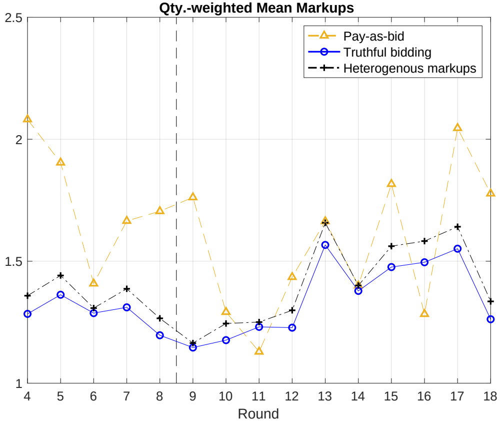
PAB and truthful bidding

Truthful Bidding (uniform price auction) does not necessarily lead to lower market clearing prices



Markups under different auction formats

Qty-weighted avg. markups: p_c/c_i and b_i/c_i



- Uniform price auction would have given place to a lower exercise of market power
- Lower market power UP auction not a mechanical feature of model: PAB bidders still face a trade-off between bidding low to get selected and bidding high to maximize their payoff

Total procurement costs

- Uniform price subsidy

$$S_{U_t} = \sum_i \frac{q_i}{Q} \theta \max\{p_c - cp_t, 0\}$$

- Pay-as-bid subsidy

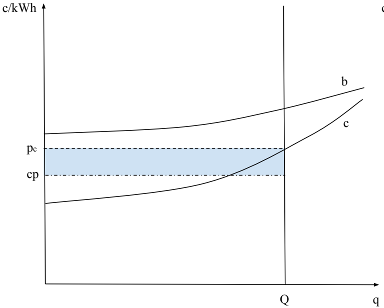
$$S_{PAB_t} = \sum_i \frac{q_i}{Q} \theta \max\{b_i - cp_t, 0\}$$

  over all the quantities up to Q (government demand)
  - p_c: market clearing price assuming uniform pricing
  - cp_t: capture price
  - θ: time duration of output (1 hour)
- S_{U_t} and S_{PAB_t} in €per kW of installed capacity
- Define S_U and S_{PAB} as discounted sum of per-period subsidies

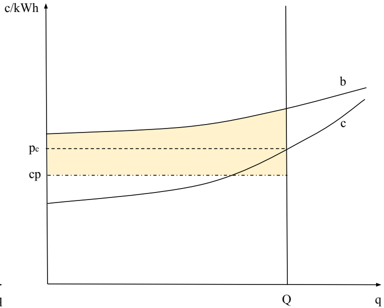
$S_U < S_{PAB}$ and $S_U > S_{PAB}$ are possible

Subsidy under uniform pricing can be lower than under pay-as-bid

Uniform pricing

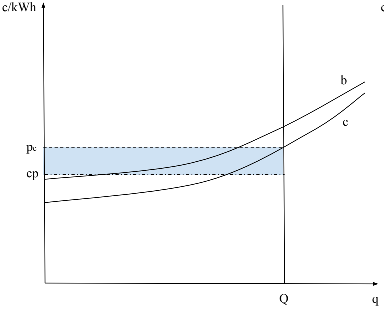


PAB

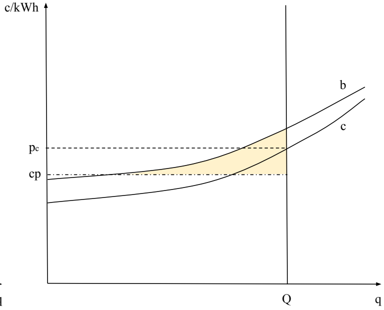


Subsidy under pay-as-bid can be lower than under uniform pricing

Uniform pricing

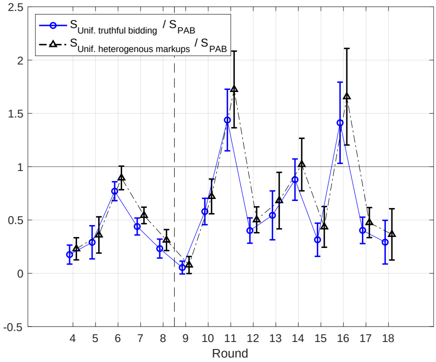


PAB



Aggregate bid curve *b* much closer to incremental cost curve

Subsidies under pay-as-bid and truthful bidding



- Ratio of subsidy under truthful bidding and PAB: S_U/S_{PAB}
  - Subsidy payments under uniform auctions lower mainly in early rounds
  - Less certainty in ranking in later rounds when estimated margins were lower

Differences in subsidies

Δ subsidies (truthful bidding - PAB) (€-cent per kW of capacity installed)			
	All rounds	Period 1	Period 2
Mean	-93.27	-125.71	-56.2
S.E.	53.93	57.57	49.77
25th perc.	-122.1	-144.19	-96.86
Median	-85.02	-118.3	-46.98
75th perc.	-54.25	-95.87	-6.69

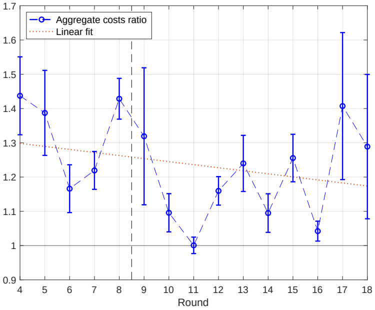
Δ subsidies (heterogeneous markups - PAB) (€-cent per kW of capacity installed)			
	All rounds	Period 1	Period 2
Mean	-73.89	-105.87	-37.35
S.E.	51.86	63.17	49.43
25th perc.	-102.72	-124.34	-78.02
Median	-65.64	-98.45	-28.13
75th perc.	-34.87	-76.02	12.15

- These values **translate to an approximate benefit of 200k €per auction round in period 1** of switching to uniform pricing in the truthful bidding case.

Cost efficiency of auction

Aggregate incremental costs in pay-as-bid relative to truthful bidding

- Does PAB pick up low cost-firms over time?
- Compare total costs under PAB vs total costs under Truthful bidding



- For each round, the dots indicate the mean of the ratio of aggregate costs under PAB and aggregate costs under Truthful bidding
- Bars represent ± 1 S.D. using 200 bootstrapping samples averaged over the scenarios for forecast prices

Conclusion

- We develop and estimate a multi-unit auction model to empirically infer the unobservable costs of bidders in renewable energy (RE) auctions in Germany
- Our results suggest that non-discriminatory pricing rules can substantially reduce subsidy expenditures, while also highlighting a broader trend toward increased cost efficiency in RE auctions over time
- Bid prices and costs in solar auctions are strongly correlated with bidder size (heterogeneous over time)
- Our empirical insights offer guidance for the design of environmental policies aimed at fostering the adoption of RE

Thank you!

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Additional slides

Table: German solar auctions, 2015-2019

# Round	Date	Technology	Pricing rule	Volume (MW)	Ceiling price (€-cent/kWh)
1	15/04/2015	Solar	pay-as-bid	150	11.29
2	01/08/2015	Solar	uniform pricing	150	11.18
3	01/12/2015	Solar	uniform pricing	200	11.09
4	01/04/2016	Solar	pay-as-bid	125	11.09
5	01/08/2016	Solar	pay-as-bid	125	11.09
6	01/12/2016	Solar	pay-as-bid	160	11.09
7	01/02/2017	Solar	pay-as-bid	200	8.91
8	01/06/2017	Solar	pay-as-bid	200	8.91
9	01/10/2017	Solar	pay-as-bid	200	8.84
10	01/02/2018	Solar	pay-as-bid	200	8.84
11	01/04/2018	Solar / Wind	pay-as-bid	200	8.84
12	01/06/2018	Solar	pay-as-bid	182	8.84
13	01/10/2018	Solar	pay-as-bid	182	8.75
14	01/11/2018	Solar / Wind	pay-as-bid	200	8.75
15	01/02/2019	Solar	pay-as-bid	175	8.91
16	01/03/2019	Solar	pay-as-bid	500	8.91
17	01/04/2019	Solar / Wind	pay-as-bid	200	8.91
18	01/06/2019	Solar	pay-as-bid	150	7.50

Notes: List of German solar auctions: April 2015 to June 2019. Solar was single winning technology in case bids from wind were admitted in the same auction round. Annual auction volume is determined by the government's RE goals and broken down into auction rounds. The price ceiling is the maximum allowed bid price in each auction round.

Heterogeneous markups by size

	(1)	(2)	(3)
$\mathbb{1}$(large bidder)	-0.042*	-0.039*	-0.029
	(0.021)	(0.022)	(0.019)
Avg. system cost (€/kWh)			-0.150**
			(0.073)
Constant	1.058***	1.171***	2.014***
	(0.016)	(0.101)	(0.467)
N	233	233	233
Adjusted R^2	0.02	0.06	0.11
Mean DV	1.05	1.05	1.05
Land-type FE	No	Yes	Yes
State FE	No	Yes	Yes

Notes: DV: Markups. Sample limited to UP rounds 2 and 3. Standard errors clustered at the bidder level. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

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DV: Markups

	(1)	(2)	(3)	(4)
$\mathbb{1}$(large bidder)	-0.038	-0.031	0.015	
	(0.024)	(0.027)	(0.034)	
PAB P1	0.296***	0.298***	0.345***	0.275***
	(0.041)	(0.041)	(0.084)	(0.086)
PAB P2	0.379***	0.378***	0.469***	0.468***
	(0.058)	(0.058)	(0.089)	(0.143)
$\mathbb{1}$(large bidder) $\times$ PAB P1	-0.242***	-0.247***	-0.274***	-0.205
	(0.078)	(0.077)	(0.075)	(0.127)
$\mathbb{1}$(large bidder) $\times$ PAB P2	-0.271***	-0.275***	-0.294***	-0.326**
	(0.073)	(0.071)	(0.066)	(0.132)
N	1,424	1,424	1,424	1,424
Adjusted R^2	0.12	0.12	0.14	0.38
Mean DV	1.27	1.27	1.27	1.27
Land FE	No	No	Yes	Yes
State FE	No	No	Yes	Yes
Year FE	No	No	Yes	Yes
Bidder FE	No	No	No	Yes

Notes: DV: Markups defined as $b_{i,k}/c_{i,k}$. All regressions include a constant term and control for auction volume. Bid-specific controls include distance to network and solar irradiation. Standard errors clustered at the bidder level. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Probability of winning the auction

	(1)	(2)	(3)	(4)	(5)
$\mathbb{1}$(large bidder)	0.064	0.075	0.075		
	(0.070)	(0.069)	(0.068)		
$\mathbb{1}$(PAB P1)	-0.019	-0.193***	-0.140	-0.196	-1.501***
	(0.056)	(0.067)	(0.104)	(0.131)	(0.323)
$\mathbb{1}$(PAB P2)	-0.030	-0.273***	-0.365***	-0.443***	-1.462***
	(0.052)	(0.060)	(0.065)	(0.088)	(0.291)
$\mathbb{1}$(large bidder) × $\mathbb{1}$(PAB P1)	0.262**	0.312***	0.306***	0.331**	0.208*
	(0.106)	(0.114)	(0.115)	(0.129)	(0.118)
$\mathbb{1}$(large bidder) × $\mathbb{1}$(PAB P2)	0.168**	0.199***	0.144**	0.242***	0.173**
	(0.074)	(0.064)	(0.064)	(0.085)	(0.079)
Estimated cost		-0.069***	-0.067***	-0.066***	-0.196***
		(0.013)	(0.011)	(0.014)	(0.035)
Estimated cost × $\mathbb{1}$(PAB P1)					0.188***
					(0.042)
Estimated cost × $\mathbb{1}$(PAB P2)					0.132***
					(0.036)
N	1,441	1,424	1,424	1,424	1,424
Adjusted R^2	0.13	0.17	0.21	0.29	0.30
Mean DV	0.40	0.39	0.39	0.39	0.39
Bid-specific controls	No	Yes	Yes	Yes	Yes
Land FE	No	No	Yes	Yes	Yes
State FE	No	No	Yes	Yes	Yes
Year FE	No	No	Yes	Yes	Yes
Bidder FE	No	No	No	Yes	Yes

Notes: DV: bid awarded (binary). Linear probability model. All regressions include a constant term and control for auction volume. Bid-specific controls include distance to network and solar irradiation. Standard errors clustered at the bidder level. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Bid prices and cost pass-through

	(1)	(2)	(3)	(4)
𝟙(large bidder)	1.426	1.374	0.154	
	(1.714)	(1.728)	(2.004)	
𝟙(PAB P1)	3.482***	3.556***	4.944***	3.719***
	(0.954)	(0.969)	(0.780)	(1.088)
𝟙(PAB P2)	1.675*	1.761*	3.335***	1.889
	(0.932)	(0.951)	(0.807)	(1.159)
𝟙(large bidder) × 𝟙(PAB P1)	-0.571	-0.470	0.833	-2.204
	(2.937)	(2.879)	(2.797)	(2.652)
𝟙(large bidder) × 𝟙(PAB P2)	-3.703**	-3.705**	-2.021	-3.204
	(1.753)	(1.748)	(2.070)	(3.179)
Estimated cost	0.715***	0.720***	0.800***	0.671***
	(0.110)	(0.112)	(0.091)	(0.139)
𝟙(large bidder) × cost	-0.189	-0.188	-0.043	-0.208
	(0.210)	(0.211)	(0.240)	(0.373)
𝟙(PAB P1) × cost	-0.555***	-0.568***	-0.734***	-0.609***
	(0.116)	(0.118)	(0.099)	(0.136)
𝟙(PAB P2) × cost	-0.353***	-0.366***	-0.534***	-0.348**
	(0.124)	(0.126)	(0.106)	(0.151)
𝟙(large bidder) × 𝟙(PAB P1) × cost	-0.004	-0.017	-0.160	0.277
	(0.399)	(0.390)	(0.369)	(0.316)
𝟙(large bidder) × 𝟙(PAB P2) × cost	0.536**	0.538**	0.319	0.434
	(0.225)	(0.224)	(0.274)	(0.410)
N	1,424	1,424	1,424	1,424
Adjusted R^2	0.74	0.74	0.81	0.86
Mean DV	6.57	6.57	6.57	6.57
Bid-specific controls	No	Yes	Yes	Yes
Land FE	No	No	Yes	Yes
State FE	No	No	Yes	Yes
Year FE	No	No	Yes	Yes
Bidder FE	No	No	No	Yes

Notes: DV: Bid values. All regressions include a constant term and control for auction volume. Bid-specific controls include distance to network and solar irradiation. Standard errors clustered at the bidder level. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

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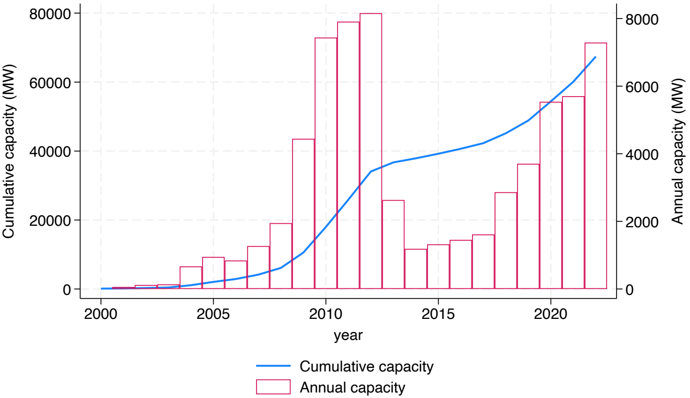
Evolution of the Germany Solar Market

Figure: Evolution of the Germany Solar Market



Source: Federal Ministry of Economics and Climate Action, Working Group Renewable Energy Statistic (AGEE-Stat)

RE Auctions - Further details

- Federal Network Agency: auctioning schedule and total auction volume
- 24 months for realization of projects
- Technology specific (mostly) or with technology specific price-ceiling
- Location specific bids
- Submit bids (price, quantity) with *project plan* and *initial security*: 5 €/kW; total security of 50 €/kW in case of succesful bid
- Special rules for agricultural land (since June 2017); yet only binding in Bavaria

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Summary Statistics - Auction Data (pay-as-bid, 4/2016-6/2019)

	UP	PAB		All
		Period 1	Period 2	
Bid-specific variables:				
Bid value (€-2019 c/kWh)	8.78	7.47	5.84	7.11
	(1.23)	(1.02)	(1.11)	(1.84)
Bid volume (MW)	4.48	5.25	6.27	5.57
	(2.99)	(3.25)	(7.44)	(5.76)
System cost (€-2019 c/kWh)	6.33	5.79	4.89	5.48
	(0.28)	(0.34)	(0.33)	(0.70)
Module cost (€-2019 c/kWh)	3.29	2.78	1.73	2.38
	(0.13)	(0.23)	(0.21)	(0.71)
Solar irradiation (kWh/m^2)	1095.30	1093.49	1099.26	1097.32
	(42.30)	(39.85)	(46.42)	(44.21)
Distance to network (km)	20.29	21.47	19.84	20.28
	(11.95)	(11.37)	(10.96)	(11.31)
Auction-specific variables:				
Share of eligible bids	0.89	0.88	0.92	0.90
	(0.01)	(0.04)	(0.06)	(0.06)
# bids per round	117.50	84.00	78.60	87.39
	(4.95)	(23.63)	(31.75)	(30.64)
# bidders per round	63.50	37.40	33.40	39.56
	(2.12)	(8.68)	(13.75)	(15.63)
# bidders awarded per round	21.50	12.60	17.10	16.17
	(6.36)	(1.52)	(13.61)	(10.43)
Observations	235	420	786	1,573
Number of auctions	2	5	10	18

Notes: Period 1: rounds 4 to 8, period 2: rounds 9 to 12, and period 3: rounds 13 to 18.

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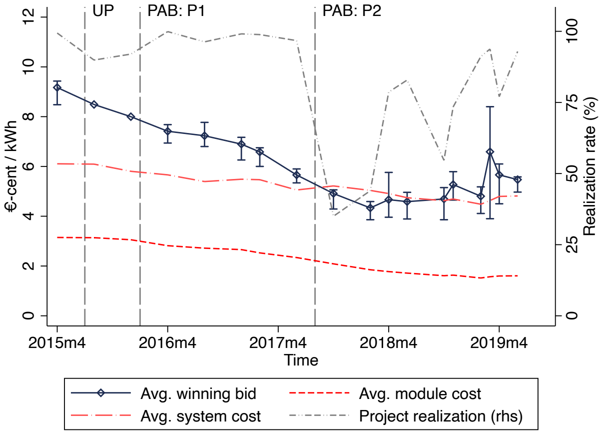
German solar auctions: Jan 2015- June 2019

Figure: Price ceiling, auction volume, and winning bids



- Define three periods in line with aggregate price trend

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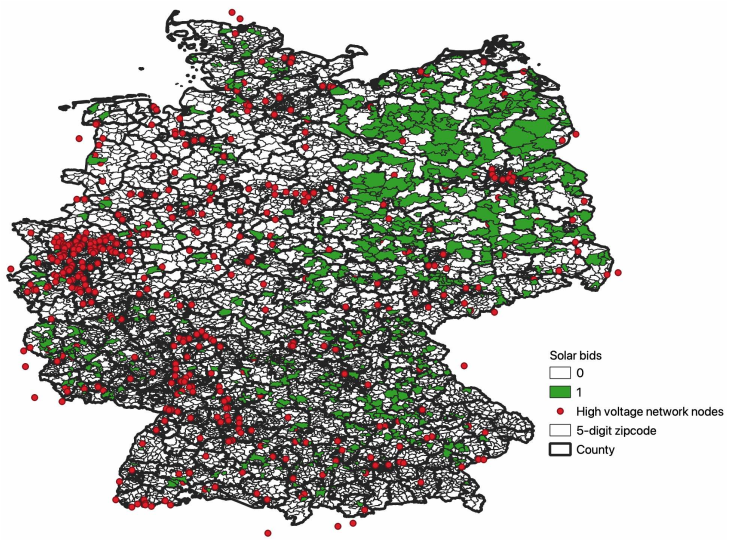
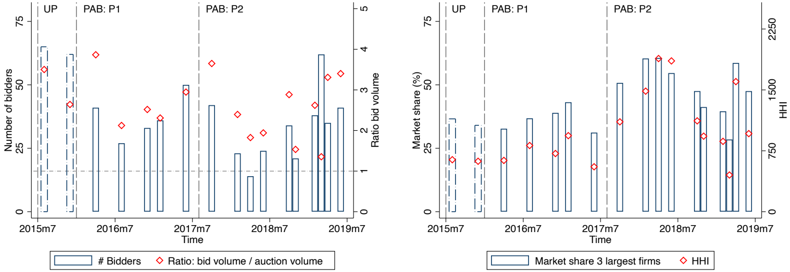
Location of solar plants and high-voltage network



Evolution of competition in solar auctions



- **Left:** # bidders per round and ratio of bid volume to auction volume
- **Right:** Market share of three largest firms (C3) and HHI
- Three auctions implemented as joint solar and wind auctions (orange). Solar as single winning technology.

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Expected payoff and strategy without future payoffs, PAB

- Firm i maximizes expected value of

$$\Pi_i(s_i) = \int_0^{Q_i(\boldsymbol{y}^{-1}(\cdot;\boldsymbol{s}))} \sum_{k=1}^{K_i} (b_{i,k} - c_i(q_{i,k}; s_i))\mathbb{1}(q_{i,k} \leq q_i < q_{i,k+1})dq_i,$$

where $Q_i(\boldsymbol{y}^{-1}(\cdot;\boldsymbol{s}))$ is the quantity firm i gets awarded when all firms' supply schedules are the vector $\boldsymbol{y}(p;\boldsymbol{s})$

- Set of all supply schedules in $\boldsymbol{y}(\boldsymbol{p};\boldsymbol{s})$ is a Bayesian Nash equilibrium if each firm i maximizes expected value of Π_i

Recovering Costs, PAB

- Perturbation argument (Kastl 2011, 2012: residual supply, this paper: residual demand) gives

$$\Pr(b_{i,k} < p_c < b_{i,k+1})[b_{i,k} - c_i(q_{i,k}; s_i)] = \Pr(b_{i,k+1} \leq p_c)(b_{i,k+1} - b_{i,k}),$$

which gives following expression:

$$c_i(q_{i,k}; s_i) = b_{i,k} - \frac{\Pr(b_{i,k+1} \leq p_c)}{\Pr(b_{i,k} < p_c < b_{i,k+1})}(b_{i,k+1} - b_{i,k})$$

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Expected payoff and strategy without future payoffs, uniform

- Firm i maximizes expected value of

$$E\Pi_i(s_i) = \int_0^{Q_i(\boldsymbol{y}^{-1}(\cdot;\boldsymbol{s}))} \sum_{k=1}^{K_i} (p_c(\boldsymbol{y}(\cdot;\boldsymbol{s})) - c_i(q_{i,k};s_i)) \mathbb{1}(q_{i,k} \leq q_i < q_{i,k+1}) dq_i,$$

where $p_c(\boldsymbol{y}(\cdot;\boldsymbol{s}))$ is the market clearing price.

Recovering Costs, uniform

- Perturbation argument (Kastl 2011, 2012: residual supply, this paper: residual demand) gives

$$\underbrace{\Pr(b_{i,k} < p_c < b_{i,k+1})}_{\equiv M_1}[E(p_c|b_{i,k} < p_c < b_{i,k+1}) - c_{i,k}] = \underbrace{-\, q_{i,k} \frac{\partial E(p_c \mathbb{1}(b_{i,k} \le p_c \le b_{i,k+1}))}{\partial q_{i,k}}}_{\equiv M_2}$$

Solving for the costs gives

$$c_{i,k} = E(p_c|b_{i,k} < p_c < b_{i,k+1}) + \frac{M_2}{M_1},$$

which has the usual interpretation of a uniform price setting where the cost is the price minus a markup since $\frac{M_2}{M_1} < 0$ and therefore, costs are lower than p_c.

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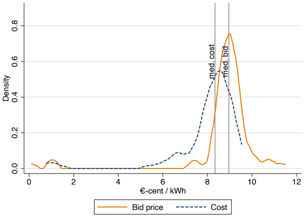
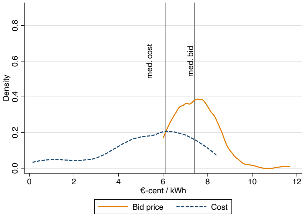
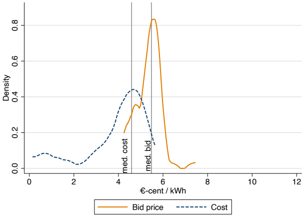
Estimated costs and observed bids densities: no future payoffs



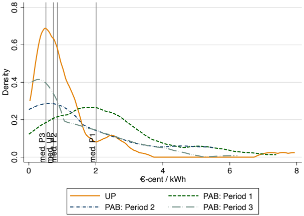
(a) UP: Auction rounds 2-3



(b) PAB, Period 1: Auction rounds 4-8



(c) PAB, Period 2: Auction rounds 9-18



(d) Lerner Index, all three periods

Expected payoff and strategy, uniform auction

- The structure of the UP case is the same as for PAB except that the expression for π_i:

$$\pi_i = \sum_{k=1}^{K_i} \left[\sum_{t=13}^{T=252} \underbrace{\delta^t \left[\mathbb{1}(b_{i,k} > cp_t)(p_c(\boldsymbol{y}(\cdot; \boldsymbol{s})) - c_{i,k}) + \mathbb{1}(b_{i,k} \leq cp_t)(cp_t - c_{i,k}) \right]}_{\text{Discounted future profits}} \right]$$

$$\times \mathbb{1}(q_{i,k} \leq q_i < q_{i,k+1})$$

- where K_i is the number of bid steps and the contribution from a single step k is:

$$\pi_{i,k} \equiv \sum_{t|b_{i,k} > cp_t} \delta^t (p_c - c_{i,k}) + \sum_{t|b_{i,k} \leq cp_t} \delta^t (cp_t - c_{i,k})$$

Recovering costs, uniform auction

- Perturbation argument becomes

$$\underbrace{\Pr(b_{i,k} < p_c < b_{i,k+1})}_{\equiv M_1} \pi_{i,k} = \underbrace{-\,q_{i,k} L_1(cp_t, p_c) \frac{\partial E(p_c \mathbb{1}(b_{i,k} \leq p_c \leq b_{i,k+1}))}{\partial q_{i,k}}}_{\equiv M_2}.$$

- After solving for $c_{i,k}$ and recalling that M_2 contains the function L_1:

$$c_{i,k} = \frac{1}{L_2} \left[L_1(cp_t, p_c) E(p_c | b_{i,k} < p_c < b_{i,k+1}) + L_3(cp_t, p_c) + \frac{M_2}{M_1} \right].$$

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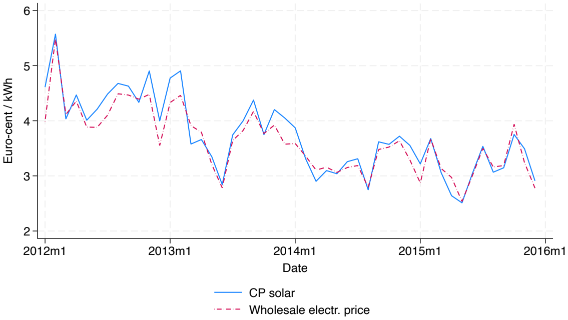
Data and prediction of capture prices

- For each auction round τ, the investor has information on past capture prices and wholesale electricity market prices
  - Average capture prices in four year-period leading up to the auction
  - Monthly variation in capture prices equal to the observed variation over the previous four years
- We employ long-term price and volatility forecasts from **government documents** and **policy reports** that are publicly available (Federal Ministry of Economics, State-level information)
- Main driving forces of price level and volatility:
  - Increased electricity demand (electrification)
  - Decreased electricity supply (nuclear and coal phase out)
  - Increased RE capacity (according to RE targets set by the government)

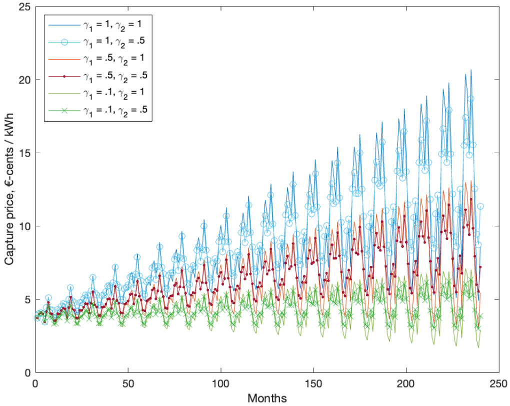
Monthly capture price and wholesale electricity price in Germany, 2012-2015



Source: Monthly capture prices for solar PV and wholesale electricity prices available from `https://www.netztransparenz.de/`

- **Level:** Take nominal predictions and interpolate linearly between years
- **Volatility:** Take predicted volatility in 2035 as endpoint and interpolate linearly (monthly) with respect to baseline volatility measures
- Account for uncertainty by simulating a total of 9 scenarios, multiplying the baseline growth rate and volatility by the factors 0.9,1,1.1

Simulation of capture price paths for 240 months (20 years), auction round 4: April 2016



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