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Efficient promotion of renewable energy with reverse auctions

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Efficient Promotion of Renewable Energy with Reverse Auctions

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Abstract

Despite negative experiences with auctioning off subsidies for renewable energy in some countries, tenders are increasingly used today. We develop a reverse auction which accounts for particularities of intermittent renewable energy sources. Determining the quantity, demanded by the regulator, is internalized and directly linked to his two main objectives. On the one hand, the regulator seeks for a high share of renewable energy. On the other hand, he wants to enhance burden sharing between electricity consumers and renewable electricity producers. We further account for asymmetric information in reverse auctions. We analyze incentives for bidders to manipulate the auction outcome and adapt the design to prevent this behavior. Regional features as grid and generating capacity can be considered to optimize the deployment of renewable energy. We thereby introduce a link to fossil capacity auctions.

Keywords Auction Design, Tendering, Renewable Energy, Adverse Selection, Moral Hazard, Burden Sharing

JEL C72, D44, D47, D82, L10, Q48

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1 Introduction

So far, many countries supported renewable energy projects via feed-in tariffs (FiTs) and contracts for differences (CfDs). The regulator estimates the price per kilowatt hour (kWh) to guarantee a sufficiently large producer rent incentivizing investments in renewable energy. In the case of FiTs the producer receives this price as remuneration. Under a CfD regime he receives the difference between this price and the average electricity spot price weighted by the electricity generation of the respective technology. The resulting costs on top of the electricity spot price (denoted as difference costs) are usually paid by electricity consumers as an additional position on their bill.

These instruments mainly focus on increasing the share of renewables, that is why they have been very successful in promoting renewable energy in the starting phase. As countries leave this first stage, the regulator's trade-off becomes more pronounced. On the one hand, the producer surplus must be high enough to encourage the implementation of projects, but on the other hand too generous producer rents result in an unnecessary high financial burden for consumers.

For FiTs and CfDs to be adequate, an accurate estimation of actual costs that investors of renewable energy projects face is crucial but at the same time challenging. The solar power boom in Germany from 2010 until 2012 is an example of overestimation, resulting in windfall profits for investors at the cost of consumers.

Despite negative experiences with auctioning off subsidies for renewable energy in some countries (e.g. UK), more and more countries switch from FiTs to tenders (REN21, 2014). The German government for instance is currently testing a design for a reverse auction to promote solar power by running three auctions in 2015. The first auction produced ambivalent results. The demanded quantity was reached but the average auction price was higher than the coexisting FiT (Bundesnetzagentur, 2015). Nevertheless, auctions shall be developed for wind energy projects until 2017 (EEG, 2014, § 2).

In an ideal auction, participants bid their total costs truthfully. Thus, the regulator is able to observe the true amount of required support and does no longer rely on own estimations. Competition among investors should then induce cost-efficient support of renewable energy sources (RES) and thus a more balanced burden sharing between producers and consumers.

Auctions in reality are, however, characterized by incentives for bidders to overbid or

understate their true total costs as they exploit information asymmetry between them and the auctioneer. Communicating the target quantity for renewable energy projects before the auction facilitates bidders' strategic behavior. That is why we design an auction with uniform pricing that considers prevailing information asymmetry and limits strategic bidding. In our setup the demand for new renewable energy installations is not defined ex ante by the regulator but it results from optimizing his utility that depends on the trade-off between increasing the share of renewables and limiting producer rents. This approach that internalizes the optimal demand for renewables is an innovation in mechanism design. It allows to limit producer rents while incentivizing to bid true costs. This makes our design superior to other auction designs, in particular when compared to pay-as-bid auctions.

The paper is structured as follows. Section 2 briefly discusses why previous renewable energy auctions failed and to what extent renewable energy auctions today mitigate former problems. Section 3 illustrates the issue of information asymmetry in the context of reverse auctions which includes both an adverse selection and a moral hazard problem. We present the game and develop a mechanism that limits incentives to over- or underbid for certain types of agents. In designing an auction for intermittent renewables their characteristics play a major role. We focus on wind energy because it displays most peculiarities. Additionally, we consider transmission bottlenecks and a link to capacity auctions for fossil fuels. We illustrate our findings by an example using spot market data for Germany and offer recommendations for implementing reverse auctions in Section 4. Section 5 concludes.

2 Renewable energy auctions

Klemperer (2002) claims that what matters for successful auction design is basically what matters for regulators of any industry. That is to prevent collusion, entry-deterrence and predation. He further emphasizes that good mechanism design cannot be "one size fits all" but that is has to be tailored to the specific context (Klemperer, 2002). This section demonstrates that designing a successful renewable energy auction is not an easy task.

Countries' experience with auctions for RES offer a variety of lessons to be learned. An example of an unsuccessful design is UK with its so-called non-fossil fuel obligation (NFFO) in place from 1990 to 1998. In this period five auctions were held for renewable energy. Bid prices declined from one auction to another but many projects were not

realized. Three main problems in the mechanism design were detected that explain this outcome. First, the regulator's budget was too small. Second, no penalties were in place to punish bidders who did not complete a project. Third, it was not necessary to have a planning permission before entering the auction (Mitchell and Connor, 2004).

Del Rio and Linares (2014) provide an overview of auction designs in other countries. They name lower support prices compared to other support mechanisms and declining support levels over time as positive features of tenders. Nevertheless, there are also countries for which these two observations are not true. The list of problems is way longer with the utmost flaw being low effectiveness. Projects were either not built or the contracted capacity was lower than the initial target (Del Rio and Linares, 2014).

In most renewable energy auctions the remuneration of successful bidders is generation-based. Boute (2012) however, explores the question whether RES can be promoted by means of capacity markets. Capacity markets intend to provide investment incentives to ensure long-term security of supply. Therefore firm capacity that offers reliable electricity generation is needed but intermittent RES as wind and solar power are not characterized by reliability. Boute (2012) argues that RES can participate in capacity markets if regulations account for peculiarities of intermittent RES.

Some South American countries promote RES with a related system. These countries target firm electricity delivery (in MWh) for a certain period. A capacity market, in contrast, aims at sufficient capacity (in MW) to ensure security of supply in the long-run. In Colombia, wind projects can take part in the so-called reliability charge auctions (the same rules apply as for fossils) but not a single wind project was among the winning bids (Mastropietro *et al.*, 2014). This outcome emphasizes why it is more common to use separate auctions for RES with specific rules.

Brazil uses such a setup. In those auctions firm energy certificates (FEC) are auctioned in which generators declare their expected energy delivery. Deviations from these projections, less than 90 percent or more than 130 percent of the contracted generation, are penalized (Porrua *et al.*, 2010). Penalties are however, milder for RES compared to conventional sources. Even though bid prices tend to be converging for RES and fossils in South America, a comparison of these technologies is not appropriate as there is no level playing field in terms of requirements to fulfill (Mastropietro *et al.*, 2014). Besides, the auction design revealed some shortcomings. A central problem is the incentive for wind investors to overstate their power plant's performance indicated by implausibly high capacity factors. This incentive results from penalties being too mild and contract terms being too generous (Elizondo Azuela *et al.*, 2014).

In addition, observed low bid prices may rather be the consequence of underbidding than an indicator for competitiveness of RES. So far it is not clear whether all winning projects will be implemented (Batlle *et al.*, 2012).

These few examples already emphasize inefficiencies of reverse auctions caused by bad design. Moreover, strategic bidding is a problem. Milgrom (2004) points at weaknesses of uniform price auctions in practice if one bidder learns that he is pivotal. In this case high prices are a natural consequence as experienced in California’s electricity markets in 2000 and 2001 (Milgrom, 2004). Thus, a good design should prevent such learning effects.

Pay-as-bid auctions are believed to lead to lower total promotion costs but they are even easier to manipulate. The superiority of pay-as-bid pricing in terms of total costs is only the case if bidders bid truthfully. The matter is, why would they? Pay-as-bid pricing rather causes bidders to estimate the price of the last accepted bid and increase their bid just below this threshold. If they fail in their assessment they are not awarded and actually more expensive projects win the auction (Grimm *et al.*, 2008). There are some arguments that point at the superiority of uniform pricing compared to pay-as-bid pricing (Harbord and Pagnozzi, 2014).

Accounting for the flaws in previous auction mechanisms we design a reverse sealed-bid auction based on uniform pricing that internalizes the optimal quantity of renewables. This limits strategic bidding and at the same time it allows to cut producer rents to achieve balanced burden sharing.

3 Information asymmetry in reverse auctions

Reverse auctions display information asymmetry leading to both a moral hazard and an adverse selection problem. Regarding the moral hazard problem, hidden action does not relate to the agent’s effort as it typically does in an insurance setting (Arrow, 1985) but to the fact that the principal cannot observe whether the agent bids truthfully. The game can be described by $n = 2 + 1$ players, since the principal (regulator) faces two types of agents (bidders). The “good” type (G) is an investor who wants to implement a renewable energy project while the “bad” type (B) is a representative of fossil energy who intends to impede an increasing share of renewable energy. For type B more renewable energy leads to losses. Firstly, as a consequence of declining residual

load.¹ Secondly, because of the merit order effect of RES² that causes a decline in infra-marginal rents.

Both types want to maximize their profits. Profits for a bidder of type G increase with the auction price p as any price higher than his total costs corresponds to higher rents. This link leads to the moral hazard problem. Hence, in a pay-as-bid auction bidders speculate on the highest successful bid. In a uniform price auction bidders would need to manipulate the clearing price. This action is far more risky and thus intricate for the bidder.

Type B prefers the lowest possible amount of renewable energy. This can be achieved by placing low bids without realizing the project in case of winning the auction (in the absence of penalties or generation-based support). This directly replaces projects which otherwise would have been realized. Moreover it results in a lower average price (pay-as-bid auction) or a lower clearing price (uniform price auction). This discourages bidders of type G to participate.

The regulator faces a trade-off. On the one hand, he wants to increase the share of renewable energy. For instance to reduce CO₂ emissions or energy imports. On the other hand, associated costs for consumers should be as low as possible. It is difficult to adjust FiTs or CfDs optimally. A too high remuneration causes high producer rents while too low payments hamper the development of renewable energy. For enhanced burden-sharing, producers' surplus has to be cut without choking off RES deployment.

The general setup of the game is closely related to the “lemons” problem described by Akerlof (1970). The principal is not able to identify agents' types while agents know their own type. The scheme must therefore be self-selective and ensure that only type G has an incentive to participate in the auction while type B never does. This would solve the adverse selection problem but the moral hazard problem for type G remains as they may have an incentive to overbid their true costs to gain additional rents. The auction design should therefore incentivize to bid truthfully.

Generally, the game can be described by four stages as depicted in Fig. 1. After Nature has chosen the agent's type, they submit their bids. The regulator then determines the outcome of the auction and projects are being implemented (or not).

The regulator does not have a chance to distinguish between type G and B ex ante.

¹ Residual load is the difference between total load and load served by RES.

² The merit order effect describes the decrease in spot prices with increasing electricity generation of RES (Sensfuß *et al.*, 2008).

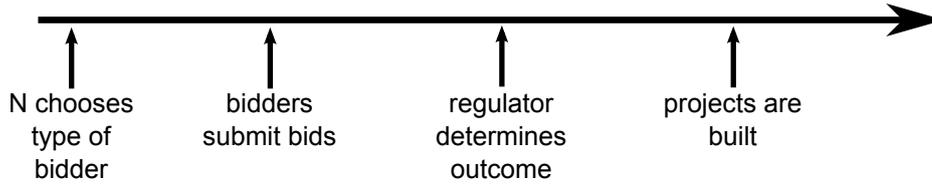


Figure 1: Timing of events.

He will only learn ex post if type B agents have been awarded. In the worst case, only bidders of type B win the auction and no projects are implemented at the last stage. Modifications of the game improve the outcome (see Fig. 2).

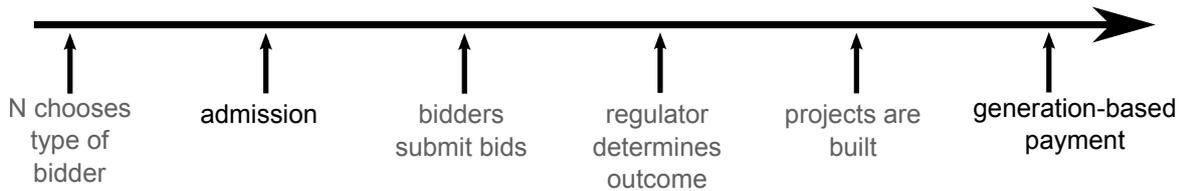


Figure 2: Timing of events with two additional stages.

The last stage ensures that in contrast to capacity-based remuneration only bidders who effectively generate electricity receive a payment. A crucial point of any auction design is step four of the game. What are useful rules for the regulator to determine the outcome? In auctions so far, the regulator communicates the target quantity ex ante or this quantity is determined by the maximum budget he wants to spend. This approach seems appropriate only if the regulator strictly prefers one of his two objectives over the other. That is to say, he does not care about costs if he wants to achieve a certain quantity of RES or he does not care about the quantity of RES that is realized once he has decided how much money to spend.

In reality, the regulator calculates expected costs with respect to a target quantity or calculates the expected quantity subject to a maximum budget. Thus both objectives are based on expectations. Problems of this approach are uncertainty and time inconsistency as objectives have to be adjusted over time. Ongoing discussions on optimal quantity or the maximum budget attract lobbying that compromises the regulator's objectives.

Stage four is essential to solve the moral hazard problem and consequently influences the agents' bidding behavior in stage three. We will discuss these two stages in the subsequent sections.

In the second stage of the modified game a selection process takes place based on eligibility criteria. We suggest that bidders have to present a construction permit,

an operation license, two wind yield reports and the grid connection point. This preparatory work is time-consuming and costly but it is necessary anyway for project realization. It does not cause any extra costs for type G , though it does for type B which bad agents may not be willing to take in the absence of remuneration at the end of the auction. The introduction of admission requirements weakens the effect of bad agents. Additionally a minimum threshold for the wind yield could be defined to keep bad agents from participating in the auction with inadequate sites. These selection criteria also comprise a feasibility check for renewable energy projects because only well-planned projects will receive a license. Hence, the probability of projects being realized, if successful in the auction, increases. It is a promising approach to control the adverse selection problem resulting from stage one.

The assumed superiority of reverse auctions when compared to FiTs is based on the assumption of high producer rents under a FiT regime. High producer surplus leading to high costs for electricity consumers is a severe problem with respect to consumers' acceptance for the deployment of renewables. Thus, the regulator's objective to cut costs aims at equal burden sharing. We develop a uniform price auction which incorporates the regulator's objectives directly to determine the target quantity. The result is a flexible demand which evolves endogenously. This limits redistribution from electricity consumers to producers and enhances burden sharing. It provides a practical solution to the moral hazard problem as truthful bidding becomes a dominant strategy.

3.1 Model setup

Taking into account the considerations above the optimal demand for RES (q^*) should be chosen as to maximize the regulator's utility reflecting his trade-off. Let us consider n bidders. Each of them offers a certain quantity q_i for a price $p(q_i) := p_i$. All bids are sorted in ascending order. If we assume bidders 1 to l with $1 \leq l \leq n$ place successful bids, the resulting regulator's utility is

$$u_l = f(\chi_l, \varphi_l). \tag{1}$$

χ_l increases with the deployment of renewable energy reflecting the regulator's objective to promote RES. To account for technical restrictions, e.g. an immature grid, the regulator defines a maximum quantity q_{max} . Usually the maximum demand will not be binding ($q^* \ll q_{max}$) and thus it does not affect the clearing price. Using q_{max} for

normalization yields

$$\chi_l := \frac{\sum_{i=1}^l q_i}{q_{max}} \quad (2)$$

leading to $0 \leq \chi_l \leq 1$. φ_l , in contrast, decreases with increasing redistribution from consumers to producers. A reasonable measurement for redistribution is the generators' average return on sales which is given by the ratio of aggregated producers' surplus Π and their actual costs C . To capture that φ_l decreases with increasing return on sales, we define

$$\varphi_l := 1 - \frac{\Pi_l}{C_l} \quad (3)$$

leading to $0 \leq \varphi_l \leq 1$. To identify the utility maximizing quantity q^* , the regulator calculates u_l for $l = 1, 2, \dots, n$. Exactly this l which maximizes utility is denoted by l^* . It determines all successful bidders 1 to l^* . All bidders with higher bids than l^* are not being awarded (see example in Section 4). Thus, the equilibrium quantity is determined by

$$q^* = \min \left\{ q_{max}, \sum_{i=1}^{l^*} q_i \right\}. \quad (4)$$

This additionally enforces $q^* \leq q_{max}$. In the following we examine the most common case with non-binding q_{max} ($q^* < q_{max}$).³

Assuming l successful bidders, total promotion costs can be calculated as

$$C_l = p_l \sum_{i=1}^l q_i. \quad (5)$$

If each generator places a bid which equals his total costs, associated costs are

$$C_l^{gen} = \sum_{i=1}^l q_i p_i. \quad (6)$$

This would equal total promotion costs under pay-as-bid pricing if bidders bid truthfully. Subtracting the costs given in Eq. 6 from total promotion costs (Eq. 5) yields the aggregated producers' surplus

$$\begin{aligned} \Pi_l &= C_l - C_l^{gen} \\ &= \sum_{i=1}^l (p_l - p_i) q_i. \end{aligned} \quad (7)$$

The auction itself delivers all necessary information to calculate the regulator's utility.

³ The unlikely case that $\sum_{i=1}^{l^*} q_i > q_{max}$ results in a reverse auction with the target quantity being announced ex ante so that the following analysis would not be necessary.

Nevertheless, this system works properly solely if bidders bid truthfully.

3.1.1 Strategic bidding behavior

We first analyze incentives to overbid before assessing impacts of underbidding. Let us assume generator j does not place a bid which reflects his total costs but it has a mark up Δp_j . The generator's position will change from j to k with $k \geq j$, given bids are ordered from lowest to highest. The price will increase from p to \hat{p} for generators with position j to k while p remains unchanged for all other positions. To quantify the impact of overbidding we have to calculate the change in utility Δu caused by bidders changing positions. The difference in aggregated generators' costs is

$$\Delta C_l^{gen} = \sum_{i=1}^l (\hat{p}_i - p_i) q_i \quad (8)$$

The difference in total promotion costs equals

$$\Delta C_l = (\hat{p}_l - p_l) \sum_{i=1}^l q_i. \quad (9)$$

This yields under consideration of Eq. 7

$$\Delta \Pi_l = \Delta C_l - \Delta C_l^{gen}. \quad (10)$$

Combining Eq. 3 with Eq. 10 and rearranging produces

$$\Delta \varphi_l = \frac{\Delta C_l^{gen}}{C_l + \Delta C_l} - \frac{\Delta C_l}{C_l + \Delta C_l} \varphi_l. \quad (11)$$

$\Delta \varphi_l$ depends on the position of generator l with respect to generator j . We find

$$0 = \Delta C_{j-1} \leq \Delta C_j \leq \Delta C_{j+1} \leq \dots \leq \Delta C_k \geq \Delta C_{k+1} = 0 = \dots = \Delta C_n \quad (12)$$

and

$$0 = \Delta C_{j-1}^{gen} \leq \Delta C_j^{gen} \leq \Delta C_{j+1}^{gen} \leq \dots \leq \Delta C_k^{gen} = \Delta C_{k+1}^{gen} = \dots = \Delta C_n^{gen}. \quad (13)$$

All generators preceding generator j are not affected. Under consideration of Eq. 11, 12 and 13 we find

$$\Delta \varphi_{max} = \Delta \varphi_{k+1}. \quad (14)$$

Whether Eq. 14 simultaneously implies

$$\Delta u_{max} = \Delta u_{k+1} \quad (15)$$

depends on the underlying utility function. Increasing χ_l usually causes an increasing marginal utility with respect to φ_l . If $\Delta\varphi_l$ was constant for any $l > k$ this would mean a steadily rising additional utility Δu_l violating Eq. 15. However, $\Delta\varphi_l$ is decreasing for any $l > k$. The question is if this decrease is high enough to compensate the increasing marginal utility. Eq. 11 simplifies to

$$\Delta\varphi_l = \frac{\Delta C_k^{gen}}{C_l}, \quad \forall l > k \quad (16)$$

if Eq. 12 is taken into consideration. We define

$$\begin{aligned} \epsilon_{\Delta\varphi_l, \chi_l} &:= \frac{d\Delta\varphi_l}{d\chi_l} \frac{\chi_l}{\varphi_l}, \quad \forall l > k \\ &= -1. \end{aligned} \quad (17)$$

The elasticity indicates a proportional decrease of $\Delta\varphi_l$ for any increase in χ_l . Furthermore we define

$$\epsilon_{MU_\varphi, \chi_l} := \frac{dMU_\varphi}{d\chi_l} \frac{\chi_l}{MU_\varphi} \quad (18)$$

as elasticity of marginal utility MU_φ with respect to the input χ_l . This elasticity shows how the marginal utility of φ_l reacts to an increase of χ_l . A necessary condition to verify Eq. 15 is that the relative decrease of $\Delta\varphi_l$, which is caused by an increase of χ_l , overcompensates the respective relative increase of MU_φ . This means

$$-\epsilon_{\Delta\varphi_l, \chi_l} > \epsilon_{MU_\varphi, \chi_l}. \quad (19)$$

Since an increase from $l = k + 1$ to $l = k + 2$ does not only lead to an increase in χ_l but also to simultaneously decreasing φ_l in most cases

$$\epsilon_{\Delta\varphi_l, \varphi_l} > -\epsilon_{MU_{\chi_l}, \varphi_l} \quad (20)$$

is the second necessary condition to verify Eq. 15. The relative decrease of $\Delta\varphi_l$, which is caused by a decrease of φ_l , has to overcompensate the respective relative increase of MU_φ .

The less concave a utility function the lower is the impact of χ and φ on the change of marginal utilities. Thus, less concavity increases the likelihood to fulfill Eq. 15. A

CES utility function contains the whole range of concavity from perfect substitutes to perfect complements. Applying Eq. 19 and 20 to a CES utility function $u_l = [\alpha\varphi_l^\theta + \beta\chi_l^\theta]^{1/\theta}$ with $\alpha + \beta = 1$ yields

$$\alpha\varphi_l^\theta + \theta\beta\chi_l^\theta + (1 - \theta)\beta\chi_l^\theta \frac{\chi_l}{\varphi_l} \frac{d\varphi_l}{d\chi_l} > 0 \quad (21)$$

$$\alpha\varphi_l^\theta + \theta\beta\chi_l^\theta > 0 \quad (22)$$

as necessary conditions. Eq. 21 is always met for positive θ since all three terms are positive in this case. This simultaneously fulfills Eq. 22. Thus for any CES utility function with an elasticity of substitution $\sigma = \frac{1}{1+\theta} \geq 1$ (including the Cobb-Douglas case) Eq. 15 is met.

Eq. 15 implies that for any $k < l^*$ we get $\hat{q}^* \leq q^*$ and $\hat{p}^* \leq p^*$ respectively. In contrast to a pay-as bid auction, a rational bidder has no incentive to overbid in this auction design, as he harms himself. An advantage for bidder j may only occur if he increases the bid slightly above the clearing price ($k \geq l^*$) and if at the same time

$$\Delta u_{max} > u_{l^*} - u_k \quad (23)$$

holds. However, neither the clearing price nor the behavior of the utility function in the area of the clearing price is known. For this reason it is very risky for a generator to bid a higher price than his costs, as he might dismiss or at least harm himself. This risk even increases if bidder j considers that other bidders may also set bids above their real costs. Thus, our mechanism is robust against overbidding.

What about underbidding? Fossil power plant generators have an incentive to participate in the auction even though they do not intend to realize a project. Their only motivation is to perform price dumping by submitting a low bid and squeezing out RES projects. This protects profits of fossil power plants because of lower electricity generation by renewables and higher electricity prices at the spot market. We investigate this issue and assume a fossil generator places a bid below the clearing price. Thus, the generator will be at position j with $j < m$. In this case, we find

$$0 = \Delta C_{j-1} \geq \Delta C_j \geq \Delta C_{j+1} \geq \dots \geq \Delta C_{n+1} \quad (24)$$

and

$$0 = \Delta C_{j-1}^{gen} \geq \Delta C_j^{gen} \geq \Delta C_{j+1}^{gen} \geq \dots \geq \Delta C_{n+1}^{gen}. \quad (25)$$

The behavior of ΔC and ΔC^{gen} does not allow a clear statement about the impact of

underbidding with respect to the regulator's optimal demand. Demand may slightly increase or decrease depending on other generators' bids. The behavior of q^* cannot be anticipated by a generator who wants to manipulate it. In a reverse auction with fixed demand an artificially low bid would exactly displace the quantity that is assigned to his own bid. In our framework both is possible, an (over)compensation of the replacement (q^* increases) or even an additional displacement (q^* decreases). Our mechanism does not prevent underbidding but it increases uncertainty of the outcome for agents of type B . Nevertheless, underbidding can be treated by certain conditions for admission (see Section 4).

3.1.2 Extensions

Modeling redistribution proportional to the ratio of producers' surplus and total costs is plausible. The ratio corresponds to the average return on sales and can be interpreted as degree of redistribution. The higher the degree of redistribution the lower the regulator's utility. Nevertheless, it does not limit return on sales to a certain absolute limit. If the average return on sales shall be restricted to less than a certain ratio x , Eq. 3 can be rewritten as

$$\varphi_l := 1 - \frac{\Pi_l}{C_l x} \quad (26)$$

leading to

$$u_l = f(\chi_l, \max\{0, \varphi_l\}). \quad (27)$$

The analyses in Section 3.1.1 also hold for this extension.

An analogous adjustment also allows to replace the objective of low redistribution by low total costs. Instead of a ratio between producers' surplus and total costs we use the ratio between total costs and maximal total costs

$$\tilde{\varphi}_l := 1 - \frac{C_l}{C_{max}}. \quad (28)$$

If we assume that a generator j increases his bid by Δp_j , Eq. 12 is the result while Eq. 13 does not play a role anymore. Thus, there is no impact on the clearing price if $k < l^*$. Instead of a disincentive for overbidding as described in Section 3.1.1 the generator is indifferent in this framework. Besides this the analyses of Section 3.1.1 hold for this extension, too. We suggest to apply the return on sales as described in Section 3.1.

3.2 Optimized deployment of renewables

Wind conditions are decisive for generators' revenue if remuneration is generation-based. Therefore best locations will be chosen first, but sites of poorer quality will be chosen in the long run, too. There are two main reasons why the comparative advantage of projects with best sites should be attenuated.

First, wind conditions are important, but not the only criteria for using wind turbines efficiently. A windy region is not necessarily a region of high electricity demand and grid capacity might be tight. High additional electricity supply in this region may endanger grid stability whereas grid extensions are costly. Though this finding is not new, intermittent electricity generation exacerbates it. Thus, grid capacity should also play a role for awarding contracts.

Second, if a high share of RES is essential in the long run (take for instance the EU's objectives for emission reduction) focusing on best locations will not be sufficient in the long run. Hence, less favorable sites will be used in the future anyway. The expansion of promotion to a broader range of wind conditions can be seen as the anticipation of future developments. This may be advantageous since a development which is only driven by lowest marginal abatement costs does not necessarily lead to an optimal solution (Vogt-Schilb and Hallegatte, 2014) because of dynamic effects (e.g. learning by doing) which cause a change of marginal abatement costs. For instance, wind projects were also built at less favorable sites in the last decade. This has enabled a technological progress on a wider basis resulting in a technology tailor-made for less wind. This valuable progress would not have been possible with the promotion of solely best sites.

In line with the arguments stated above, most FiTs are graded regarding wind conditions. Less windy locations receive a slightly higher remuneration, whereas improper locations are excluded from promotion. In Germany the graduation is achieved referring to the so-called reference yield model which relates the electricity output of a wind turbine to its specific reference yield. Depending on the ratio of electricity output and reference yield the remuneration is adjusted. The reference yield can be easily calculated assuming certain wind conditions.

An undifferentiated auction abolishes this graduation. However, different auctions can be held for different wind classes referring to a modified reference yield model. Respective forecasts have to be used instead of output data since the information must be available before the wind turbine is built. In Germany two certified forecasts of

the electricity yield of planned wind turbines are usually necessary to be granted a loan. To discourage agents of type B from participating in the auction, wind yield reports should be a necessary precondition for participation anyway. The ratio of electricity output and reference yield determines the auction group a project belongs to. This yields nn groups. Competition among projects takes place within a group but not between. Note that the agent has no incentive to manipulate the wind yield. A lower wind yield would allow access to a group with a potentially higher clearing price. However, a low wind yield means poorer conditions for a loan.

Total maximum utility is the sum of each group's utility maximum

$$u_{max} = \sum_{ii=1}^{nn} u_{ii,max}. \quad (29)$$

The introduction of groups does not change the analysis of this section in general. It is not necessary to define q_{max} for each of the nn groups because the problem is just a maximization of total utility u subject to $\sum_{ii=1}^{nn} q_i^* \leq q_{max}$. Thus, the marginal utility

$$MU_{ii,i} = \frac{u_{ii,i} - u_{ii,i-1}}{q_{ii,i} - q_{ii,i-1}} \quad (30)$$

is decisive. The group with the lowest utility loss should be the first to face reductions in demand if necessary. This procedure continues until the constraint is satisfied.

Holding different auctions with respect to the ratio of electricity output and reference yield results in price differentiation. This increases competition within groups. In an undifferentiated auction additional rents would occur for best sites.

3.3 Consideration of grid congestion and generating capacity

In contrast to conventional power plants electricity generation from renewable energy sources is often decentralized. This saves money since it relieves the transmission grid. In Germany a procedure exists to calculate avoided grid costs by decentralized energy supply (VdN, 2007). For the calculation of difference costs in the presence of FiTs, avoided grid costs are not published for every renewable power plant so far. Anyway, assigning avoided grid costs to each power plant is easily feasible if the power plant's grid connection point is known. Individual avoided grid costs p_i^{grid} consider adjacent grid capacity of each renewable energy project.

Not only grid capacity but also electricity demand may vary a lot within a country or

region. Solar and wind power plants cannot deliver electricity on demand because of their dependency on weather. They cannot guarantee security of supply, but at least they contribute since the probability of a scarcity event decreases with an increase in renewable capacity. It is sensible to establish renewable energy capacity particularly in regions with low generating capacity to reduce supply shortages. This requires a regional valuation of generating capacity which can be realized in two different ways.

First, the central spot market may be organized regionally which leads to different spot prices p_{spot} , if the grid connecting two regions is congested. In this case the average spot price will vary and thus influence the difference cost of each project individually.

Second, a capacity market can be organized regionally to reveal information about regional scarcity of capacity in the absence of regional spot markets. The regulator just needs to define regional capacity targets. This results in a region-specific capacity price p_{ij}^c with ij indicating the region. Dividing the capacity price by the 8760 hours of a year results in capacity payments per electricity unit (kWh or MWh)

$$\tilde{p}_{ij}^c = \frac{p_{ij}^c}{8760}. \quad (31)$$

This implies that a wind turbine with high output has a higher probability of contributing to security of supply than one with lower output. Furthermore a capacity market attenuates the merit order effect, as decreasing spot prices are balanced by increasing capacity prices (Schäfer and Schulten, 2014). This allows the assessment of true difference costs p' while the merit order effect causes distortions at the spot market, hence distorting difference costs. Eventually difference costs instead of the generator's bid should be decisive for the regulator. They can be described by

$$p'_{ii,i} = p_{ii,i} - \bar{p}_{spot} - p_{ii,i}^{grid} - \tilde{p}_{ij}^c \quad (32)$$

with \bar{p}_{spot} as average spot market price and $p_{ii,i}$ as price bid of generator i in region ii .

4 Recommendations for implementation

In reverse auctions the auctioneer is not able to distinguish different types of bidders ex ante. Since only bidders of type G should participate in the auction, the auction process must be designed to be self-selective in the sense that type B has no incentive

to participate at all. These disincentives are present in the form of admission requirements before the auction takes place. Strategic bidding behavior in the auction is then limited by replacing exogenously given demand for renewables with endogenously derived optimal demand. For optimal deployment of renewable energy it might be useful to hold regionally differentiated auctions (see Section 3.2 and 3.3 which is possible with our design.

Admission

The analysis in Section 3.1.1 illustrates that bidders are discouraged to overbid while the extension introduced in Section (3.1.2 shows no incentives to overbid. There may, however, be incentives for underbidding. On the one hand, this is advantageous for fossil power plant generators to hamper the deployment of renewable energy. On the other hand, experience with tenders emphasizes problems with participants who only speculate with selling permits. They can be seen as a mild sub-type of type B agents. Thus, in some tenders a deposit is demanded from every bidder to avoid this behavior. However, this is also an obstacle for bidders of type G . Since it is easier to overcome for big players than for small ones, it represents entry-deterrence and hampers competition.

We do not recommend a deposit, but the demonstration of all necessary construction permits, operating licenses and two certified wind yield reports for admission. Since these are necessary requirements for project realization anyway, small projects are not discriminated against. The main drivers for project realization are not costs in monetary terms, but costs in terms of time. To gather all necessary documents is a time-consuming and challenging process. Moreover participation in the auction should require a reasonable minimum value for the ratio of electricity output and reference yield as it restricts the number of sites to the economically sensible sites. With less available sites competition increases which blocks agents of type B .

The grid connecting point should also be demanded for admission because it is necessary to evaluate the grid properties of a project. The grid operator is able to assess expected avoided grid costs of a project if he knows the grid connecting point and the wind yield. That is why these should be included in the pre-qualification requirements as well.

Contracts for differences

Some reverse auctions make use of penalties if RES deliver more or less electricity than contracted (Porrua *et al.*, 2010). More attempts exist to control the electricity production by renewables better. Germany for example debated whether renewables should be responsible for balancing their energy supply with demand. These suggestions are useless as they put renewable energy at disadvantage when compared to fossil energy. A lignite power plant for example does not have an intermittent electricity generation, but it does not follow load perfectly either. If every power plant is responsible for balancing energy itself, the result cannot be more efficient than a market solution as provided by the market for balancing energy.

Neglecting ramping costs, a lignite power plant delivers electricity as soon as the spot price is above its operating costs. A well-designed market for renewable energy should provoke the same behavior for renewables. This is achieved by offering CfDs instead of FiTs. Thus, a generator who placed a successful bid does not receive a price per electricity unit, but the difference between his bid and the average electricity spot price weighted by the electricity generation of wind power plants. This ensures the generation of electricity only if the spot price is higher than operating costs of the generator.

Optimal demand

A tendering system is supposed to promote renewable energy on the one hand and improve burden-sharing on the other hand. We recommend a reverse auction based on a demand function which maximizes utility for the regulator with respect to these two objectives. In that way welfare losses as a result of sub-optimal demand are eliminated. Moreover it prevents overbidding.

The relative importance of both objectives can be expressed by assigning weights in the utility function. If the weight for low redistribution is set to zero this objective is not considered. Only the deployment of RES matters then as generally the case with FiTs. Hence, our system allows a smooth transition from FiTs to tenders by adjusting the weights. This is advantageous, since a gradual change is accompanied by higher regulatory certainty.

Regional adjustment

Section 3.2 provides arguments for a differentiated auction design. Such a differentiation is feasible in our setup as demand is endogenous. The consideration of individual grid and generating capacity leads to respective discounts for bids resulting from regional capacity prices \tilde{p}_{ij}^c and individual avoided grid costs $p_{ii,i}^{grid}$. A higher bid in a region with low generating and high grid capacity may be preferred to a cheaper one located where more electricity production is not needed. According to Eq. 32 difference costs $p'_{ii,i}$ are decisive for the regulator. Since this is just a static approach the outcome may change if for instance grid capacity is extended. However, the mechanism would consider such changes in grid capacity. In Tab. 1 we demonstrate our procedure in an example for the first of nn groups in Germany.

i	$q_{1,i}$ [GWh]	$p_{1,i}$	\bar{p}_{spot}	\tilde{p}_{ij}^c	$p_{1,i}^{grid}$	$p'_{1,i}$	φ_l	$u_{1,l}^{\alpha=0.5}$	$u_{1,l}^{x=0.1}$	$u_{1,l}^{\alpha=0.8}$
2	320	80.96	35.09	4.07	5.26	36.54	1.000	0.170	0.170	0.493
1	110	80.43	35.09	1.51	4.43	39.40	0.952	0.205	0.151	0.515
4	300	83.19	35.09	1.51	5.83	40.76	0.953	0.266	0.197	0.571
7	290	84.69	35.09	5.95	2.57	41.08	0.959	0.310	0.244	0.610
3	150	83.06	35.09	4.07	2.05	41.85	0.956	0.355	0.272	0.643
8	160	86.96	35.09	5.95	3.41	42.51	0.953	0.398	0.297	0.672
6	340	84.27	35.09	1.51	2.72	44.95	0.906	0.397	0.102	0.651
5	80	84.02	35.09	1.51	1.76	45.66	0.901	0.414	0.043	0.660
9	260	89.24	35.09	4.07	3.40	46.68	0.888	0.422	0.000	0.660
10	100	89.76	35.09	1.51	2.97	50.19	0.834	0.419	0.000	0.634

Table 1: Example of the auction outcome of group 1 with individual quantities $q_{1,i}$ and bids $p_{1,i}$. Subtracting the average spot price \bar{p}_{spot} , regional-specific capacity price \tilde{p}_{ij}^c and individual avoided grid charges $p_{1,i}^{grid}$ yields the adjusted bid price $p'_{1,i}$ resulting in adjusted utility $u_{1,l}(p')$. The results for different parameters of the utility function are given in the last three columns. $u_{1,l}^{\alpha=0.5}$ means $\alpha = \beta = 0.5$, $u_{1,l}^{x=0.1}$ additionally considers $x = 0.1$ while $u_{1,l}^{\alpha=0.8}$ means $x = 0$ but $\alpha = 0.8, \beta = 0.2$. All prices in €/MWh. The highest utilities are given in bold.

We suggest a Cobb-Douglas utility function with $u_l = \varphi_l^\alpha \chi_l^{1-\alpha}$. Tab. 1 shows data for ten virtual bidders ranked by increasing adjusted bids $p'_{1,i}$. For demonstration purposes we constrain to ten bidders although in reality more bidders with smaller generation capacities are more likely. This does not harm the general functioning of our mechanism. The amount of electricity generators offer in the auction is captured by $q_{1,i}$. The defined maximum quantity q_{max} is assumed to equal 10 TWh which is about 1.5 % of annual gross electricity generation in Germany.⁴ Individual price

⁴ The actual number is not crucial for our mechanism as long as $q_{max} < q^*$. It is just a matter of calibration.

bids are $p_{1,i}$ in €/MWh. The group analyzed in our example consists of projects with lower wind yields. Currently this means a feed-in tariff of nearly 90 €/MWh in Germany. Therefore bids are given by random numbers between 80 and 90 €/MWh in our example.

We use spot market data for Germany. There is just one spot market, hence solely one national spot price. The expected average spot price \bar{p}_{spot} is approximated by its future (Phelix Base Year Future) that is traded at the Energy Exchange (EEX). We use the average price of the future in 2014 for an electricity supply in 2015 which amounts to 35.09 €/MWh (EEX, 2015).

Germany did not yet introduce a capacity market. Nevertheless we assume a regional capacity market to illustrate our model. A capacity market compensates possible funding shortfalls of an energy-only market which are called missing money in this context. In particular the promotion of renewable energy may cause such shortfalls as spot prices decrease because of the merit order effect. According to Sensfuß (2013) the merit order effect of renewable energy amounted to 8.91 €/MWh in 2012. If the market was in an equilibrium before renewables were introduced this amount would equal missing money. Based on this analysis and accounting for possible adjustments of the power plant mix we assume 5 €/MWh as the average missing money. To get different values for \tilde{p}_{ij}^c we calculate random numbers between 0 and 1. These are assigned to the probabilities of a slightly skewed log-normal distribution ($\sigma = 0.5$) since this distribution restricts \tilde{p}_{ij}^c to positive values. Without a regional capacity market \tilde{p}_{ij}^c equals zero. The values of \tilde{p}_{ij}^c are anyway not decisive since it just serves as illustration.

The grid operator can calculate avoided grid charges $p_{ii,i}^{grid}$ for every bidder using power plants' expected electricity yield and their grid connecting point (both communicated by bidders in line with admission requirements). In 2013 average avoided grid costs for promoted onshore wind power amounted to 3.27 €/MWh in Germany. For our example we again assume a log-normal distribution with a low skewness ($\sigma = 0.5$). Assigning random numbers between 0 and 1 to the probabilities of the distribution yields reasonable values for $p_{1,i}^{grid}$.

All these components are needed to calculate the adjusted price bid for every participant $p'_{1,i}$ according to Eq. 32. Tab. 1 presents adjusted price bids in ascending order while i indicates the order of original bids. In our example adjusted price bids lead to a new order of power plants (see Fig. 3). The utility is calculated based on these adjusted price bids. The last three columns of our table show the utility that every

single power plant delivers given that power plant l is price setting. The columns differ in parameters of the used Cobb-Douglas utility function. $u_{1,l}^{\alpha=0.5}$ means an equal weight of φ_l and χ_l since α and β equal 0.5. The regulator's demand is determined by the quantity that provides highest utility. Thus, power plant 9 is price setting in this example. This result holds for any $\sum_{ii=1}^{nn} \sum_{i=1}^n q_{ii,i} \leq q_{max}$ and is depicted in Fig. 3.

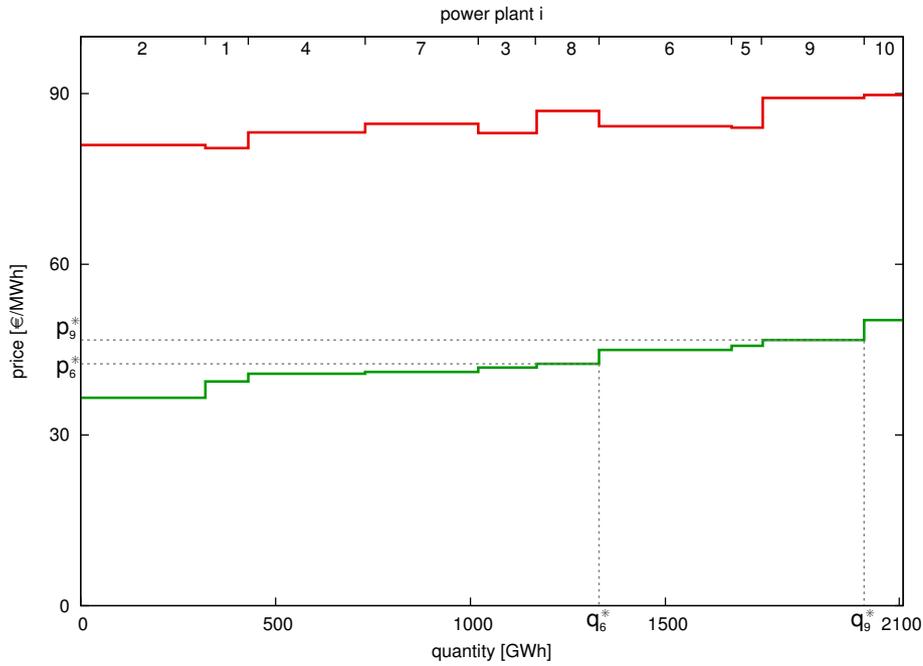


Figure 3: Visualization of the result of Tab. 1. Adjusted bid prices p'_i lead to a new order of bids. Choosing $\alpha = \beta = 0.5$ the optimal quantity $q_9^* = \sum_{i=1}^9 q_i$ is determined by maximum utility so that bidder 10 is not awarded. Introducing $x = 0.1$ or $\alpha = 0.8$ leads to an optimal quantity q_6^* .

The example shows $\varphi_9 = 0.888$ for the price setting bidder 9. This means an average return on sales of 11.2 %. However, the average return on sales could be limited using Eq. 26. Choosing $x = 0.1$ restricts the average return on sales to *less* than 10 %. Leaving $\alpha = 0.5$ the respective utilities are given by $u_{1,l}^{x=0.1}$ in the next-to-last column of Tab. 1. Then only the first six generators place successful bids leading to an average return on sales of about 4.7 %. A higher emphasis on φ eventually yields the same result in this example. Results for $\alpha = 0.8$ are given in the last column.

The auction should take place once every year. First, to ensure sufficient competition resulting from many participating bidders. Second, it guarantees that speculation costs are sufficiently high. That is to say a bidder who can participate in the auction several times a year, is more likely to overbid and take the risk of not being awarded. A successful bidder gets a CfD which is valid for 20 years to reduce uncertainty. To seek for a timely realization of projects the contract should expire if there was no

realization within three years. If the bidder is not responsible for the delay of his project an extension of the 3-year period shall be possible. A successful bidder is not allowed to take part in the auction with the same project again.

If renewable energy is competitive with fossil energy at some point in the future our auction design does not lead to welfare losses, since CfDs might be zero or even negative. The participation of RES projects in the auction may still be sensible because of the certainty it delivers as the 20-year contracts reduce spot price risks and stabilize income.

5 Conclusions

Reverse auction designs mainly differ in pricing rules, eligibility criteria, product definitions and penalties. Some commonalities are generation-based payments and auctioning off a predetermined quantity. In our model quantities are not defined ex ante, but they result from the trade off between increasing the share of renewables and an improved burden-sharing.

This is achieved by the introduction of a utility function which depends on both objectives. Demand of the regulator is determined by the utility maximum, so it is flexible. Our analysis shows disincentives for overbidding. This solves the moral hazard problem and allows to limit producer rents while true bidding is incentivized. This makes our design superior to other auction designs, in particular when compared to a pay-as-bid auction.

In contrast, underbidding may not be prohibited by flexible demand in all cases. It depends on other bidders' behavior. However, pre-qualification requirements such as construction permits, operating licenses and wind yield reports can solve this adverse selection problem. Flexible demand allows a straightforward differentiation of the auction in terms of wind yields, since there is no necessity to define further target quantities. Grid and generating capacities are considered by individual or regional discounts. This is an advantage in comparison to FiTs as it accounts for more characteristics. Our mechanism allows a smooth transition from FiTs or CfDs to reverse auctions.

We argue that the use of a reverse auction may still be beneficial as soon as RES become competitive. However, we do not provide a detailed analysis for this scenario which could be done in future work. Future research could also discuss how capacity

markets and tenders will interact in the future. Finally the peculiarities of other intermittent renewables (e.g. solar) could be considered.

References

- AKERLOF, G. A. (1970). The Market for “Lemons”: Quality Uncertainty and the Market Mechanism. *The Quarterly Journal of Economics*, **84**, 488–500.
- ARROW, K. J. (1985). *Principals and Agents: The Structure of Business*, Boston: Harvard Business School Press, chap. 2: The Economics of Agency, pp. 37–51.
- BATLLE, C., PÉREZ-ARRIAGA, I. J. and ZAMBRANO-BARRAGÀN, P. (2012). Regulatory Design for RES-E Support Mechanisms: Learning Curves, Market Structure, and Burden-Sharing. *Energy Policy*, **41**, 212–220.
- BOUTE, A. (2012). Promoting Renewable Energy through Capacity Markets: An Analysis of the Russian Support Scheme. *Energy Policy*, **46**, 68–77.
- BUNDESNETZAGENTUR (2015). Vorläufige Ergebnisse der ersten Ausschreibungsrunde für Photovoltaik (PV) – Freiflächenanlagen vom 15. April 2015. Available at: http://www.bundesnetzagentur.de/SharedDocs/Downloads/DE/Sachgebiete/Energie/Unternehmen_Institutionen/ErneuerbareEnergien/PV-Freiflaechenanlagen/Gebotstermin_15_04_2015/Hintergrundpapier_PV-FFA_Runde1.pdf?__blob=publicationFile&v=1, accessed 5 June 2015.
- DEL RIO, P. and LINARES, P. (2014). Back to the Future? Rethinking Auctions for Renewable Electricity Support. *Renewable and Sustainable Energy Reviews*, **35**, 42–56.
- EEG (2014). Erneuerbare-Energien-Gesetz vom 21. Juli 2014 (BGBl. I S. 1066). Available at: http://www.gesetze-im-internet.de/bundesrecht/eeg_2014/gesamt.pdf, accessed 5 June 2015.
- EEX (EUROPEAN ENERGY EXCHANGE) (2015). Phelix Base Month Future. Available at: <https://www.eex.com/de/marktdaten/strom/terminmarkt/phelix-futures#!/2015/06/05>, accessed 5 June 2015.
- ELIZONDO AZUELA, G., BARROSO, L. A. and CUNHA, G. (2014). Promoting Renewable Energy through Auctions: The Case of Brazil. In *Live Wire*, The World Bank, vol. 13.

- GRIMM, V., OCKENFELS, A. and ZOETTL, G. (2008). Strommarktdesign: Zur Ausgestaltung der Auktionsregeln an der EEX. *Zeitschrift für Energiewirtschaft*, **32**, 147–161.
- HARBORD, D. and PAGNOZZI, M. (2014). Britain’s Electricity Capacity Auctions: Lessons from Colombia and New England. *The Electricity Journal*, **27**, 54–62.
- KLEMPERER, P. (2002). What Really Matters in Auction Design. *The Journal of Economic Perspectives*, **16**, 169–189.
- MASTROPIETRO, P., BATLLE, C., BARROSO, L. A. and RODILLA, P. (2014). Electricity Auctions in South America: Towards Convergence of System Adequacy and RES-E Support. *Renewable and Sustainable Energy Reviews*, **40**, 375–385.
- MILGROM, P. R. (2004). *Putting Auction Theory to Work*. Cambridge: Cambridge University Press.
- MITCHELL, C. and CONNOR, P. (2004). Renewable Energy Policy in the UK 1990–2003. *Energy Policy*, **32**, 1935–1947.
- PORRUA, F., BEZERRA, B., BARROSO, L. A., LINO, P., RALSTON, F. and PEREIRA, M. (2010). Wind Power Insertion through Energy Auctions in Brazil. In *Proceedings of the IEEE General Meeting*, Minneapolis.
- REN21 (2014). Renewables 2014. Available at: http://www.ren21.net/Portals/0/documents/Resources/GSR/2014/GSR2014_full%20report_low%20res.pdf, accessed 5 June 2015.
- SCHÄFER, S. and SCHULTEN, L. (2014). *A Market Design to Improve the Transition towards Sustainable Electricity Generation*. Working Paper 39, MAGKS Joint Discussion Paper Series in Economics.
- SENSFUSS, F. (2013). Analysen zum Merit-Order Effekt erneuerbarer Energien. Available at: http://www.impres-projekt.de/impres-wAssets/docs/Merit-Order-2012_final.pdf, accessed 5 June 2015.
- SENSFUSS, F., RAGWITZ, M. and GENOESE, M. (2008). The Merit-Order Effect: A Detailed Analysis of the Price Effect of Renewable Electricity Generation on Spot Market Prices in Germany. *Energy Policy*, **36** (8), 3086–3094.
- VDN (VERBAND DER NETZBETREIBER) (2007). Kalkulationsleitfaden §18 Strom-NEV. Available at: https://www.bdew.de/bdew.nsf/id/DE_VDN-Kalkulations

leitfaden_18_StromNEV/\$file/2007-03-03_VDN-Kalkulationsleitfaden%
20%20%20%C2%A7%2018%20StromNEV.pdf, accessed 13 November 2014.

VOGT-SCHILB, A. and HALLEGATTE, S. (2014). Marginal Abatement Cost Curves and Optimal Timing of Mitigation Measures. *Energy Policy*, **66**, 645–653.