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

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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)

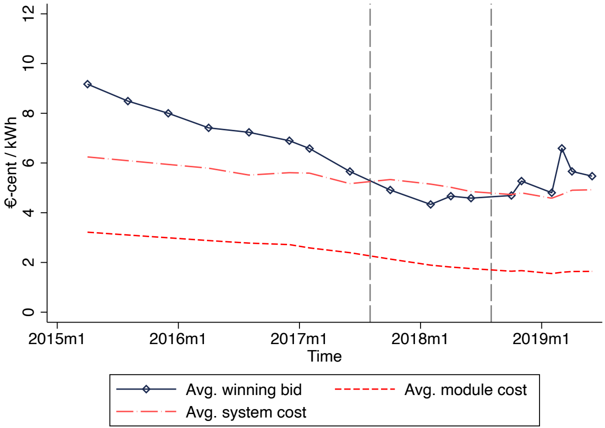
- Yet, determinants of the market participants' bidding behavior has not been widely studied
  - Importance for total deployment cost of technologies and for successful auction implementation

Research questions

- Study the role of cost and market factors in observed price developments in RE auctions
- How does the auction design impact market outcomes?
  - Uniform vs. discriminatory (pay-as-bid) auctions and subsidy payments

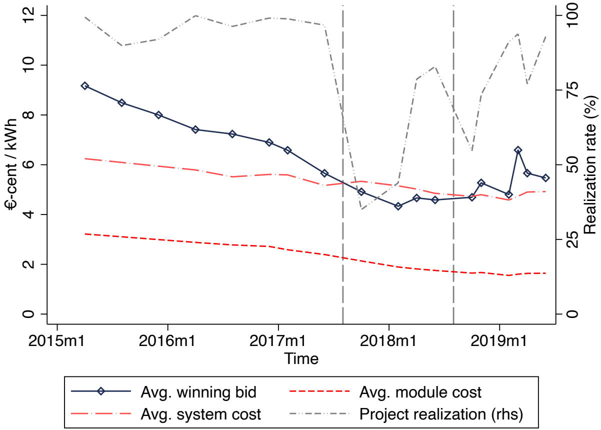
Solar auctions in Germany: Jan 2015 - June 2019

Figure: Avg. winning bids and avg. industry costs



Solar auctions in Germany: Jan 2015 - June 2019

Figure: Avg. winning bids, avg. ind. costs, and project realization rates



- Define three main periods in line with aggregate price evolution

This paper

- Uses unique bid-level data for German RE auctions (2015-2019) - with focus on utility scale solar photovoltaic (solar) plants
- Recovers bidders' costs by estimating a structural model of multi-unit auctions
- Documents correlations of bidders' cost/market factors on bid prices and profit margins over time
- Studies counterfactual outcomes from uniform auction design: prices and subsidies, and increased govt. demand

Literature (selected)

- 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)
- 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)
- 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 (2022); 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 (except two rounds w/ uniform pricing)
- 20 years payment guarantee (one-sided 'Contract for Differences', CfD)

Additional auction details

Subsidy payments

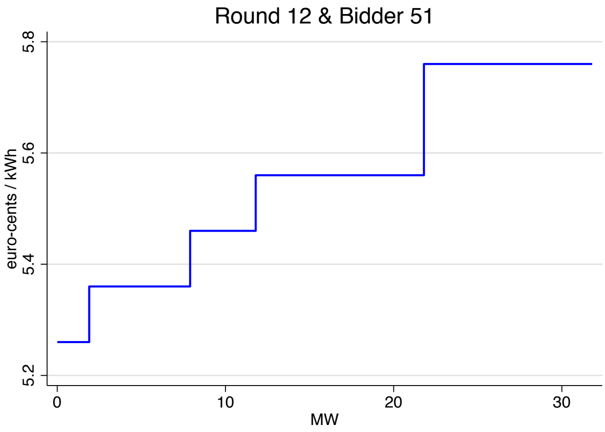
One-sided CfD

- Grid operator pays a premium for every unit of delivered electricity if electricity spot price 'too low'
- Premium: difference between individual bid and capture price cp_t (average market price) of solar at the EPEX spot market

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

- cp_t is calculated for the entire solar portfolio in Germany on a monthly basis
- This support mechanism guarantees generators receive at least their bid
- Insurance against low capture prices and attempts to eliminate long-term risk

An example of a bid curve



Number of steps

Data

RE auctions:

- All individual bids from 18 auction rounds (2015-2019), anonymized
- Focus on pay-as-bid auctions between April 2016 and June 2019 (16 rounds), 2 early rounds were uniform-price auctions
- For winning bids: information on project realization and annual production

Additional data:

- Aggregate cost development (industry data)
- Data on average solar irradiation (German Weather Service)
- Information on high-voltage electricity network

Summary statistics | Auction rounds | Location of bids and network | Evolution of competition

Model of multi-unit auctions

- Building on Hortacsu & McAdams (2010), Kastl (2011, 2012) we empirically estimate costs taking into account discreteness of bids
- There are T auction rounds, where each auction is a discriminatory auction of Q_t divisible units (gov. demand for solar capacity)
- In each round, there are N_t bidders, that are 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
- **Allow for heterogeneous groups:** bidders assumed to be symmetric conditional on belonging to group g, defined by bidder size

Expected payoffs

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

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

- and maximizes the expected value of

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

- 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 the capture price: $E[cp_t] = cp_0 \times \phi_t \times \sigma_t$
- 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
- 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 the 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

- Perturbation argument following (Kastl 2011, 2012), adapted to procurement setting

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

where the $L(\cdot)$ are functions of the discount factor also.

Recovering Costs

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where the $L(\cdot)$ are functions of the discount factor also.

- **This yields the following expression for cost:**

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

- **Goal:**
  - Estimate $c_{i,k}$ using expression above
  - b_i observed in data, p_c obtained by simulating residual demand curves

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  - Estimate $c_{i,k}$ using expression above
  - b_i observed in data, p_c obtained by simulating residual demand curves

- **Robustness:** estimate 'myopic' version in which everything depends on auction payoff $(y_i^{-1}(q; s_i) - c_{ik})$ yields comparable cost estimates.

Estimating the cost of production

Resampling of competitors bids to construct simulated residual demand curves

1. Fix bidder i from group $g \in G$ and observed supply schedule $\{b_{i,k}\}$.
2. From n_g bidders in group g, draw random subsample of $n_g - 1$ bid vectors with replacement, weight of $1/n_g$ to each bid vector from group g.
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.**

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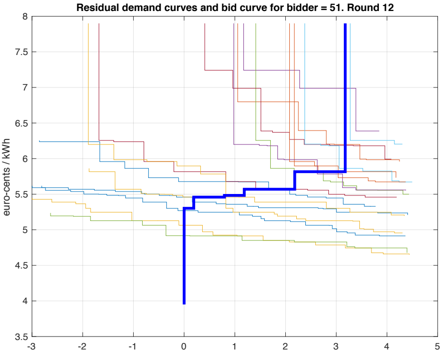
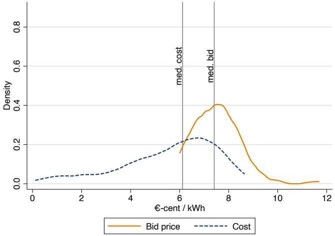
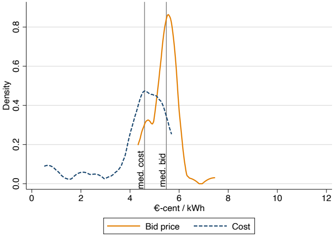


Estimated costs vs. observed bids densities

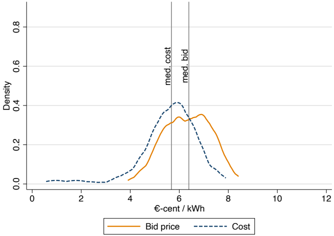
Qty-weighted avg. bids. Period 1: R4 - R8, Period 2: R9 - R12, Period 3: R13 - R18



(a) Period 1



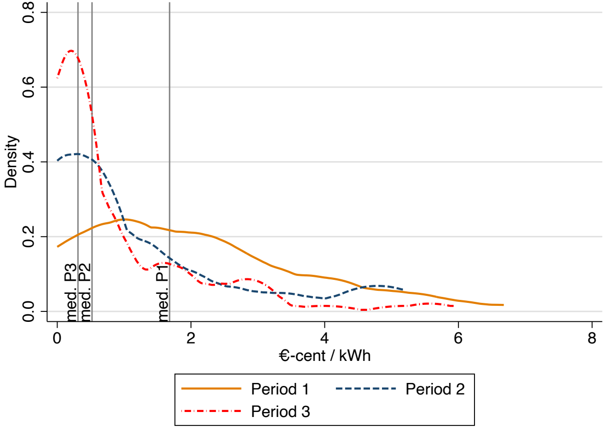
(b) Period 2



(c) Period 3

Estimated margins ($b_i - c_i$)

Qty-weighted avg. bids. Period 1: R4 - R8, Period 2: R9 - R12, Period 3: R13 - R18



Correlation between MCs, bids, and market factors

Set of linear regressions:

- Accounting for land type, state, year (and bidder) FEs
- DV: estimated cost, bid values, prob. of winning

Main findings:

- Bidding values correlate with estimated costs, bidder size, and distance to network
- Evidence of heterogeneous cost pass-through by **bidder size** and over **time**

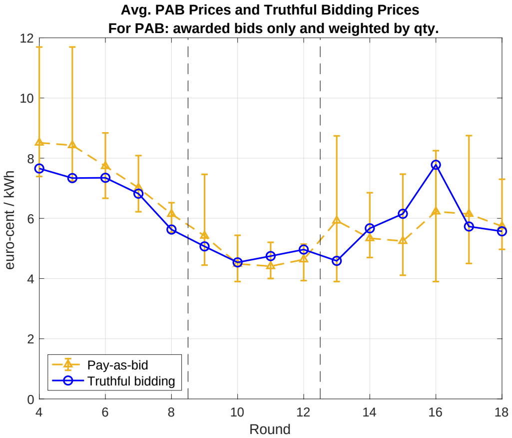
Counterfactual 1: pay-as-bid (PAB) vs. uniform price auction

- Assume bidders bid truthfully ($b = c$) as an approximation to uniform auction
- For each round, pool all estimated costs in increasing order: perfectly competitive supply curve
- Find intersection with volume demanded by regulator $\Rightarrow$ single market clearing price
- All bidders with inframarginal costs receive market clearing price
- No theoretical ranking between PAB vs. uniform price

PAB and truthful bidding

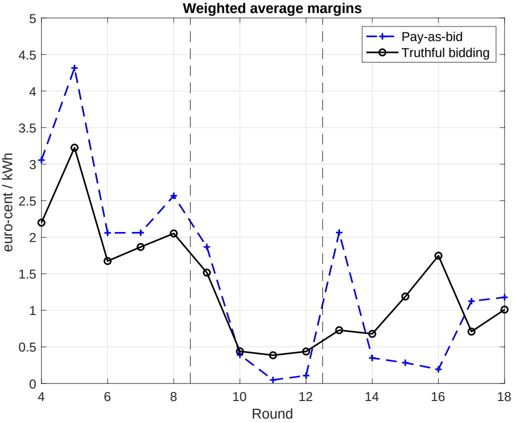
P1: Rounds 4 - 8, P2: Rounds 9 - 12, P3: Rounds 13 - 18

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



Margins under different auction formats

Qty-weighted avg. bids. P1: Rounds 4 - 8, P2: Rounds 9 - 12, P3: Rounds 13 - 18



Notes: Truthful bidding is a counterfactual where each firm submits bids that are equal to their estimated MC. Pay-as-bid refers to the observed bids.

Subsidies under different auction formats

- Uniform price subsidy

$$S_U = \sum_i q_i \max\{p^* - cp, 0\}$$

- Pay-as-bid subsidy

$$S_{PAB} = \sum_i q_i \max\{b_i - cp, 0\}$$

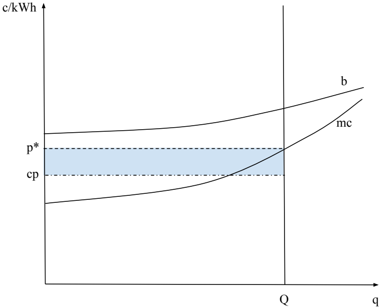
over all the quantities up to Q (government's demand), where:

  - p^*: market clearing price assuming uniform pricing (intersection of cost curve and Q)
  - cp: capture price

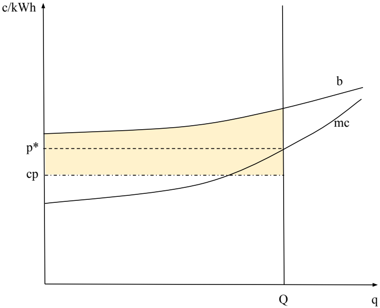
- Both $S_U < S_{PAB}$ and $S_U > S_{PAB}$ are possible

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

Uniform pricing

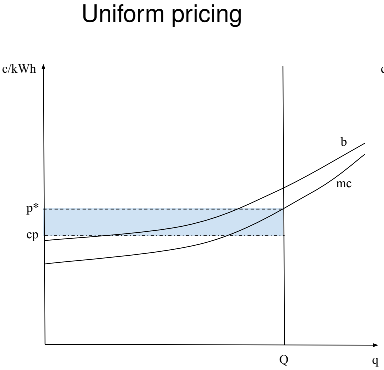


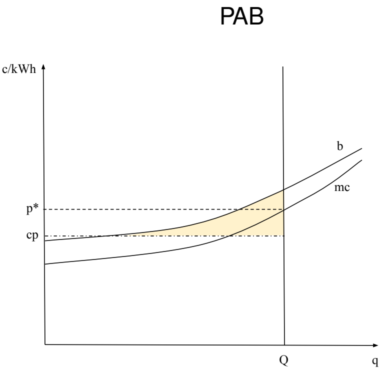
PAB



Auction formats

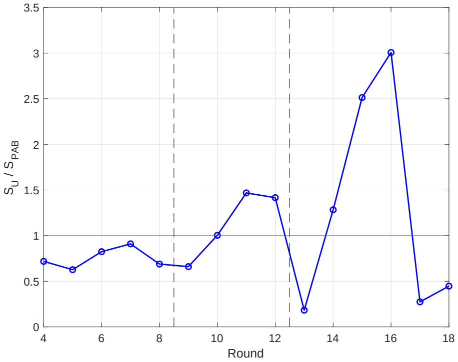
Subsidy under pay-as-bid can be lower than under uniform pricing





Aggregate bid curve *b* much closer to MC curve

Subsidies under pay-as-bid and truthful bidding



- Ratio of subsidy per kWh 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

Conclusion

- Bid prices and costs in German solar auctions are strongly correlated with bidder size (heterogeneous over time) and solar radiation
- Adopting a non-discriminatory auction results in lower subsidy expenses and market power especially in early rounds
- Our empirical insights offer guidance for the design of environmental policies aimed at fostering the adoption of RE

Thank you!

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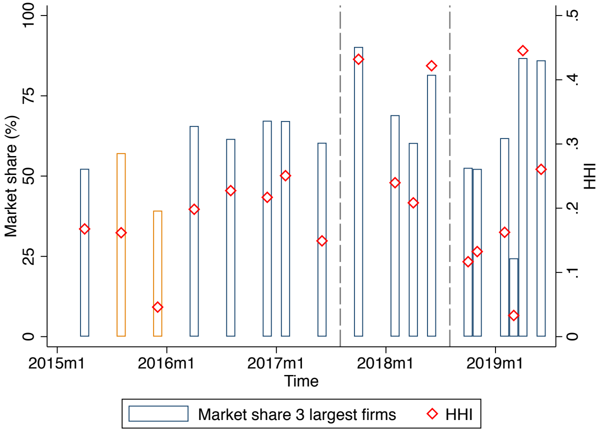
Additional slides

Degree of competitiveness, 4/2016-6/2019

Figure: Market share and HHI, awarded bids



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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
- Last succesful bid is fully awarded: no rationing
- 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)

	All		Period 1		Period 2		Period 3	
	mean	sd	mean	sd	mean	sd	mean	sd
Bid value (€-2019 c/kWh)	6.41	(1.33)	7.47	(1.02)	5.14	(0.55)	6.19	(1.15)
Bid volume (MW)	5.92	(6.32)	5.25	(3.25)	6.95	(7.23)	5.94	(7.52)
System cost (€-2019 c/kWh)	5.2	(0.54)	5.79	(0.34)	5.23	(0.29)	4.72	(0.20)
Solar irradiation (kWh/m^2)	1097.25	(44.31)	1093.49	(39.85)	1101.99	(45.47)	1097.92	(46.86)
Distance to network (km)	20.41	(11.13)	21.47	(11.37)	19.41	(10.49)	20.06	(11.19)
Land types (share):								
- Agriculture or grassland	0.26	(0.44)	0.17	(0.38)	0.38	(0.49)	0.28	(0.45)
- Non-conventional buildings	0.13	(0.34)	0.1	(0.29)	0.15	(0.36)	0.15	(0.36)
- Government land	0.09	(0.28)	0.06	(0.24)	0.06	(0.23)	0.12	(0.33)
- Adjacent to railway or road	0.27	(0.45)	0.28	(0.45)	0.21	(0.41)	0.3	(0.46)
- Site with previous usage	0.24	(0.43)	0.39	(0.49)	0.2	(0.40)	0.15	(0.35)
1(large bidder, project size)	0.22	(0.41)	0.17	(0.38)	0.39	(0.49)	0.17	(0.38)
Share of eligible bids	0.91	(0.00)	0.88	(0.00)	0.92	(0.01)	0.92)	(0.00)
# bids per round	80.4	(28.54)	84	(23.63)	64.75	(28.27)	87.83	(32.85)
# bidders per round	34.73	(12.12)	37.4	(8.68)	25.75	(11.73)	38.5	(13.40)
# bidders awarded per round	15.6	(11.16)	12.6	(1.52)	11.75	(2.22)	20.67	(17.10)
HHI	1061.39	(452.30)	730.82	(150.81)	1583.71	(366.76)	988.64	(374.20)
C1, bid volume per round (%)	24.03	(8.11)	19.33	(3.60)	32.26	(7.77)	22.47	(7.65)
C3, bid volume per round (%)	44.81	(10.59)	36.56	(4.82)	56.6	(4.77)	43.83	(10.07)
C5, bid volume per round (%)	56.79	(11.23)	47.93	(5.81)	68.57	(6.58)	56.33	(10.52)
Observations	1206		420		259		527	
Number of auction rounds	15		5		4		6	

Notes: Period 1 covers auction rounds 4 to 8, period 2 includes rounds 9 to 12, and period 3 includes rounds 13 to 18. Periods defined according to aggregate price trend. Rounds prior to 2016 omitted.

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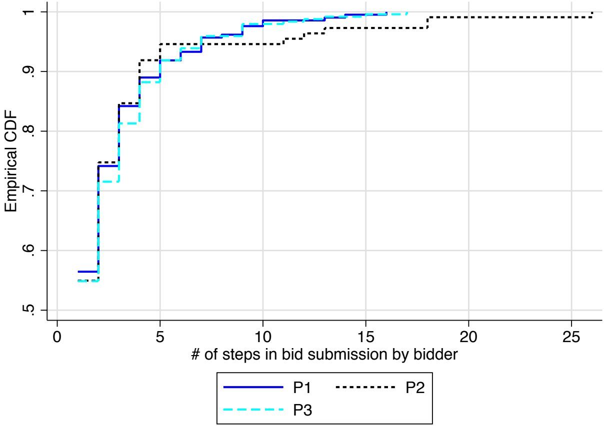
Number of “steps” in submitted bid curves



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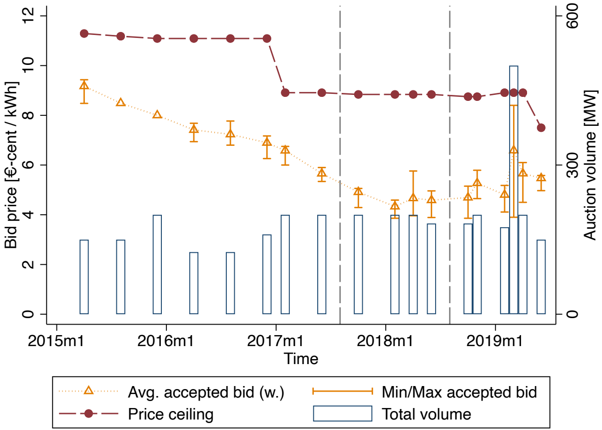
German solar auctions: Jan 2015- June 2019

Figure: Price ceiling, auction volume, and winning bids



- Define three periods in line with aggregate price trend

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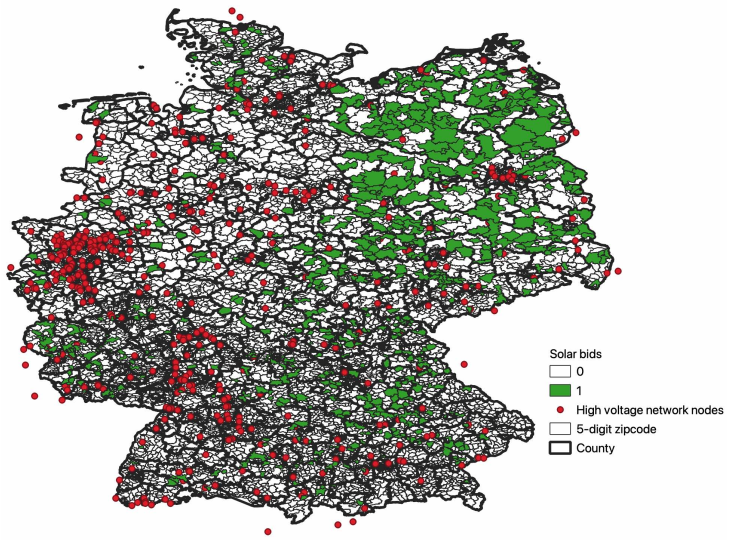
Location of solar plants and high-voltage network



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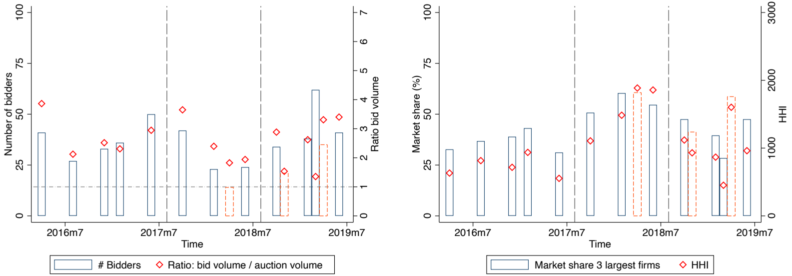
Evolution of competition in solar auctions



- **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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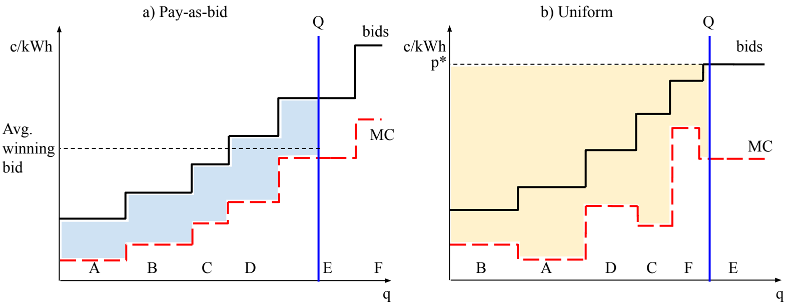
Multi-unit Auctions and Pricing Rules

- Bidders’ strategies can be different under different auction formats
- No theoretical ranking for revenue



Subsidies

Distribution of payoffs (market-premiums)

Figure: Distribution of market premiums

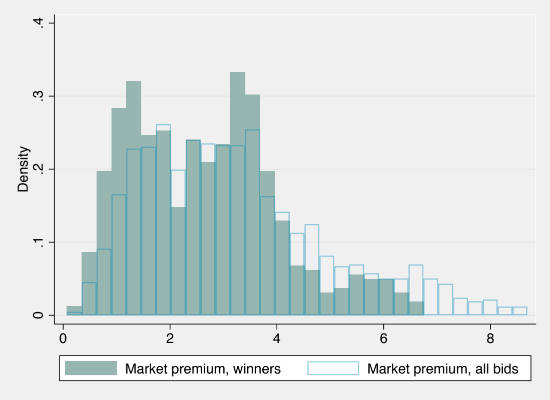


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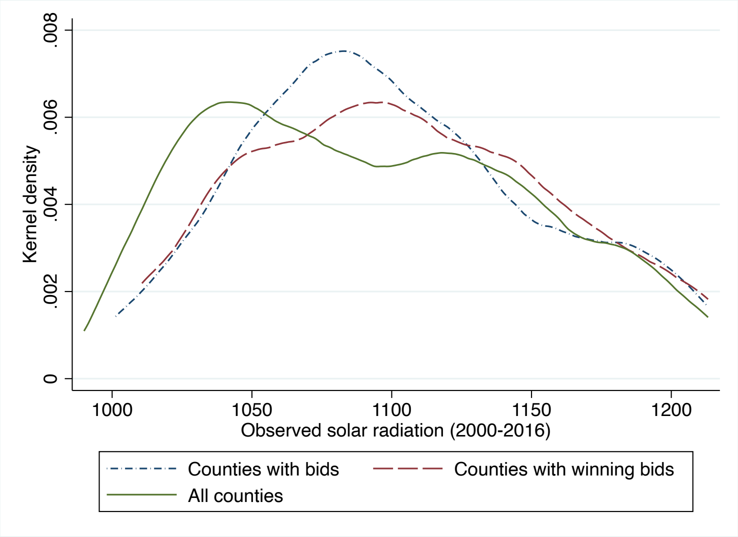
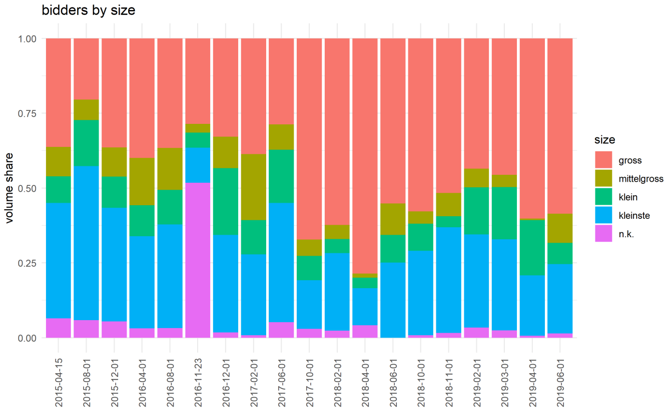
Figure: Selection of investment sites: solar radiation



Bidder composition: size



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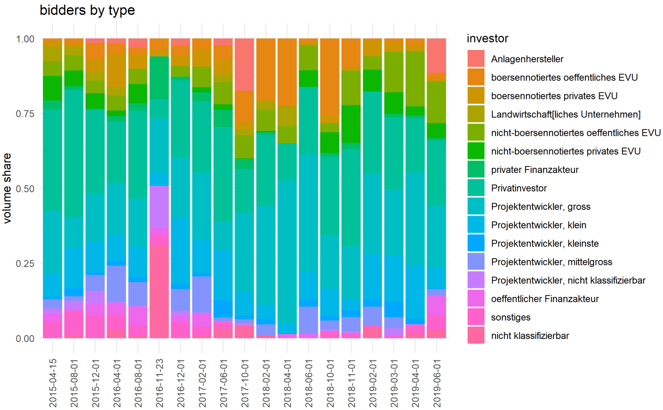
Bidder composition: type



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