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

Stefan Lamp
TSE

Mario Samano
HEC Montreal

Silvana Tiedemann
Hertie

Introduction

- Climate change mitigation policies envision large investment in **R**enewable **E**nergy (**RE**) Technologies
  - 350 billion USD in 2020 (IEA), solar responsible for 45% between 2013 and 2018 (IRENA and CPI)
  - Ambitious RE targest for Europe: 22% in 2020 → 42.5% in 2030 (REPowerEU)

Introduction

- Climate change mitigation policies envision large investment in **R**enewable **E**nergy (**RE**) Technologies
  - 350 billion USD in 2020 (IEA), solar responsible for 45% between 2013 and 2018 (IRENA and CPI)
  - Ambitious RE targest for Europe: 22% in 2020 $\rightarrow$ 42.5% in 2030 (REPowerEU)
- Important adjustment in policy instruments: 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 question

- Study the role of **auction design** and that of **cost and market factors** in observed price developments in RE auctions
  - What explains **observed price evolution**?
  - **How does the auction design impact market outcomes**? Uniform vs. pay-as-bid and subsidies

This paper

- Uses **unique bid-level data** for German RE auctions (2015-2019) - with focus on utility scale solar PV
- Recovers **bidders' marginal 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
- Estimates **counterfactual outcomes** from uniform auction design, subsidies, and increase govt. demand

Contributions

- Study RE auctions in **industrial country with experience in solar PV** and **without default risk** by the government
- Contribute to **policy discussion on effective auction design**: ranking pay-as-bid vs. uniform auction is empirical question
- Use **rich micro-data on individual bids** to document bidding behavior in new market

Literature (selected)

- **Energy and Renewable Auctions:**
  Fabra and Montero (2020); Hortacsu, Luco, Puller and Zhu (2019); Hortacsu and Puller (2008); Reguant (2014); Ryan (2021); Wolak (2003, 2007)
- **Empirical Analysis of Multi-Unit Auctions:**
  Methods: Hortacsu and McAdams (2010, 2018); Kastl (2011, 2012); Wolak (2007); Reguant (2014)
  Application: Elsinger, Schmidt-Dengler and Zulehner (2019)

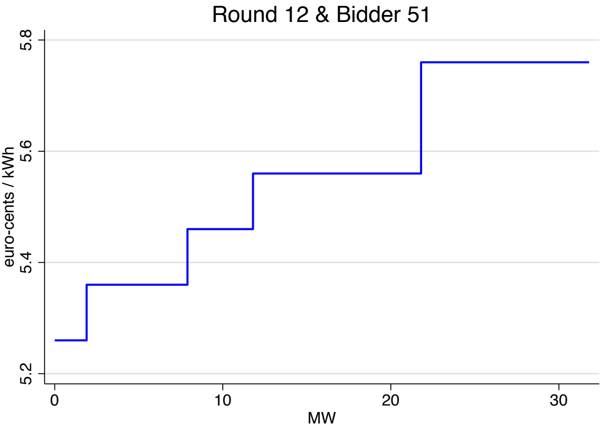
1. Background and Data
2. Recovering Valuations
3. Analyzing Bidding Behavior
4. Auction Format and Subsidies

RE Auctions - Germany

- Introduced in 2015 for ‘large’ solar PV, wind, and biomass installations
  - Focus on utility-scale solar PV ($>$ 750 kW and $\leq$ 20 MW)
- **Multi-unit auctions**: total volume set by government, bidders are allowed to submit multiple quantity-price pairs
- **Pay-as-bid** (except two rounds w/ uniform pricing)
- 20 years payment guarantee (sliding feed-in premium, FIP))

Additional auction details

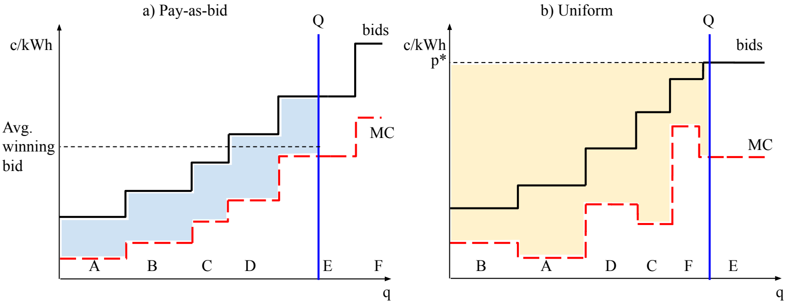
An example of a bid curve



Number of steps

Multi-unit Auctions and Auction Formats

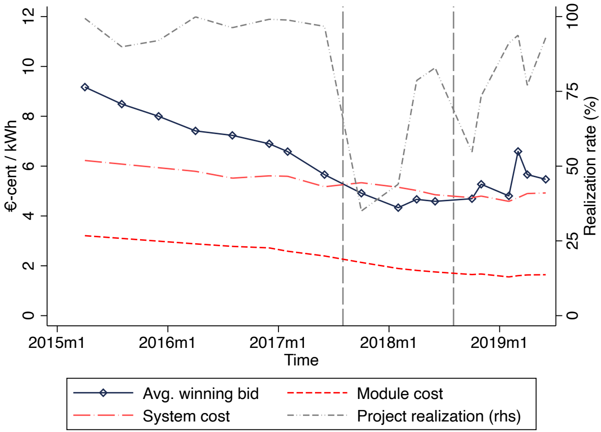
- Strategies can be different under different auction formats
- No theoretical ranking for revenue



Subsidies

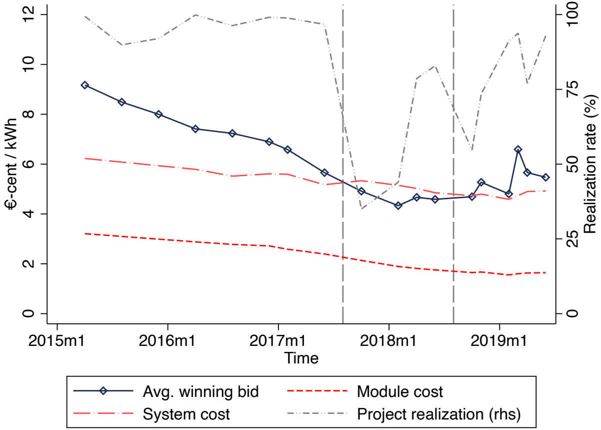
Solar PV auctions in Germany: 2015-2020

Figure: Winning bids, costs, realization rates



Solar PV auctions in Germany: 2015-2020

Figure: Winning bids, costs, realization rates

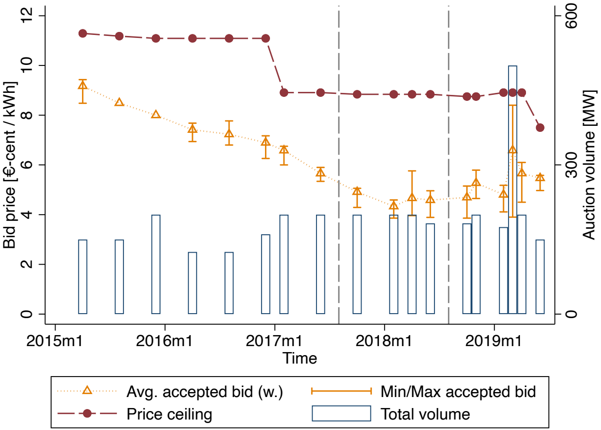


- **Define three periods** in line with decline of avg. winning bids and change in regulation (EEG 2017)

Estimated margins

Solar PV auctions in Germany: 2015-2020

Figure: Price ceiling, volume, winning bids



Subsidy payments

Sliding feed-in premium

- 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

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

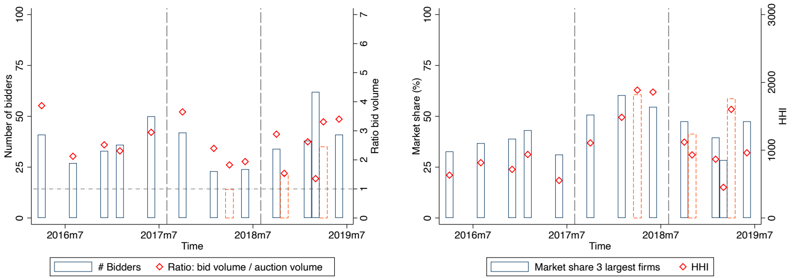
- cp_t is calculated for the entire solar portfolio in Germany on a monthly basis
- This **support mechanism guarantees generators receive at least their bid**
- Insurance against low capture prices and attempts to eliminate long-term risk

Data

- **Auction data:**
  - Anonymized bidding data from 18 auction rounds (2015-2019)
  - Focus on pay-as-bid auctions between April 2016 and June 2019 (16 rounds), 2 early rounds were uniform-price auctions
  - Information on project realization
  - Aggregate outcomes from auctions *as available to all market participants* (Federal Network Agency)
- **Additional data:**
  - Aggregate cost development (industry data)
  - Data on average solar radiation (German Weather Service)
  - Information on high-voltage electricity network

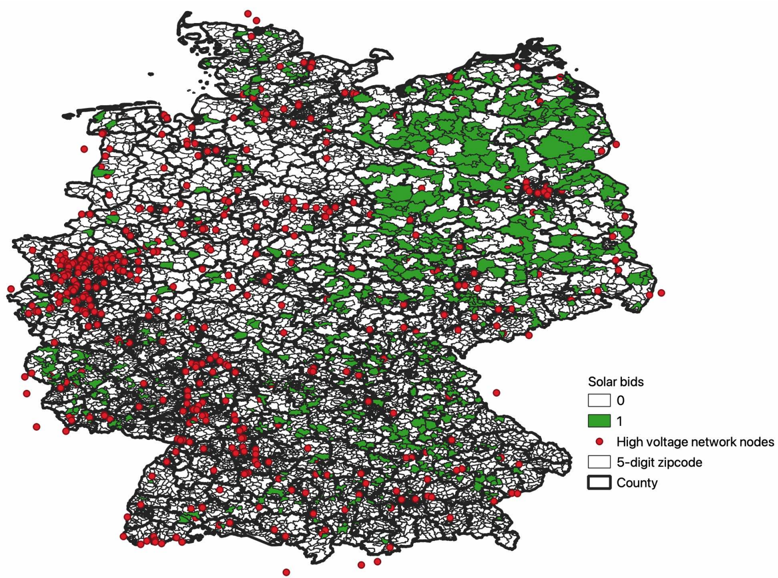
Summary statistics

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
- Blue: Solar-only rounds
- Orange: Joint solar + wind

Location of solar PV plants



Model of multi-unit auctions

- We build on Wilson's (1979) iid private value framework as implemented in Hortacsu & McAdams (2010), Kastl (2011), Reguant (2014), and Elsinger et al (2019)
- Each firm has a marginal cost $c_i(q; s_i)$
- Firm i submits a non-decreasing supply schedule

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

  and maximizes expected value of

$$\Pi_i(s_i) = \int_0^{Q_i(\boldsymbol{y}^{-1}(\cdot;\boldsymbol{s}))} [y_i^{-1}(q; s_i) - c_i(q; s_i)] dq$$

  where $Q(\cdot)$ is the quantity firm i gets awarded when all firms' supply schedules are $\boldsymbol{y}(\boldsymbol{p}; \boldsymbol{s})$
- $\boldsymbol{y}(\boldsymbol{p}; \boldsymbol{s})$ is an equilibrium if each firm i maximizes expected value of Π_i

Equilibrium Price and Bids

- 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

Marginal Costs

- Perturbation argument (Kastl 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:

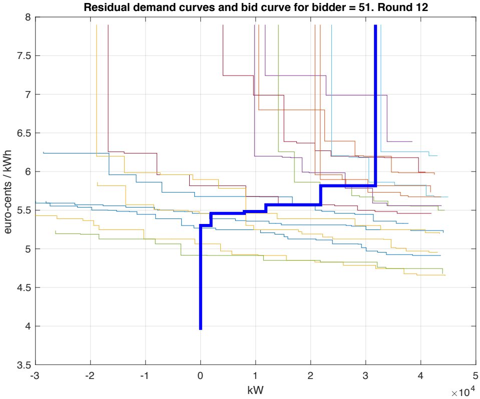
$$c_i(q_{i,k}; s_i) = b_{i,k} - \frac{\Pr(b_{i,k+1} \leq p_c)}{\Pr(b_{i,k} < p_c < b_{i,k+1})}(b_{i,k+1} - b_{i,k})$$

- Goal: to estimate $c_i(q, s_i)$ using expression above
- b_i observed in data
- p_c obtained by simulating residual demand curves

Finding the valuations

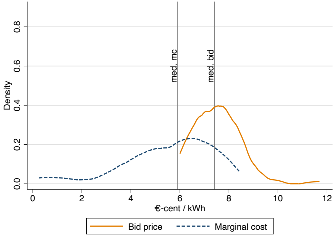
Resampling of competitors bids to construct simulated residual demand curves

1. Fix bidder i and bid function in auction t
2. Draw $N-1$ bid functions (4-dimensional Gaussian kernel) and compute residual demand (N bidders in auction t)
3. Compute the market clearing price p_C given the bid function
4. Repeat S times $\Rightarrow$ distribution of market clearing prices

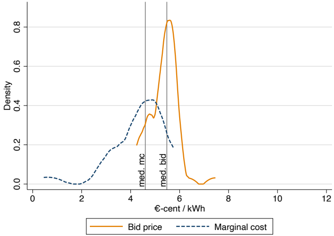


Estimated valuations vs observed bids densities

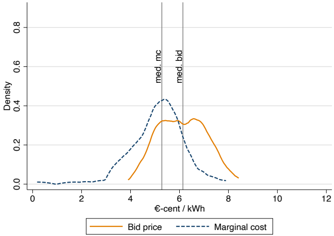
P1: Rounds 4 - 8, P2: Rounds 9 - 12, P3: Rounds 13 - 18



(a) P1



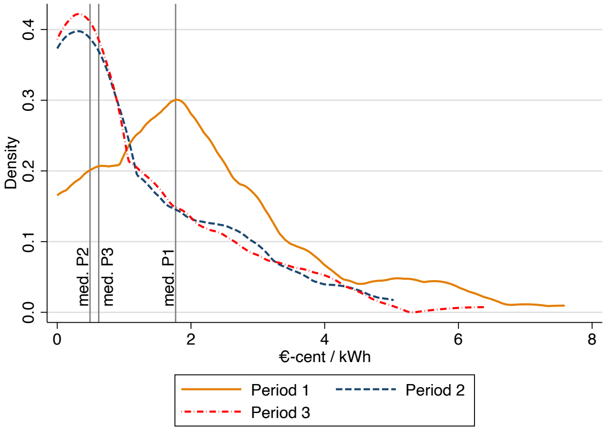
(b) P2



(c) P3

Estimated margins

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



Avg. winning bids and system costs

The correlation between MCs, bids, and mkt factors

- What observable characteristics are correlated with est. MCs?
- What factors are correlated with higher prob. of winning?
- Evidence of pass-through?
- FEs: Auction round, landtype, state (and bidder)
- All standard errors clustered at bidder level

DV: Marginal costs

	(1)	(2)	(3)	(4)
Distance to network	0.662	0.521	0.403	0.204
	(0.426)	(0.427)	(0.362)	(0.405)
System costs	8.306***	8.278***	2.423	2.390
	(1.880)	(1.855)	(2.666)	(2.880)
Auction volume $>$ 200MW	0.820***	0.865***	0.299	0.516**
	(0.191)	(0.209)	(0.228)	(0.206)
Solar irradiation		-4.589***	-5.517**	-4.371*
		(1.455)	(2.197)	(2.451)
Large bidder (size, p90)		0.110	0.267*	
		(0.141)	(0.150)	
N	1143	1143	1143	1143
r2_a	0.07	0.08	0.20	0.26
DV_mean	5.52	5.52	5.52	5.52
LandFE	No	No	Yes	Yes
StateFE	No	No	Yes	Yes
YearFE	No	No	Yes	Yes
BidderFE	No	No	No	Yes

Standard errors in parentheses
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Notes: DV: estimated marginal costs. Standard errors clustered at the bidder level.

DV: Bidding values

	(1)	(2)	(3)	(4)	(5)
Est. marg. cost	0.373***	0.152***	0.159***	0.144***	0.128***
	(0.046)	(0.024)	(0.025)	(0.024)	(0.027)
Distance to network			0.483*	0.486*	0.417
			(0.283)	(0.278)	(0.334)
Large bidder (size, p90)=1			-0.461***	-1.502***	
			(0.125)	(0.223)	
Auction volume $>$ 200MW			-0.114	-0.107	-0.083
			(0.138)	(0.140)	(0.160)
Large bidder (size, p90)=1 $\times$ Est. marg. cost				0.185***	0.236***
				(0.046)	(0.040)
N	1143	1143	1143	1143	1143
r2_a	0.25	0.66	0.67	0.68	0.76
DV_mean	6.45	6.45	6.45	6.45	6.45
LandFE	No	Yes	Yes	Yes	Yes
StateFE	No	Yes	Yes	Yes	Yes
YearFE	No	Yes	Yes	Yes	Yes
BidderFE	No	No	No	No	Yes

Standard errors in parentheses
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Notes: DV: bidding values. Standard errors clustered at the bidder level.

DV: Bid awarded (yes = 1, no = 0)

	(1)	(2)	(3)	(4)	(5)
Bid price (deflated)	-0.214***				
	(0.018)				
Est. marg. cost		0.011	0.003	0.003	0.004
		(0.012)	(0.009)	(0.009)	(0.011)
Auction volume $>$ 200MW			0.656***	0.648***	0.648***
			(0.053)	(0.051)	(0.067)
Large bidder (size, p90)=1			0.233***	0.235***	
			(0.076)	(0.077)	
Solar irradiation				-0.255	-0.397
				(0.554)	(0.495)
Distance to network				-0.082	-0.089
				(0.109)	(0.114)
System costs				-1.442	-1.875**
				(0.884)	(0.934)
N	1143	1143	1143	1143	1143
r2_a	0.16	0.04	0.19	0.19	0.26
DV_mean	0.40	0.40	0.40	0.40	0.40
LandFE	Yes	Yes	Yes	Yes	Yes
StateFE	Yes	Yes	Yes	Yes	Yes
YearFE	Yes	Yes	Yes	Yes	Yes
BidderFE	No	No	No	No	Yes

Standard errors in parentheses

DV: Bidding values

	(1)	(2)	(3)	(4)
Est. marg. cost	0.177***	0.072***	0.071**	0.046*
	(0.031)	(0.025)	(0.027)	(0.024)
Period=2	-1.707***	-0.769***	-0.771***	-1.102***
	(0.262)	(0.210)	(0.206)	(0.236)
Period=3	-2.087***	-1.537***	-1.583***	-1.809***
	(0.311)	(0.224)	(0.227)	(0.260)
Period=2 × Est. marg. cost	-0.079*	-0.036	-0.038	0.030
	(0.047)	(0.041)	(0.044)	(0.039)
Period=3 × Est. marg. cost	0.176***	0.209***	0.188***	0.204***
	(0.053)	(0.043)	(0.044)	(0.048)
Auction volume > 200MW		-0.124	-0.090	-0.077
		(0.130)	(0.135)	(0.151)
Large bidder (size, p90)=1		-0.357***	-0.294	
		(0.131)	(0.231)	
Large bidder (size, p90)=1 × Est. marg. cost			-0.004	0.136
			(0.041)	(0.087)
Period=2 × Large bidder (size, p90)=1			-2.889***	-1.596***
			(0.355)	(0.522)
Period=3 × Large bidder (size, p90)=1			-1.033	-0.035
			(0.676)	(1.138)
Period=2 × Large bidder (size, p90)=1 × Est. marg. cost			0.559***	0.334***
			(0.074)	(0.082)
Period=3 × Large bidder (size, p90)=1 × Est. marg. cost			0.203**	0.061
			(0.100)	(0.149)
N	1143	1143	1143	1143
r2_a	0.55	0.72	0.72	0.80
DV_mean	6.45	6.45	6.45	6.45
LandFE	No	Yes	Yes	Yes

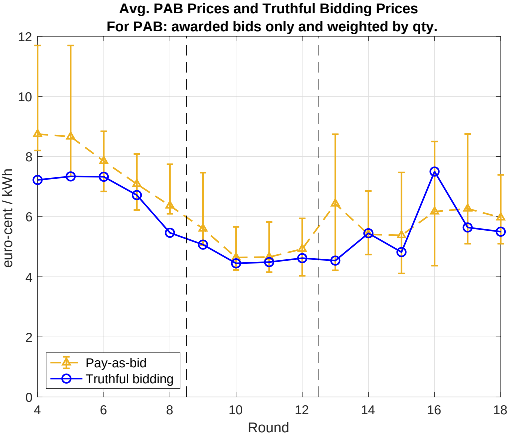
Counterfactual 1: Pay-as-bid (PAB) vs. Uniform price auction

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

PAB and Truthful Bidding

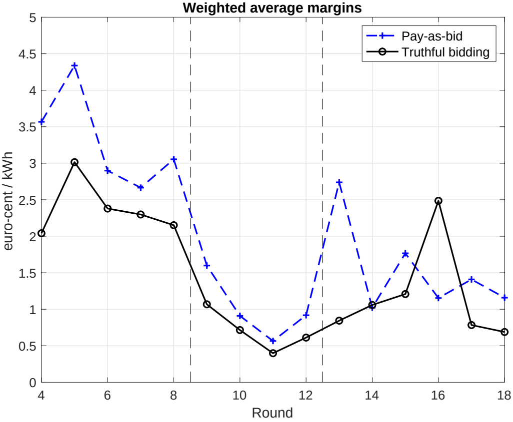
P1: Rounds 4 - 8, P2: Rounds 9 - 12, P3: Rounds 13 - 18

Even Truthful Bidding (uniform price auction) would not yield a downward trend in market clearing prices



Margins Under Different Auction Formats

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.

Counterfactual 2: Subsidies Under Different Auction Formats

- p^*: market clearing price assuming uniform pricing (intersection of MC and Q)
- cp: capture price
- **Uniform price subsidy**

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

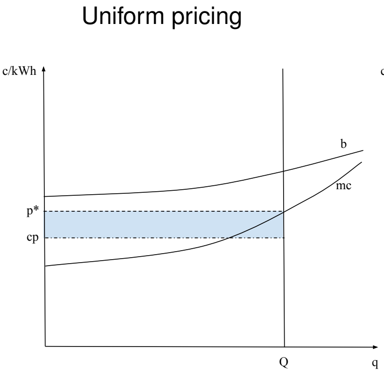
over all the quantities up to Q (government's demand)

- **Pay-as-bid subsidy**

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

over all quantities awarded Both $S_U < S_{PAB}$ and $S_U > S_{PAB}$ are possible

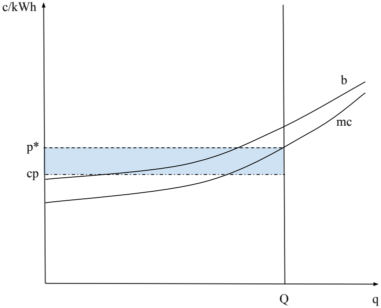
Subsidy under uniform pricing can be lower than under pay-as-bid



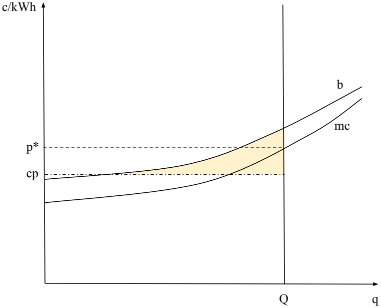
Auction formats

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

Uniform pricing

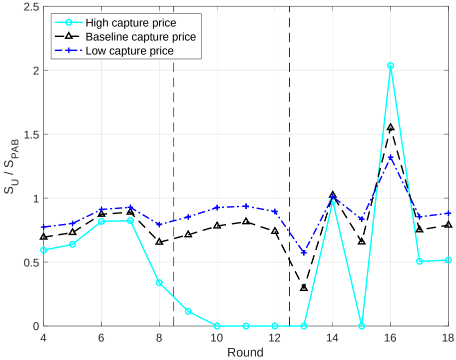


PAB



Aggregate bid curve *b* much closer to MC curve

Subsidies under pay-as-bid and truthful bidding



- Plot of ratio of subsidy per kWh under truthful bidding and PAB: S_U / S_{PAB}
- As capture price $\nearrow \Rightarrow$ subsidy under truthful bidding $\searrow$ and...
- subsidy under truthful bidding **lower** than under PAB

Counterfactual 3: Increase in volume

- Inverse elasticity from a 10% increase in govt demand
- Under truthful bidding: elasticity = 0.1248
- Under PAB: elasticity = 0.1301
- Elasticity is simple average over the per-round elasticities

$\Rightarrow$ A 1% increase in government demand $\Rightarrow$ increase of **0.12%** of the clearing price under truthful bidding and a **0.13%** under pay-as-bid

Conclusion

- **Bid prices and marginal costs** in German solar PV auctions are strongly correlated with solar irradiation, auction volume, and the bidder size
- Adopting a non-discriminatory auction results in **lower subsidy expenses and market power**
- Our empirical insights **offer guidance** for the design of environmental policies aimed at fostering the adoption of RE

Thank you!

Stefan Lamp (TSE) stefan.lamp@tse-fr.eu

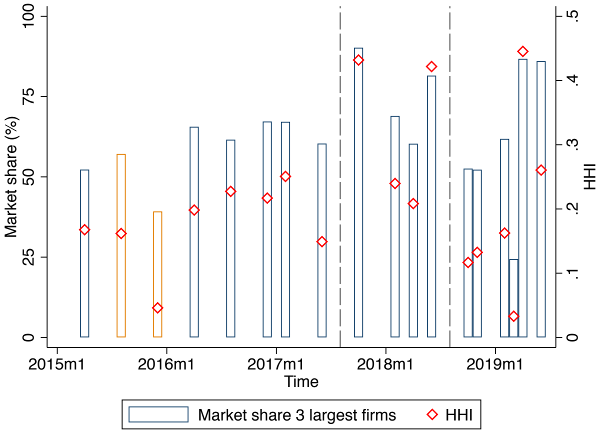
Mario Samano (HEC Montreal) mario.samano@hec.ca

Silvana Tiedemann (Hertie) tiedemann@hertie-school.org

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
- Special rules for agricultural land (since June 2017); yet only binding in Bavaria

Back

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

Period 1: 04/2016 - 02/2018. Period 2: 04/2018 - 06/2019, defined according to aggregate price trend. Rounds prior to 2016 omitted as either first auction participation or uniform pricing rules.

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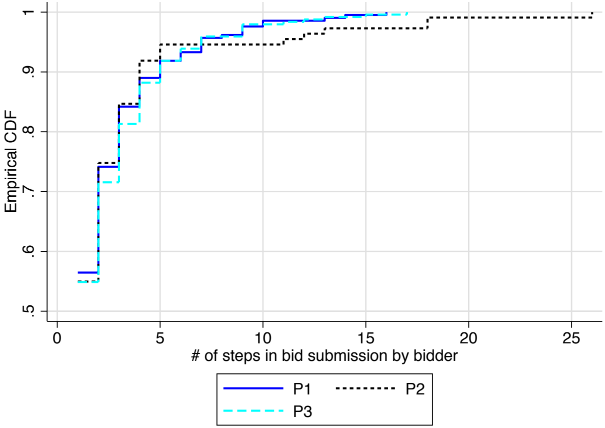
Number of "steps" in submitted bid curves



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Distribution of payoffs (market-premiums)

Figure: Distribution of market premiums

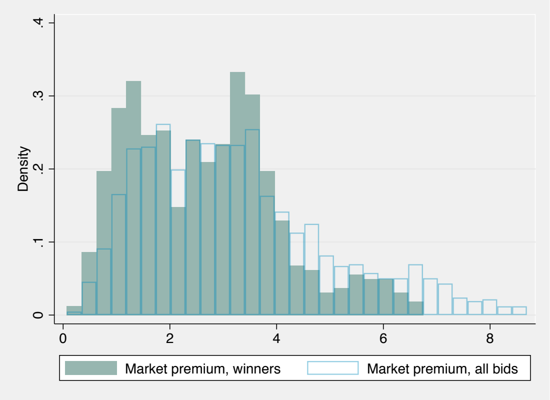

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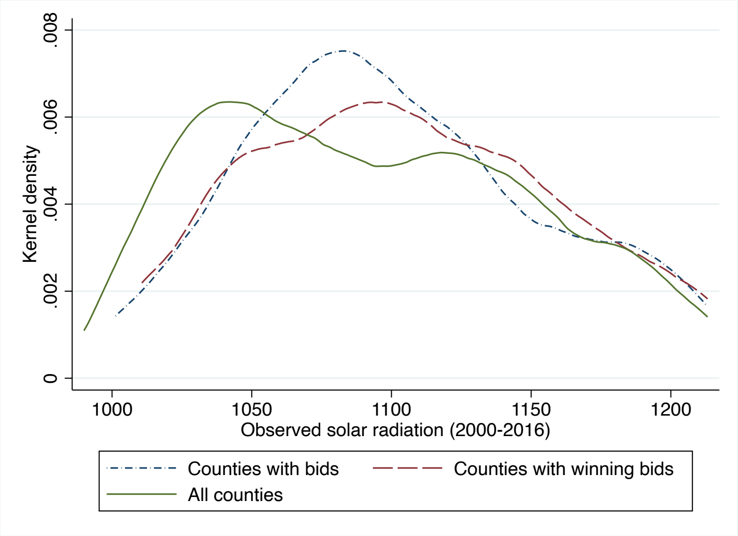
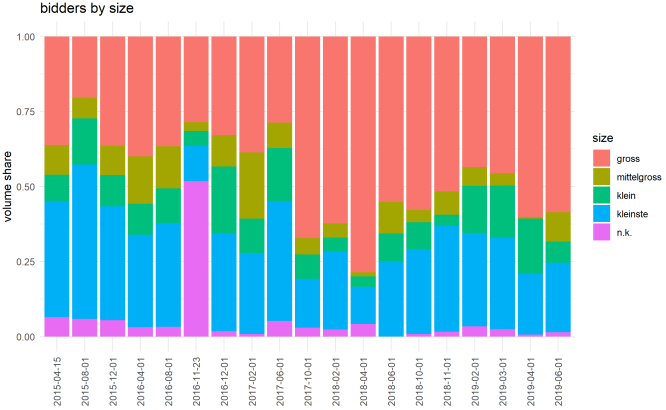
Figure: Selection of investment sites: solar radiation



Bidder composition: size



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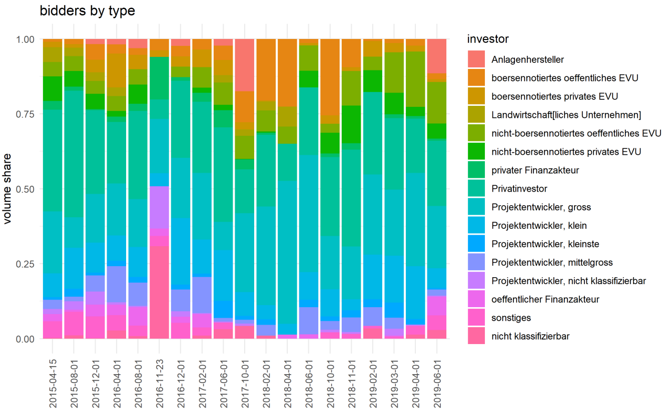
Bidder composition: type



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