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THESES SYNOPSYS FOR THE DISSERTATION

Allocation of renewable energy support through auctions

by

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Department of Mathematics

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Chapter 1

Research and topic selection background

The topic of my thesis is the allocation of renewable energy support through auctions. The used methodological framework is auction theory, and the model is based on the rules of the German PV (photovoltaic) auctions, thus the allocated support is a Feed-in Premium (FIP). The work focuses on the analysis of the participants' bidding strategy.

The field of this research - allocation of renewable energy support - gains more and more importance as climate change is becoming an increasingly tangible threat. For all EU member states renewable energy utilisation needs to be increased: to facilitate this process, the EU sets different renewable energy share targets. In order to reach these goals and to fight climate change EU countries support renewable energy generation.

EU legislation regulates the way support can be allocated (European Commission, 2014). Former support schemes led to over subsidising renewables in several countries in the first 10-15 years of the millennium, e.g. Spain, Slovakia or the Czech Republic. Cost reduction of renewable technologies was faster than the reaction of regulators setting support levels. That was the driver behind the introduction of a new, competition based support allocation mechanism: auctions.

Several countries could serve as a basis of my modelling, but probably the most adequate candidate is Germany. It is one of the pioneers in renewable energy utilisation and support, the so-called Energiewende has already started back in the '90s, and still then Germany has gone a long way: starting from a total renewable electricity generation capacity of 18.5 GW in 2002 the country achieved to build an additional three times more, arriving to around 74 GW by 2019 (Fraunhofer, 2019). Germany decided to allocate renewable energy support through auctions in 2014, and after some pilot tenders at least three auctions were organised every year. Thus, a lot of experience was gained, and the rules were adjusted according to this year after year. This makes the German system a proper one to analyse and model.

In my work as a first step of the modelling, the costs of the bidders are calculated. The basis of this calculation is the LCOE (levelised cost of electricity) methodology, however, it is upgraded and extended in this work. Not only the incomes throughout the support period are taken into account, but also the incomes after the support is expired, as usually the project lifetime is longer than the support period. For this I make my own electricity wholesale price forecast, using the EEMM model.

Also, for investment costs not a single value but a distribution is used, from which an empirical distribution can be generated for the modified *LCOE* values (indicated as LCOE'). This LCOE' will fit into the auction theoretic framework, serving as the valuation of the participants. The valuation of a player in this setting is the minimum strike price each bidder is willing to accept, in order to realise its renewable energy generation project.

Two different set of rules are analysed in my dissertation. The first one is the uniform price auction, where - as it is already proven in the literature, see e.g. (Krishna, 2010) - all participants bid equally to their true valuation. The second analysed rule is the pay-as-bid, where there is room for strategic bidding. So modelling the bidding in these auctions is more complicated.

Compared to a "traditional" auction, bidding is reversed: normally the announcer of the tender is the so-called seller, while in this case the announcer is a buyer, and all the participants (the bidders) are sellers. This way the bid indicates the support level, that is high enough for the bidders to realise their renewable projects. Thus, the winners would be the ones with the lowest bids.

In case of the uniform pricing the Nash-equilibrium bid function is the identity function. For the pay-as-bid rule, the equilibrium bid function is found through an iteraion. When calculating the optimal bids, as a first step bidders assume a pre-fixed bid distribution on other participants' bids, regardless of this being the optimal bidding strategy for others or not. Then in the next step it is checked, whether this leads to Nash-equilibrium bidding strategy or not. If not, then the iteration goes on, until the assumed and the optimal bids are very close to each other.

The main research questions of my thesis are the following:

- What is the underlying distribution of the participants' modified $LCOE$ values ($LCOE'$) (thus of their valuation), when assuming a given distribution for investment costs, and future electricity price levels are taken into account?
- How can the Nash-equilibrium bid function be specified when not only strictly monotone, but monotone functions are assumed?
- How different are these for the uniform price and the pay-as-bid auctions?

Chapter 2

Methods used in the dissertation

2.1 Modified LCOE calculation

The LCOE (Levelised Cost of Electricity) value stands for the cost per unit of produced electricity taking into account all costs during the lifetime of the investment. It can also be translated to the income per produced electricity unit that makes the net present value of incomes equal to the net present value of costs - thus it answers the question: what is the minimum fix income need (in €/MWh) that makes the investment profitable.

In the literature it is a typical approach to calculate *LCOE* values of different technologies, so their costs become comparable. Thank to this, relatively large amount of data is available to make my own estimation of the *LCOE* value of German PV investments. On one hand, the German Energiewende is well-known and a popular research topic, and on the other hand, many projects have already been realised, thus actual cost data is also available.

In my auction theory model the *LCOE* value calculated according to the original logic can not be treated as the cost of participants (or using the auction theory terminology: as their valuation). The two main reasons are: the support is not the total income per unit of generated electricity, it is only the premium that is paid, if the electricity wholesale prices are not "high enough". The other thing is, that while the assumed lifetime is 25 years, the support period only lasts for 20 years.

As a first step, we need to take into account this latter difference. In the first 20 years the source of the income is twofold: it can come from the market, and from the state (in a form of a premium). In the last 5 years the only source is the market.

The Feed-in Premium (FiP) support system that is applied in Germany - the so-called one-sided sliding premium - works the following way. The investor needs to sell its electricity on the market. If the received price is lower than the strike price (that is the result of the auction) then the investor will get a premium, that amounts for the difference between the strike price and the market price. If the market price is higher, then the investor keeps the total amount, and the state does not have to pay anything. This is the closest support type to the older FiT (Feed-in Tariff) support scheme, where the investors hardly had any price related risks, as the state bought all the generated electricity on a pre-fixed price ("Tariff").

Still, there remains some risk in the FiP system, as the support (the premium) is not calculated for every hour, but only at the end of each month. The first step is the calculation of the monthly reference price: the actual, PV generation weighted average wholesale (day-ahead) electricity price. The support is the difference between the strike price and this reference price. Each producer receives a support (in €/MWh) for each unit of electricity generated by him/her.

This means, that if the average wholesale price, weighted with the producer's own generation is higher than the reference price, then the total received support will be higher, compared to the hourly settlement situation. If the generator's own average wholesale price is lower than the reference price, then the support it receives in case of a monthly settlement will be lower compared to the hourly settlement case. This can incentivise producers to adjust their generation profile - if it is possible (Klobasa & Ragwitz, 2018). In my model I will not take this possible behaviour into account, I assume the generation curves are the same for all producers. This way the total support to be paid only differs by a few percentage in case of a monthly and an hourly settlement.

The second part of the modification is the inclusion of additional incomes. Additional incomes arise when the strike price is lower than the (reference) market price. This is beacuse in the German system, as I mentioned, the producers can keep the total amount received from the market (in contrast to e.g. the new CfD - contract for difference - system of the UK, where generators should pay back the difference between the market price and the strike price, if there is any). So it can happen, that in some periods the total income per MWh will be even higher than the strike price.

Taking all this into account the modified *LCOE* (from now on indicated as $LCOE'$) will show us the minimum strike price that makes the investment profitable (assuming the mentioned WACC values). The calculation is the following:

$$LCOE' \sum_{t=1}^{N} \frac{\sum_{m=1}^{12} E_{tm}}{(1+r)^t} + \sum_{t=1}^{N} \frac{\sum_{m=1}^{12} [p_{tm} - LCOE']^{+} E_{tm}}{(1+r)^t}$$
$$+ \sum_{t=N+1}^{n} \frac{\sum_{m=1}^{12} p_{tm} E_{tm}}{(1+r)^t} = I + \sum_{t=1}^{n} \frac{M_t}{(1+r)^t}$$

, where n= 25 years, N= 20 years, p_{tm} is the reference electricity price of month m in year t, E_{tm} is the total amount of generated electricity in month m of year t, $LCOE'$ is the strike price that makes the NPV of total income equal to the NPV of total cost, (assuming r discount rate, that equals to the assumed WACC value).

In my disssertation as a first step I present the calculation logic of LCOE, then make my own calculation based on the available data. Then I turn to the modified LCOE calculation, I show the methodology, then my results.

2.2 Auction theory model and iteration

My model is based on the general auction theoretic framework. In the general framework participants are rational and risk neutral. There is a given distribution for their valuation, that is common knowledge among everyone. The auction is symmetric, thus this is the same valuation distribution for everybody. Participants know their own valuation realisation, but do not know the exact valuation of others (only its distribution).

All participants bid with these information in hand. The players optimise their bid to have the highest expected utility. To calculate the expected utility for a given bid four elements need to be calculated: the probability of winning and of losing with the given bid, and the utility in case the player wins and in case he or she loses.

I assume that participation is for free. While this is not exactly the case in the German PV auctions (e.g. because of the bid bond, and other administrative burdens) it is a usual approach in the literature, to apply this assumption (unless we concentrate on the cost of participation itself). This way the utility of losing is 0. Thus, the formula is reducated to the probability of winning multiplied by the utility of winning.

When bids are formed the expected profit function needs to be maximised. For that the most complicated part is to calculate the probability of winning. To be able to say something about this we need all participants to assume something about the bidding behaviour of others. All participants need to know the probability of others to bid lower or higher than a given value. Thus, what they need is the bid distribution of others. I will use an assumption for this in the first step of the iteration, then whatever bid distribution is received after the optimisation will be fed into this formula in the next step of the iteration. Thus, the function to be maximised for a given valuation is the following:

$$E(\pi_j(x_j,b_j)) = P_{j,w}(b_j)U_{j,w}(x_j,b_j) =$$

$$\sum_{i=0}^{39} \binom{99}{i} (F_1(b_j) - P(b_j))^i (1 - (F_1(b_j) - P(b_j)))^{99-i} (b_j - x_j)$$

where, $P_{j,w}(b_j)$ is the probability of winning with b_j , $U_{j,w}(x_j,b_j)$ is the utility of winning with b_j in case of valuation x_j, $F_1(x) = P(X <= x)$, the assumed bid ditribution of others, $P(b_j)$ = P(X = b_j), the probability of a bid being b_j. There are always 100 participants and 40 winners on the auction.

As mentioned above, an iteration is needed to find the equilibrium bidding strategy. The logic behind the iteration is the following. In the first step participants make assumptions on the distribution of bids, and calculate their own optimal bid functions accordingly (assigning the optimal bid for every possible valuation). From this they can check whether their induced bid distribution is the same as they assumed for others or not.

If the induced bid distribution is different, then the calculation of the optimal bid function is repeated, with a new assumption on other participants' bid distribution: the induced bid distribution. The optimal bid distributions are always compared between the steps, using the NRMSE value. The iteration stops – we arrive to a Nash-equilibrium – when the assumed optimal bid distribution (for others) is the same as the calculated optimal bid distribution, meaning the NRMSE value is very low, close to 0 (in my case based on the literature this value is 0,1%). As in this case, this is the best response to others' bidding strategy for every participant (because of symmetry).

The iteration also stops, if it seems that in a step we are getting further away from Nash-equilibrium: meaning the NRMSE value starts to increase after a decrease in the previous step. In this case the iteration also stops, but if the NRMSE value was not small enough, we can not state that we arrived to Nash-equilibrium, we will call that a pseudo-Nash-equilibrium.

Chapter 3

Main results

3.1 Modified LCOE calculation

An important attribute of the modified LCOE calculation, is that there are other items on the income side, not just the income from the support. So, it can happen, that the project turns into positive without any support. If the investment cost is low enough, and the electricity prices are high enough, even a 0 $LCOE'$ value can be the result of the calculation. This way, the "critical investment cost" (if all other inputs are fix) can be calculated: how low should the investment cost be, to make the project profitable without any support? Or in other words: what is the investment cost that makes the NPV of incomes and costs equal without any support? So, for a critical investment cost, the $LCOE'$ will be exactly 0. This value can be calculated with different inputs: as it is shown on 3.1, different WACC values and different OPEX (operation and maintenance costs) result in different critical investment costs.

After calculating the $LCOE'$ value with different fix inputs, now I turn to the calculation of the distribution of $LCOE'$, based on the assumed distribution of the investment cost. As stated above, the $LCOE'$ calculation is an optimisation, so to get the distribution I simulate 10 000 investment cost values from the assumed distribution. For all 10 000 values I make the optimisation, and calculate the $LCOE'$ value. This way I get the empirical distribution of the $LCOE'$ value. In case of a lower investment cost than the "critical investment cost", I assume that the needed support is 0, thus, the minimum of the $LCOE'$ is 0 (no one would ask

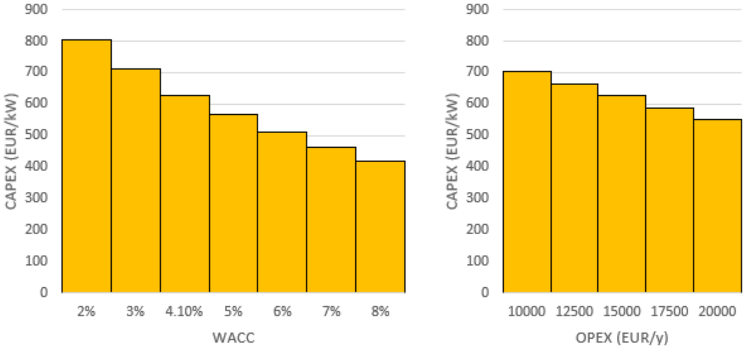

Figure 3.1: Critical investment costs for different WACC and OPEX values, source: own figure

for a negative support).

The sorted $LCOE'$ values are presented on 3.2. It is very interesting, that the first 759 elements are 0 - thus, from the simulated 10 000 investment costs 759 is lower than the critical investment cost. For these projects I still assume that project developers will take part in the auction, as it is possible, that they can make their investment more profitable if they win. In my model I assume a simplification that there is no cost of participation, so they are incentivised to participate.

3.2 Equilibrium searching algorithm

Based on the literature in case of the uniform price auctions using the identity function as bid function is a Nash-equilibrium strategy. In case of the pay-as-bid auctions it is much more complicated to find the Nash-equilibrium bid function. The above presented iteration serves to search for this bid function.

In the specific case I model in this work with the valuations coming from the modified LCOE calculation the iteration will not reach a real Nash-equilibrium, however, the assumed and resulting optimal bids are very close to each other. To quantify this distance I use the NRMSE value. I assume that we arrived to Nash-equilibrium if this distance – between the assumed and optimal bids – is less than 0.1%. However, the iteration is stopped also, if after decreasing NRMSE

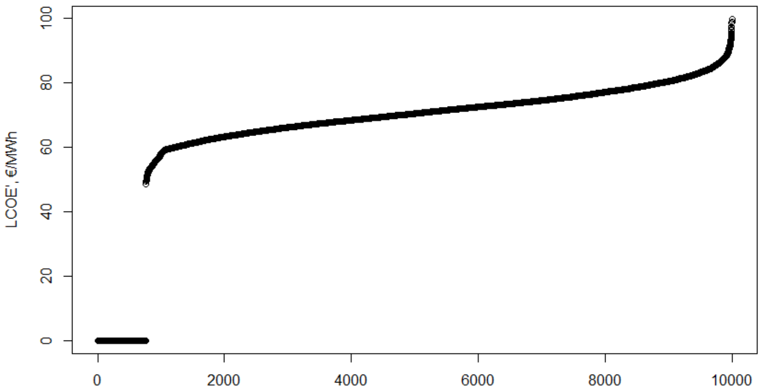

Figure 3.2: Empirical distribution of $LCOE'$ calculated from the simulated 10 000 investment costs, source: own figure

values we get an icreasing value, as in that case one can assume that there is a distancing from Nash-equilibrium. So, the participants may choose to play the last bid function, where the NRMSE was decreasing, that we call a “pseudo-Nash-equilibrium” bid function. In case of this modelling, the resulting NRMSE value was around 0.25%, thus the assumed and optimal bids are already very clost to each other, but we still did not arrive to a real Nash-equilibrium.

We recieve different bid functions if the participants stop the iteration at the first or the second distancing. However, it can be stated both cases, that the form of the bid function is special. Players with valuations smaller than a given value would choose very similar bids (depending on the stopping step this valuation limit is around 68.5 or 70.5 €/MWh). With valuations higher than this, players bid close to their valuations. This means that the function consists of an almost horizontal part and then turns to a close to 45° increasing part. This is the same form in case of both stopping step, the only difference is in the valuation limit.

Figure 3.3 presents the bid function in case of the first stopping step, when participants assume F_4 bid distribution. Valuations are on the X axis, optimal bids are on the Y axis for 10 000 valuations.

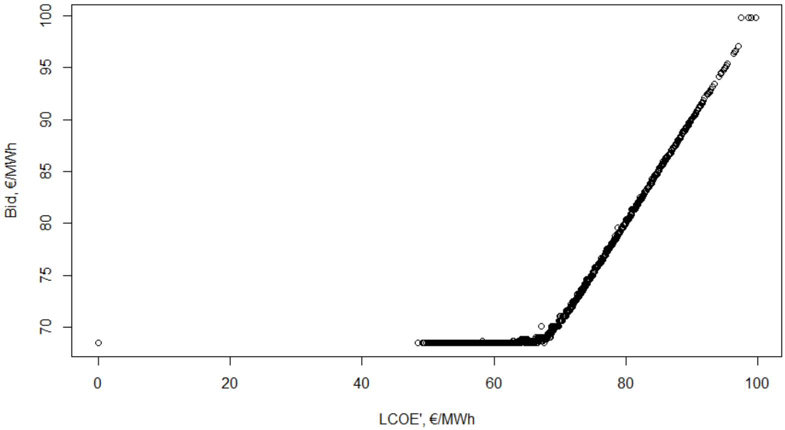

Figure 3.3: Bid function when participants assume F_4 bid distribution, source: own figure

For 1000 datapoints (valuations) I also analysed the case when a possibility of tie is also taken into account by the participants. This led to a quite long optimisation time, so only the first 5 steps were carried out. The results were very similar to the original case (assuming normal distribution, 1000 valuations, without taking into account ties), the NRMSE values in case of assuming F_3, F_4 and F_5 only differed in the first, second and third decimal point, respectively. The form of the bid functions was also very similar.

Another extension was to start the iteration with a different bid distribution assumption: instead of normal, uniform distribution was applied. Very similarly to the original iteration here also the F_4 and the F_{10} bid distribution assumptions were the ones where the iteration stopped. Both of them was a pseudo-Nash-equilibrium, but the NRMSE values were low, 0.54 and 0.22%. Again, the form of bid functions was also very similar, so it seems this result is very robust.

3.3 Auction results for uniform pricing

Assuming the above found equilibrium bidding strategies the auctions were simulated 1000–1000 times for both pricing rules. In order to make the results more comparable the same 1000*100 valuations were used in both cases.

Using the valuations and the equilibrium bid functions 100 bids are received on each auction, from which the smallest 40 are chosen as winners. From this the support levels and the total support need can be calculated.

The support need and the minimum and maximum winning bid in the uniform pricing can serve as the basis of comparison, as this is the situation when all participants admit their true valuations, no strategic bidding is in place.

In case of the uniform pricing rule the support need received by all winners will be the 41th lowest bid from the sorted 100 bids in each auction. From the 1000 auctions the lowest and highest support level was 64.8 and 71.6 €/MWh, while the average was 68.4 €/MWh.

The total support need is the aggregate support level that the state has to pay for the winners throughout the entire support period. To be able to calculate this we have to assume something about the future electricity prices. Here I use the same assumption that was used for the calculation of the LCOE' values, as a best estimate. Same stands for the production profiles.

First the monthly PV market values (the production weighted monthly average wholesale electricity prices) are quantified. When these are higher than the support level, then no support needs to be paid for that month. When it is lower, than the support level, then the difference needs to be paid for each MWh of produced electricity.

Because of symmetry and because of uniform pricing all participants will receive the same support, so the calculation only has to be made once, and then multiplied by 40. The calculation is represented with the following formula:

$$\sum_{t=1}^{20} \frac{\sum_{m=1}^{12} [TSZ - p_{tm}]^{+}}{(1+r)^{t}}$$

, where, TSZ is the support level, p_{tm} is the monthly average PV market value in year t and month m, r is the assumed discount factor. [1]

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[1] this is assumed to be the social discount factor, level is 4.1%.

The results indicate the net present value of the total support need (in 2019 real values) is between 4.32 and 7.53 million € on the simulated 1000 auctions. The average total support need is 5.95 million €. This means, that the support need is very much variant based on the exact valuations of the participants on a given auction. The total support need can be +/-27% different from the average value, so there is a high risk. This might be an important message for policy makers. However, as it will be shown in the next section, the average support need is lower than is case of the pay-as-bid pricing.

3.4 Auction results for pay-as-bid pricing

In case of the pay-as-bid auction one of the most important results is the equilibrium bid function. According to the literature (Krishna, 2010) it is typical to bid higher than the valuation in a pay-as-bid auction. This is confirmed by my model as well. The bid function was already analysed shortly above, so I will turn to the support levels and resulting total support need.

As it was stated above, the first and the second case when the iteration is stopped (assuming F_4 and F_{10} bid distribution) results in functions with an almost horizontal and an increasing part. This latter is there, because trivially none of the participants will bid under their valuations. This is because if they receive a lower support level than what would be needed for them to realise their project with the given expected return on investment, they would not be incentivised to carry out the investment. So a lower support level than one's LCOE' would mean the project would not be realised, that would leave the participant with the same utility as they had never come to the auction. Thus, a positive utility could only be gained from the auction if the support level is higher than the LCOE'. This means, that all participants will bid higher or equal to their valuation, even if then the probability of winning might be very small.

The first part of the bid functions represents that there are many bids around 68.5 €/MWh (when participants assume F_4 bid distribution) and around 70.5 €/MWh, when F_{10} is assumed. This might seem to be a small difference, but as it is shown, this has a high impact on the total support need.

The reason for that, is in the 2030's the forecasted electricity prices (PV market values) are many times close to these values, meaning in case of a support level around 68 €/MWh there is no need to pay, while in case of a 70 €/MWh support need arises. This altogether leads to rather different support needs.

First I have a look at the support levels. In case of the pay-as-bid auctions we have 40 different suport levels within one auction, and we have altogether 1000 auctions, so we have 1000*40 support levels.

For the case when participants assume F_4 bid distribution the minimum and maximum support levels among the 1000 auctions are 68.45 and 71.42 €/MWh, while the average is 68.63 €/MWh [2]. When assuming F_{10} the minimum and maximum values are 70.53 and 72.25 €/MWh, the average is 70.53 €/MWh. These are much closer to each other than in case of the uniform pricing, and it is visible also, that the average is very close to the minimum.

The total support need is calculated similarly to the uniform pricing case, but there is a slight difference because of the 40 different support levels within one auction. We can not mulitply simply with 40 the support need of one participant, but we need to calculate the support need one by one for each participant separately.

The total support need is much less volatile than in case of the uniform pricing. When participants optimise assuming F_4 bid distribution then the minimum and maximum total support need is 5.98 and 6.39 million €, with an average of 6.07 million € [3].The average value is only 2% higher than in case of the uniform pricing, while the risk to have a very high support need is much lower.

However, when the participants assume F_{10} bid distribution then the resulting bid function leads to a much higher support need: minimum, maximum and average values are 7.00, 7.09 and 7.00 million € respectively [4]. This is, in case of the average, a 17% increase in support need compared to the uniform pricing.

What is particularly interesting in that latter case is that the volatility, thus the risk of having support need other than the average is extremely low. On 963 auctions out of the 1000 the total support need only differs with maximim 1 euro from the average. So even if the average is higher, it is almost sure to have that exact support need regardless of the valuations of the particular participants (iF

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[2] when we assume only 1000 datapoints these are already somewhat higher: 68.54 and 71.72 €/MWh, the average is 68.86 €/MWh

[3] iteration with only 1000 points result in 6.09, 6.61 and 6.18 million € total support need

[4] this result is only available for the 1000 datapoint case

all of them are using the bid function resulting from assuming F_{10} bid distribution).

One of the novelties of my model is to assume project promoters with a 0 valuation also participate in the auction. This might lead to this unusual bidding strategy. It is something that might gain importance even further in the future, as with the decreasing investment costs more and more projects would be profitable without support.

An important result for policy makers is that auction rules do have an impact on bidding strategies. This is not a novelty on its own, but in my model it is also important, that the total expected support need might be significantly higher in case of the pay-as-bid rule than in case of the uniform pricing.

This does not contradict to former results, such as the revenue equivalence theorem (Krishna, 2010), as that theorem assumed Nash-equilibrium bid functions, while my iteration only provides different pseudo-Nash-equilibrium bid functions (though these seem to be not too “far” from a Nash-equilibrium strategy, because assumed and optimal bidding is very similar).

To sum up, policy makers should consider that uniform pricing might lead to lower overall support need on average, but with a significant risk based on the valuation of the particular participants. While in case of the pay-as-bid pricing the risk comes from the bidding strategies – based on which equilibrium is found by participants average support need can be only slightly, or much higher than in case of the uniform pricing. Within one equilibrium bidding strategy, however, there is very low risk in total support need, regardless of the exact valuations. This also means that the pay-as-bid rule would for sure lead to a higher support need than the average support need in case of uniform pricing, depending on the exact equilibrium bid function it can be either 2 or even 15% more expensive.

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