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Cream-skimming through PPAs - Interactions between private and public long-term contracts for renewable energy

Mats Kröger*

July 16, 2024

Abstract

Public support systems and private investments in renewable energy are increasingly existing side-by-side and are both emphasized in policy proposals on the European and national levels. This paper assesses the interaction between the two approaches with respect to cream-skimming, i.e., the potential for low-cost projects to sign private contracts that increase the costs of publicly supported renewable energy. This paper uses a stylized microeconomic model and a numerical simulation to assess this question. It finds that the incentive to cream-skimming exists when governments employ any form of resource differentiation in their renewable energy contracts. The numerical analysis shows that, at current price levels, cream-skimming could increase power prices by 2-6% depending on the PPA's mark-up. The effect is larger for a wider cost-distribution of renewable energy projects, which might occur as the energy transition proceeds.

Keywords: climate policy, renewable energy, distributional consequences, cream-skimming, contracts for differences

JEL Codes: D44, Q42, Q48

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1 Introduction

Long-term contracts play an important role in the financing of the renewable energy transition since solar and wind energy have high investment costs but low operational costs. By fixing a price for the produced electricity, long-term sales contracts "derisk" the investment into a renewable energy plant because they allow for predictable revenue streams and thereby improve financing conditions (i.e., reducing financing costs) (May and Neuhoff, 2021, Đukan and Kitzing, 2023). The improved financing conditions directly reduce the costs of the energy transition for electricity consumers and society at large. Thus, even though carbon prices should, in theory, suffice and be the first-best option to induce sufficient renewable energy investment (Kalkuhl et al., 2013, Gugler et al., 2021), policy intervention can serve to reduce the uncertainty of renewable energy investments. Additionally, support schemes remain necessary because the learning curve effects of investing in innovative technology are steep, and structural change is needed but reacts slowly to marginal pricing (Hepburn et al., 2020, Tvinnereim and Mehling, 2018).

There are two options for signing these long-term contracts. On the one hand, there is a growing consensus that contracts for differences ("CfDs") signed with public entities are the policy instrument of choice for such a derisking of the energy transition. In their most simple form, CfDs define a strike price that is guaranteed for the electricity produced by a renewable energy plant (hereafter "the producers" of electricity). Whenever the market price for electricity is below the strike price, the government agency pays the producer the difference. Meanwhile, at high market prices, the producer has to pay back the difference to the counterparty.¹ On the other hand, many sectors of the economy are looking to electrify their processes since this is, in many cases, a prerequisite for the green transition. Therefore, industrial companies (hereafter "the consumers" of electricity) have an increasing interest in insuring their cost structures against fluctuations in power prices as the importance of electricity as an input factor grows. To provide such insurance, the European Union has called for the conditions of CfDs to be passed on to consumers so that both sides of the market are hedged against power price fluctuations (European Commission, 2023). An alternative for policymakers looking to alleviate pressure on public budgets while increasing the speed of the energy transition is the promotion of private power purchasing agreements (hereafter "PPAs"), i.e., bilateral long-term contracts between electricity consumers and producers that privately derisk the investment into renewable energy plants and reduce electricity price risk for the off-taker. The European Commission sees the strengthening of PPAs as the second pillar of increasing the use of renewable electricity (European Commission, 2023).

¹See Kröger and Newbery (2024) for a detailed discussion of CfD design options.

The co-existence of these two systems of private and public long-term contracts for renewable energy is a novel and little-understood relationship that poses important questions to researchers. One crucial relationship in this regard is the incentives for leaving the public system towards private contracts. It is important to understand the distributional effects of the emergence of a private alternative to public renewable energy support. In this paper, I show that the presence of a private alternative leads to an increase in the costs of the public long-term contracts through "cream-skimming", i.e., the switching of the lowest cost projects into the private alternative. The analysis also shows that cream-skimming is harmful even to some consumers that leave the public system - as the marginal incentives for cream-skimming do not align with consumers' *ex-ante* preferences between the two options of a private system and a combination of public and private renewable energy finance. The analysis of potential remedies to cream-skimming shows that taxing the cream-skimmers can lead to a more efficient outcome. The subsequent numerical analysis quantifies that the outside option of bilateral contracts would lead to an increase of electricity costs of 2-6% in public support auctions for onshore wind energy in Germany. The paper shows that the share of firms leaving for the outside options depends on the cost mark-up of bilateral contracts in comparison to the public system, as well as the cost difference between renewable energy projects. Thus, while the incentive for cream-skimming exists, it is of moderate size. The effect is larger at higher levels of price discrimination and a wider cost distribution of projects that might arise as the energy transition proceeds.

The paper relates to three main strands of the literature. First, it relates to the theoretical, microeconomic literature on cream-skimming that explores the mechanism and its effect on the provision of public or network goods (Armstrong, 1999, Laffont and Tirole, 1990) and its relation to the cross-subsidization of consumer groups (Faulhaber, 1975). Most related to this analysis is the application in the field of finance showing that cream-skimming by over-the-counter trading hurts consumers trading at exchanges (Bolton et al., 2016). Second, the paper's application to the field of renewable energy relates to the literature on the design of renewable energy support and derisking programs, especially in the context of auction rules that involve differentiation between projects of different technology or resource quality (May, 2017, Fabra and Montero, 2023, Kröger et al., 2022) and the design of CfDs (Newbery, 2023, Favre and Roques, 2023, Veenstra and Mulder, 2024, Schlecht et al., 2024). Finally, the paper relates to the literature on electricity market liberalization (Newbery, 1999, Clifton et al., 2011), the role of the state in the financing of the renewable energy transition (Mazzucato and Semieniuk, 2018, Polzin and Sanders, 2020, Krebs, 2023), the question of how electricity prices develop under increased market liberalization (Erdogdu, 2011, Dormady et al., 2019), and the potential of private capital to finance the energy transition (Polzin and Sanders, 2020).

The paper's main contribution is twofold. First, the paper highlights a novel element of the energy transition: The interaction between private and public systems for financing renewable energy. By introducing the concept of cream-skimming to this subject, the paper makes an important contribution to the policy discourse on renewable energy support systems. The results should inform the EU policy design by considering the negative effect that cream-skimming has on the remaining electricity consumers. Second, the microeconomic model adds to the economic literature on cream-skimming, bypass, and cross-subsidization by applying it to a new subject, the generation of renewable electricity and its distribution among economic actors. It shows how financing costs, stemming from the risk exposure of long-term electricity purchase contracts, can lead to a cream-skimming incentive and present different solution options, such as taxing the cream-skimmers.

The remainder of the paper is structured as follows. Section 2 introduces the institutional background of renewable energy support via public procurement through auctions and power purchasing agreements. Section 3 reviews the economic concept of cream-skimming. Section 4 introduces the microeconomic model and shows the effects of cream-skimming on the public contract system for renewable energy. Section 5 presents the results from the numerical analysis. Section 6 concludes.

2 Institutional setting

At the beginning of the commercial deployment of renewable energy in the 1990s and 2000s, both wind and solar energy were unable to compete in liberalized wholesale markets with traditional forms of energy production due to their high levelized cost of electricity (LCOE).² However, subsequently, renewable energy saw a fast cost decrease due to economies of scale, learning, and technological progress such that they have now reached cost parity with both new and existing conventional generation plants or might even be less expensive (Kost et al., 2021). This development has changed the way that governments support renewable energy from direct subsidies to the so-called "derisking" approach. Contrary to traditional subsidies, such derisking is meant to be budget neutral for governments, as it ensures a secure remuneration level for installations but at the same time leads to the pay-back of revenues above this level in high-price periods (Beiter et al., 2024). Derisking a project's revenue stream significantly reduces its financing costs and, thereby, the costs of the energy transition (Đukan and Kitzing, 2023). CfDs derisk

²For instance, between 1985 and 2021, the average levelized costs of electricity for onshore wind power in Germany fell by 58%. Even more rapidly, the price of solar energy in Germany fell by 56% between 2013 and 2021 (International Renewable Energy Agency, 2022).

investments through a long-term contract that specifies a strike price paid for electricity in each period. Since such a two-sided design captures excess revenues in periods of high electricity prices, it can reduce the necessary support payments. For instance, the German policy of a "one-sided CfD" (also called "sliding premium") led to large windfall profits for renewable energy producers during the energy crisis that could have been prevented by a two-sided CfD design (Richstein et al., 2022). Passing on the conditions of such contracts to consumers has the double dividend of insuring both sides of the market against fluctuations in energy expenditure while leaving the price signals of the energy market intact (Neuhoff et al., 2023). CfDs can be combined with differentiated support levels based on the resource quality of renewable energy sites to reduce windfall profits that otherwise increase the cost of the energy transition (Kröger et al., 2022).

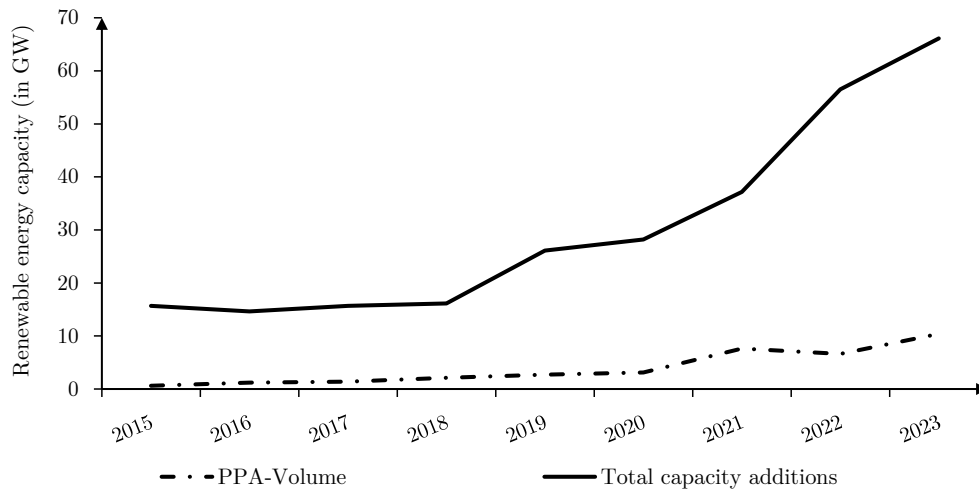
The falling generation costs have not only changed the way that governments support the energy transition but have also enabled consumers to directly contract renewable energy through so-called private power purchasing agreements (PPAs). PPAs allow electricity consumers to fulfill their corporate sustainability targets while hedging their energy costs against wholesale market volatility over long periods (Gabrielli et al., 2022, Kobus et al., 2021, Tantau and Niculescu, 2022).³ Companies can further reduce their risk from PPAs by procuring a multi-technology and multi-location PPA (Gabrielli et al., 2022). Additionally, PPAs allow for more customized contract structures than public auctions since they can be adjusted to the specific situation. Companies purchasing PPAs face a trade-off between profitability and risk reduction as well as between profitability and matching their demand profile (Gabrielli et al., 2022).⁴

A company's ability to off-take PPAs is limited by the size of its green premium (Kobus et al., 2021), the need for high electricity consumption to be the only or main investor of a renewable energy project (Kobus et al., 2021), the requirement for investment grade credit rating to become an off-taker (Kobus et al., 2021, Barringa, 2022, Deutsche Energie Agentur, 2019), and the contract's complexity requiring a sophisticated energy procurement department (Barringa, 2022, Tantau and Niculescu, 2022). Additionally, the willingness of electricity consumers to pay a green premium is expected to fall the more the energy transition proceeds as more and more companies without green priorities switch to electrification (Köveker et al., 2023). Both the scale and credit-rating barriers of PPAs lead to an advantage for large corporations in signing PPAs (Kobus et al., 2021).

³Futures contracts offered on the financial markets very rarely hedge electricity market participants over a period of more than two years. In 2022, more than 90% of volume was traded with a maximum maturity of less than two years ahead (ACER, 2023).

⁴In addition to these "corporate PPAs", bilateral contracts can also be made between renewable energy projects and utilities. These contracts are, however, out of the scope of the analysis conducted in this paper.

Another factor limiting the expansion of renewable energy via PPAs is the fact that many industrial companies only contract their input factors for the same time that they can sell their products ahead of time since they would otherwise be unilaterally exposed to price volatility. This exposure can, if the volumes become large enough, even lead to a downgrade of their credit rating, thus constraining the business’s ability to take on debt in the future (Barringa, 2022, Neuhoff et al., 2023).



The figure compares the development of renewable energy capacity additions in the European Union to the announced PPA volumes between 2013-2022. While the total capacity additions are taken from International Renewable Energy Agency (2024), the PPA announcements are based on data from RE-Source (2024). PPA numbers include repowering and short-term PPAs.

Figure 1: Development of EU-Capacity additions and announced PPA volumes

For the aforementioned reasons, not all electricity consumers will be able to sign PPAs. Therefore, critics of a PPA-based renewable energy expansion argue that the volume contracted by private actors will not be sufficient to finance the energy transition at the required speed (Barringa, 2022). Figure 1 shows the European corporate PPA volume in comparison to the total renewable capacity investments.⁵ It is evident that, despite their growth, projects financed through PPAs remain a small proportion of the total renewable capacity addition - and are far from the scale required for the EU’s climate neutrality targets. Further, according to data from Pexapark (2024), the PPA expansion is currently very concentrated. In 2023, more than 45% of PPA volume has been signed in either Germany or Spain, with the largest 10 PPA buyers accounting for 37% of all PPA volume. The PPA demand is also often driven by the financial and service industries, with large balance sheets relative to the value of the long-term contracts they sign, rather than industrial companies, which account for a large share of power demand. Even in the United States, the world’s largest PPA market, in 2019, more than half of

⁵Note that the PPA numbers can include re-powering investment for onshore wind, which are not necessarily equivalent to the net capacity addition achieved through the investment.

the PPA demand came from seven large retail and technology companies (Kobus et al., 2021). These have high energy demand from data centers and a high exposure to public scrutiny, likely resulting in high green premia. In Europe, the information technology, telecom, and healthcare sectors accounted for 44% of PPA-volume in 2023 (Pexapark, 2024). Thus, while PPAs will play an important role in the energy transition, they are unlikely to achieve the transition by themselves and will continue to co-exist with public support schemes.

3 The economics of cream-skimming

The emerging co-existence of private and public financing systems, in combination with the limited number of electricity consumers that have access to PPAs, creates the need to understand the interaction between the two systems from a distributional perspective regarding the issue of "cream-skimming" (also called "cherry picking"). Cream-skimming describes the economic situation in which a regulated firm (or institution) faces competition from an entrant who tries to attract high-value consumers. This outside option raises the price on the regulated market, thereby hurting the consumers who cannot switch due to the investment costs of bypassing the utility (Laffont and Tirole, 1990).

The concept of cream-skimming is widely discussed in fields undergoing liberalization such as health care (Herr, 2011, Bos et al., 2020, Barros, 2003), transportation (Tomeš et al., 2016, Preston et al., 1999), and education (Lankford and Wyckoff, 2001). Incentives to cream-skin arise when an incumbent firm engages in practices such as price discrimination (Laffont and Tirole, 1990) or cross-subsidization (Armstrong, 1999) under which high-value customers benefit from making outside contracts leading to a deterioration of the incumbent market. Analyzing competition between the public and private provision of a good, Steinberg and Weisbrod (2005) show that a non-profit firm can only survive entry from a profit-maximizing competitor if it behaves profit-maximizing as well. To a certain extent, price discrimination and subsidization of low-income customers are only possible if the private firm has higher costs. This finding relates to the literature discussing the universal service obligation of (formerly) public utilities that engage in cross-subsidization in order to finance service to communities that would otherwise not be serviced (Valletti et al., 2002, Choné et al., 2000, Crew and Kleindorfer, 1998).

Cream-skimming also occurs in non-regulated markets, when firms have the option to bypass an intermediary to make direct contracts with customers. Bolton et al. (2016) show that the incentives for cream-skimming exist in the financial industry, where firms have the incentive to spend costly resources in order to be able to trade over the counter instead of on exchanges. This practice reduces the quality of assets traded on the ex-

change where an average price is paid for the assets of *ex-ante* unknown quality. Similarly, Easley et al. (1996) find evidence for cream-skimming in purchased order flows. From the financial markets, there is, however, also evidence of the opposite phenomenon of "dreggs siphoning" (or bottom fishing), i.e., the phenomenon that entrants attract customers with unfavorable characteristics, such as a high default risk, due to adverse selection and lower regulatory requirements (De Roure et al., 2022, Di Maggio and Yao, 2021).

In the context of the energy sector, the issues of cream-skimming and cross-subsidization have been discussed regarding the electricity sector's liberalization since the 1990s (see, e.g., Willems and Ehlers, 2008). Cross-subsidization is usually seen as an incentive-distorting practice, and thus, market liberalization intended to reduce it (Dormady et al., 2019). Looking at cream-skimming and bypass in the natural gas sector, Davis and Hausman (2022) show how electrification results in the exit of consumers that leave the remaining households to pay for the cost of legacy gas utilities. Similarly, Gorman et al. (2020) consider "load defection", i.e., how distributed renewable energy production could lead to consumers decoupling from the electricity grid. They find that the incentives are limited for the case of American households. There are also a number of papers that consider the effect of market structure on cream-skimming in the electricity market. Bourguignon and Ferrando (2007) consider market entry into the energy industry under a universal service obligation for the incumbent. They find that the incumbent can capture a part of the surplus created through entry by leveraging the market power they have, thereby counteracting the cream-skimming by the entrant. Meanwhile, Ropenus and Jensen (2009) consider how cream-skimming in the introduction of renewable energy is affected by the industry structure. They find that a vertically integrated monopolist lowers the welfare benefits of introducing renewable energy compared to a competitive electricity industry by cream-skimming part of the surplus of renewable energy subsidies.

4 Microeconomic model

While the literature has so far mostly discussed cream-skimming in the context of energy market liberalization, the emergence of private financing for renewable energy leads to related questions but with remarkably different focuses. In this context, in which society's need for climate action exceeds companies' profit-maximizing investment and there is a limited ability of contracts to sign PPAs, the interaction between public and private support schemes in renewable energy becomes an important field of research.

The following Section 4.1 develops a model of cream-skimming behavior in a case in which a government agency supporting renewable energy faces competition from electricity consumers, which have the option to make direct contracts with the renewable energy

producers, thereby "cutting out the middleman." It shows that (i) this behavior leads to an increase in the price of the government option and that (ii) there is an excessive incentive for cream-skimming, leading to losers even among the group of cream-skimming consumers. For tractability and readability of the text, I will start by solving the model for the case of linear functions in Section 4.2. However, Section 4.3 shows that the main results hold under more general functions as well.

4.1 Set-up

The microeconomic model studies the case in which a government agency ("the regulator") procures an amount \bar{Q} of a good for which consumers have a short-run inelastic demand.⁶ The good is sold by a competitive market of firms ("the producers") with increasing costs $S(Q)$. The regulator has perfect information about producers' costs and procures the good at each project's cost. While this is a strong assumption, in our application to the renewable energy market, it is reasonable since the costs depend primarily on the full load hours of installations, which third parties can observe. In addition, renewable energy contracts are often sold through auctions, which, if model incentive compatible, should elicit projects' true costs. The model abstracts from the fact that there are also unobservable cost factors that are independent of the full load hours, i.e., assuming that these are in expectation equal between all installations. The agency then resells the good to consumers at the average price of all procured projects $\frac{\int_0^{\bar{Q}} S(Q)}{\bar{Q}}$. This set-up is similar to how European governments pass on the benefits and costs of CfDs to electricity customers. Since the government averages the price of all goods, I refer to the system of government contracts as a "contract pool".

The model investigates what happens to the cost of this government system of renewable energy contracts when the producers can bypass the government agency and instead make direct contracts with consumers. The producers incur a cost of $e(Q)$ when making direct contracts, i.e., it becomes increasingly costly to make direct contracts.⁷

The incentives for leaving the contract pool are as follows. Producers want to leave the pool whenever their revenue from a direct contract \hat{R} minus the extra costs incurred is larger or equal to their revenue from the pool \tilde{R} :

$$\text{IC1: } \hat{R}(Q) - e(Q) \geq \tilde{R}(Q) \Leftrightarrow \hat{P}(Q) - e(Q) \geq S(Q) \quad (1)$$

⁶In the assumption of inelastic demand, this paper abstracts from the question of the additionality of PPAs in assuming that the demand for renewable electricity is fixed. However, a cream-skimming effect would also arise if PPAs were additional to installations with public support.

⁷In the context of electricity markets, this assumption represents the previously discussed fact that only a small number of consumers have a large capacity to sign power purchasing agreements without impacting their credit rating.

Consumers, assuming that they derive the same utility from buying the good from the public system and bilateral contracts, want to leave the pool whenever their costs from a direct contract \hat{P} are smaller or equal to their cost from the pool \tilde{P} :

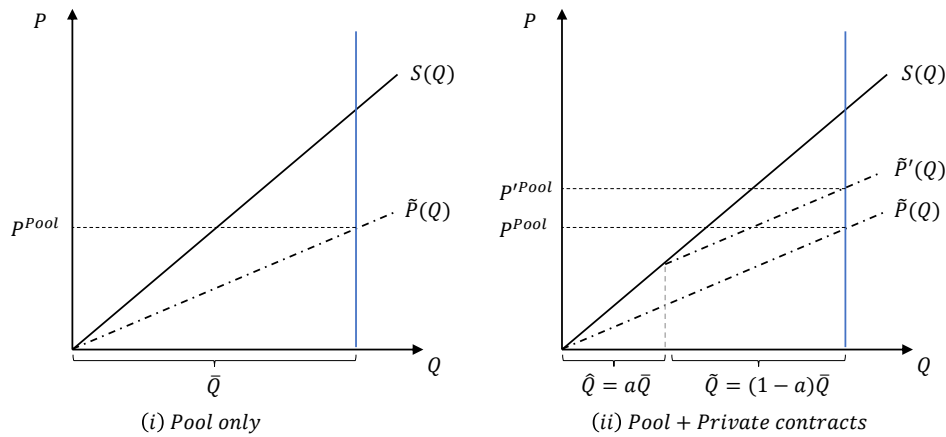
$$IC2: \hat{P}(Q) \leq \tilde{P}(Q) \Leftrightarrow \hat{P}(Q) \leq \frac{\int_Q^{\bar{Q}} S(Q)}{\bar{Q} - Q} \quad (2)$$

Thus, setting *IC1* and *IC2* equal after rearranging for $\hat{P}(Q)$, the equilibrium quantity of direct contracts will be the solution to:

$$S(Q) + e(Q) = \frac{\int_Q^{\bar{Q}} S(Q)}{\bar{Q} - Q} \quad (3)$$

In summary, this means that the equilibrium will constitute a Nash equilibrium in which producers decide to leave the pool one after the other until they can no longer find a consumer willing to make a bilateral contract. The model does not determine how the surplus from leaving the pool is divided between the producer and consumers, as this does not affect the marginal incentive for cream-skimming as long as some surplus remains with each group.

4.2 Linear case



The graph shows the equilibrium for the CfD and CfD+PPA case in the linear case.

Figure 2: Equilibrium of the model in the linear case.

To understand the incentives for cream-skimming, the model is solved for a case of linear functions. Figure 2 shows the equilibrium in the linear case in which I assume that the supply curve has the form $S(Q) = dQ$ and the demand is fixed at \bar{Q} . When producers want to bypass the pool and make direct contracts, they have to pay an extra cost $e(Q) = eQ$. Thus, in the case of a procurement through the pool alone, the cost of

the pool is equal to $\tilde{P}(Q) = \frac{d\bar{Q}}{2}$. A detailed solution of the model is found in Appendix A.1.

When the government pool faces competition from the option of private contracting, a new equilibrium emerges in which producers leave the pool according to Equation (3). In equilibrium, the share of producers leaving the pool is equal to $a = \frac{\bar{Q}}{Q} = \frac{d}{d+2e}$. As a result of this, the costs of the pool are $\frac{\bar{Q}d(d+e)}{d+2e}$, i.e., the cream-skimming leads to a cost increase of $\frac{\bar{Q}d^2}{2(d+2e)}$. It is also apparent that whenever there is no extra cost, all producers leave the pool ($\lim_{e \rightarrow 0} a = 1$), and when the cost becomes prohibitively large, all producers stay in the pool ($\lim_{e \rightarrow \infty} a = 0$).

I can calculate the total spending to consider the effects of the different options. I find that the highest costs to consumers are incurred in the PPA case, while the lowest costs are incurred in the pool-only case:

$$\begin{aligned} \text{Total Cost, only PPA:} & \quad \frac{\bar{Q}^2(d+e)}{2} \\ \text{Total Cost, only Pool:} & \quad \frac{\bar{Q}^2d}{2} \\ \text{Total Cost, Pool + PPA:} & \quad \frac{\bar{Q}^2d(d+e)(d+4e)}{2(d+2e)^2} \end{aligned}$$

Interestingly, there are also consumers who leave the pool that would have been better off with the previous "pool-only" solution. Appendix A.4 shows that any customer that signs a contract with transaction costs of $eQ > \frac{d\bar{Q}-2dQ}{2}$ would have been better off if there had not been the option to make bilateral contracts. These firms only leave the pool when they are offered bilateral contracts because they know that all cheaper bilateral contracts have already been made. Since the share of consumers benefiting from leaving the pool *ex-ante* is $\frac{d}{2d+2e} < \frac{1}{2}$ for all $e > 0$ if consumers could vote *ex-ante*, they would not want to introduce a pool solution that allows them to make private contracts.

Thus, overall, this section shows that (i) there is an incentive to leave the pool; (ii) the total costs of electricity are increased when the option to make PPAs is introduced; and (iii) there are consumers that leave the CfD even though they would have been better off without the introduction of PPAs *ex-ante*.

4.3 General case

The result that consumers leave the private system despite not profiting from it *ex-ante*, holds under more general conditions as well. In fact, one only has to assume that the functions are strictly increasing and continuous. The conditions then become as follows.

Consumers Q^* want to leave the pool if the price of staying in the pool, given that all cheaper projects have already made private contracts $\tilde{P}(Q^*)$ is larger or equal to the price of the bilateral contract offered to them $\hat{P}(Q^*)$:

$$\tilde{P}(Q^*) \geq \hat{P}(Q^*) \quad (4)$$

$$\Leftrightarrow \frac{C(\bar{Q}) + C(Q^*)}{2} \geq C(Q^*) + e(Q^*) \quad (5)$$

$$\Leftrightarrow C(\bar{Q}) \geq C(Q^*) + 2e(Q^*) \quad (6)$$

However, *ex-ante* consumers Q' would benefit from introducing the option of leaving the pool if the price of the pool in the "pool-only case" is larger than the price of the bilateral contract offered to them:

$$\tilde{P}(\bar{Q}) \geq \tilde{P}(Q') \quad (7)$$

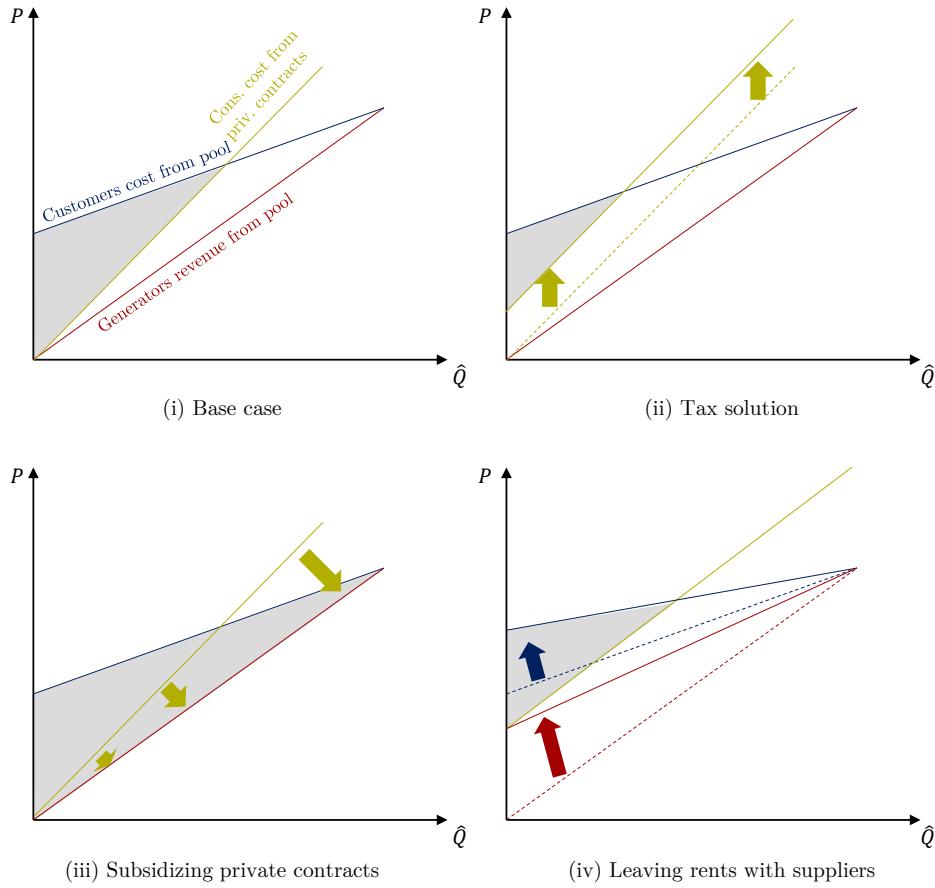
$$\Leftrightarrow \frac{C(\bar{Q})}{2} \geq C(Q') + e(Q') \quad (8)$$

$$\Leftrightarrow C(\bar{Q}) \geq 2C(Q') + 2e(Q') \quad (9)$$

From Equation (6) and Equation (9), it is evident that there is a larger number of projects that leave the pool than there is of projects benefiting from leaving *ex-ante* whenever $C(Q)$ is strictly increasing. Because then there are less Q' that fulfill Equation (9) than Q^* that fulfill Equation (6). At the same time, without extra costs, all consumers would leave the pool, but only half of them would benefit since the other half would end up signing contracts above the initial pool price. Thus, the main result holds for the general case as well.

4.4 Possible remedies

There are a number of potential solutions to the incentive for cream-skimming that can be investigated in the stylized set-up. In Figure 3, three potential solutions to the cream-skimming are displayed: A tax on PPA contracts, a subsidy for PPA contracts, and the potential of leaving some rents to the projects in the pool.



Graphs showing the conditions for the equilibrium depending on the number of firms leaving towards the private contracts \hat{Q} . Arrows indicate how the solution options affect the conditions.

Figure 3: Potential remedies for the cream-skimming

a. Taxing PPAs

One option to reduce cream-skimming could be to tax firms going into PPAs. Thereby, the conditions would change to:

$$IC1 : S(Q) \leq \hat{P}(Q) - e(Q) \quad (10)$$

$$IC2 : \hat{P}(Q) + \tau \leq \frac{\int_Q^{\bar{Q}} S(Q)}{\bar{Q} - Q} \quad (11)$$

Due to the cost increase in the PPAs that is induced by the tax, there are fewer PPAs signed in the case of a tax. One can quantify this for the linear case, which can now be solved to:

$$\left\{ \text{PPA-Volume: } \tilde{Q} = \frac{d\bar{Q} - 2\tau}{d + 2e}, \text{ Pool-Price: } \tilde{P} = \frac{d((d + e)\bar{Q} - \tau)}{d + 2e} \right\}$$

The effect would be even greater if the tax revenue were used to subsidize the pool

price. When the tax rate is set equal to $\frac{d\bar{Q}}{2}$, there is no incentive to deviate into the PPAs, even for the cheapest projects. Instead of a lump sum tax, the tax could also be set as a price-discriminating tax⁸ that is highest for the lowest cost products (e.g., $\tau(\bar{Q} - \hat{Q})$). The effect is similar, leading to lower PPAs and eliminating them altogether if set sufficiently high.

b. Subsidizing PPAs

An alternative option could be to enable more electricity consumers to sign PPAs by reducing the cost penalty through subsidies. The conditions then change to:

$$IC1 : S(Q) \leq \hat{P}(Q) - e(Q) + z(Q) \quad (12)$$

$$IC2 : \hat{P}(Q) \leq \frac{\int_{\hat{Q}}^{\bar{Q}} S(Q)}{\bar{Q} - \hat{Q}} \quad (13)$$

Depending on the subsidy amount, it is possible to eliminate the cost-increasing effect of the PPAs completely. The subsidy has, however, the effect of further increasing the pool price since lower-cost projects further deviate into the PPA. It is possible to solve the linear case with a linear subsidy $z(Q) = z * Q$ to see:

$$\left\{ \text{PPA-Volume: } \hat{Q} = \frac{d\bar{Q}}{(d + 2e - 2z)}, \text{ Pool-Price: } \tilde{P} = \frac{\bar{Q}d(d + e - z)}{(d + 2e - 2z)} \right\}$$

Thus, the subsidy can reduce both the PPA price and increase the PPA volume. If set at $z = e$, all projects will sign PPAs.

c. Leaving rents with producers

Finally, a potential solution could be to leave rents with the producers in order to reduce their incentive to leave the pool for PPA contracts. When leaving a rent of $\Gamma(Q)$ with producers below the cut-off Q^* , the constraints change to:

$$IC1 : S(Q) + \Gamma(Q) \leq \hat{P}(Q) - e(Q) \quad (14)$$

$$IC2 : \hat{P}(Q) \leq \frac{\int_{\hat{Q}}^{\bar{Q}} S(Q)}{\bar{Q} - \hat{Q}} + \frac{\int_{\hat{Q}}^{\bar{Q}} \Gamma(Q)}{\bar{Q} - \hat{Q}} \quad (15)$$

⁸In the case of renewable energy support, price discriminating surcharges to network tariffs can be such an option to reduce the windfall profits at locations with high renewable energy production.

I can solve the linear case where the electricity producers are allowed to keep a share r of their surplus. If it is assumed that rent kept by firms is $\Gamma(Q) = \frac{dr(\bar{Q}-Q)}{2}$, i.e. $Q^* = \bar{Q}$, the solution is:

$$\left\{ \text{PPA-Volume: } \tilde{Q} = \frac{d\bar{Q}(1-r)}{d-dr+2e}, \text{ Pool-Price: } \tilde{P} = \frac{\bar{Q}d(dr-d-er-e)}{d-dr+2e} \right\}$$

The price of the pool increases by the average rent that is earned by all projects in the pool, while the projects' reservation price for switching to a PPA increases by the specific rent earned by each project. Therefore, as long as $\gamma'(Q) < 0$, leaving rents with the producers will lead to a decrease in the PPA volume. However, the price of the pool will increase in comparison to the solution with perfect price discrimination and PPAs. Therefore, leaving rents with producers is not an efficient solution for reducing the deviation into PPAs.

Overall, the analysis of possible remedies shows that, in theory, all three considered options (taxes, subsidies, and leaving rents with producers) can solve the problem of cream-skimming. There are, however, further effects of the policy that differentiate the options. First, while the taxing of PPAs reduces the price of the public option through reduced cream-skimming, the other two options increase the price of the pool. Thus, especially for a PPA subsidy, it is paramount that it enables all parts of the economy to sign PPAs and not just a small share. Second, the distributional effect and the effect on public budgets differ. While increased producer rents and subsidies for PPAs will lead to costs for taxpayers or electricity customers, taxes can reduce their costs. Third, there are dynamic effects that are not considered in the model. For instance, subsidizing PPAs could lead to the wider adoption of PPAs in the electricity market, which could reduce their mark-ups through economies of learning. These effects should be considered in the choice of measures to counteract cream-skimming in the presence of bilateral contracting.

5 Numerical model

The analytical analysis revealed the challenge of combining a public and private contract system for renewable energy capacity expansion. In the following numerical model, I analyze how large the incentive for cream-skimming is. For this, the section considers the case of the German auctions for onshore wind energy. Onshore wind energy is a crucial part of the German energy transition's strategy that aims to increase the share of wind and solar energy to 80% (from 46% in 2022) of total electricity production until 2030 (Bundesregierung, 2023). As discussed in Section 2, Germany is a country that has seen significant increases in PPA activity and has many industrial companies with a large

interest in reducing their exposure to power price fluctuations, as shown in the debate about an "industrial power price".

Germany is employing price discrimination in its onshore wind auctions through the so-called "reference yield model." The reference yield model assigns each wind project a correction factor based on the relation between the full load hours achieved at the specific site and the full load hours achieved at a hypothetical reference location (the "reference yield"). The project's bid in the auction is then divided by this correction factor in order to give a bonus to projects at low-wind locations and a penalty to projects at windy sites. Since the support payments are dependent on the actual, not the corrected, bids, the reference yield model allows for higher bids at low-wind locations, thereby effectively constituting a form of price discrimination. For an analysis and discussion of the reference yield model, see (Kröger et al., 2022). The growing role of PPAs and the price discrimination through the reference yield model make Germany's wind auctions an ideal example to analyze the effect of cream-skimming on the relationship between public and private support for renewable energy.

5.1 Structure of the numerical model

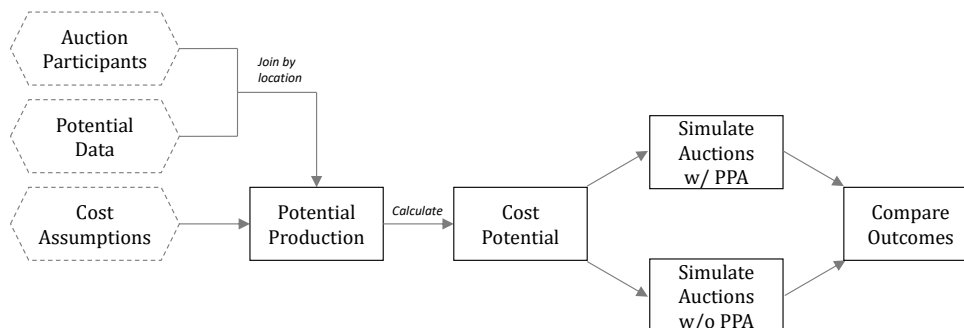
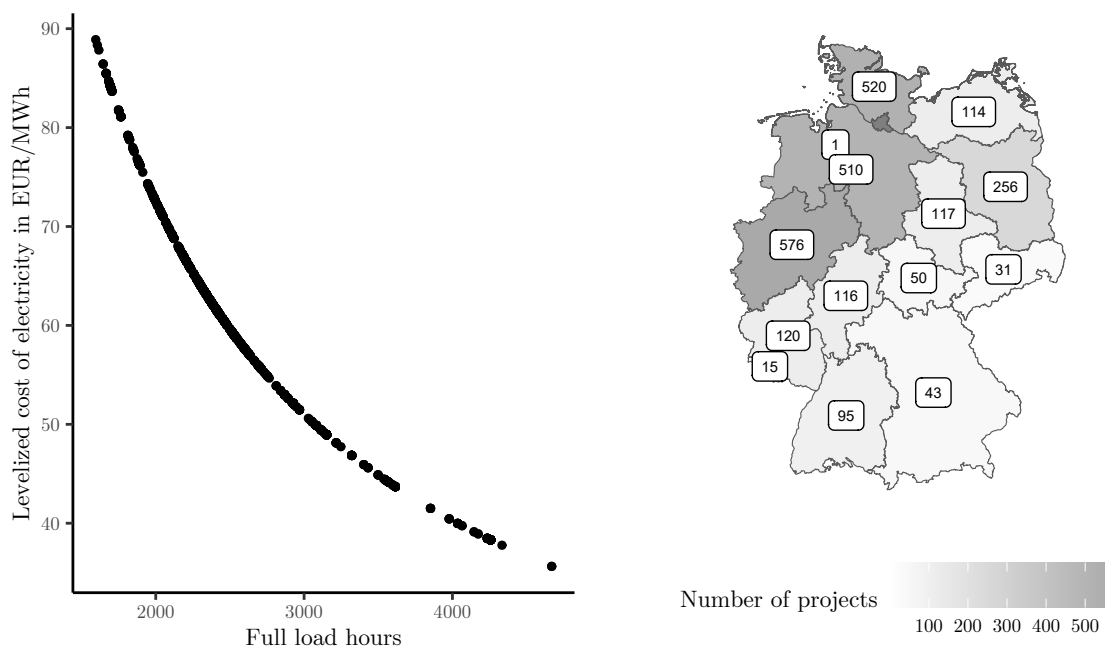


Figure 4: Structure of the numerical model

For the numerical model, I simulate the German auctions for onshore wind under the assumption that they were held for a CfD scheme. Figure 4 shows the approach of the numerical model graphically. The reason for using historical bids is that they accurately represent current planning constraints in Germany and allow me to infer the distribution of wind speeds and levelized costs of electricity in the current auctions. Since the auctions for onshore wind energy in Germany have been undersubscribed in the years considered for our analysis, it does not matter whether the auctions are held under a "pay as bid" or "last price" auction scheme since participants are likely to be able to anticipate the strike price. It is assumed that the most expensive unit in each auction sets the strike

price, and payments are determined under the current reference yield model for a CfD awarded to the producers of electricity. Under these assumptions, I calculate the result of the auction and the strike price of the CfD. In the second step, it is assumed that there is the option to leave the CfD auction toward a PPA. PPAs have a cost mark-up compared to the public system due to financing and contract costs. It is assumed that the projects can anticipate the strike price in the auction and that they maximize revenues when deciding to leave towards a private contract. The price of the CfD is then determined by the average price of all projects deciding to stay in the public system.

5.2 Data description



The left panel shows the distribution of costs between projects depending on their full load hours. The right panel shows the distribution of projects between federal states.

Figure 5: Cost and geographic distribution of the projects

To create the input data for the numerical model, I used two main sources. First, I retrieved the auction results for onshore wind energy for the years 2021-2023 from the website of the German Federal Network Agency (Bundesnetzagentur, 2023). The data contains information on participating projects and their location. Second, I use the information provided by Tröndle et al. (2019) to calculate the average full load hours achieved by the turbine potential in each German municipality.⁹ The paper assumes a V90/2000 as a turbine.¹⁰ There are some data cleaning steps necessary to combine the datasets,

⁹In order to calculate the full load hours, I divide the potential yearly production by the potential capacity for the municipalities based on the results data from the techno-social potential scenario.

¹⁰I assume a hub height of 80m since this is the standard setting in renewable ninja, the tool used by

which are described in Appendix A.6. Combining the two datasets and assuming that the projects in the auction are similar to the municipal average regarding the quality of the wind resource, one can calculate the expected production and levelized cost of electricity for each of the projects bidding in the auction. All in all, 2465 projects that can be matched to the potential data are included in our dataset. For the calculation of the levelized cost of electricity, I assume the parameters displayed in Table 1 based on Kost et al. (2021). However, the calculations deviate from the assumptions in that paper by assuming that the lifetime of the turbines is 20 instead of 15 years. The model calculates the reference yield and bid corrections in accordance with the most recent version of the reference yield model.

Variable:	Investment	Fixed OPEX	Variable OPEX	WACC
Value:	1700	20	0.008	2.5
Unit:	Euro/KW	Euro/KW	Euro/KWh	%

Table 1: Cost parameter used in the model

The resulting cost distribution is shown in the left panel of Figure 5. The mean (median) cost of the projects is 59.8 (61.1) Euro/MWh with a minimum cost of 35.6 Euro/MWh and a maximum cost of 88.9 Euro/MWh. Meanwhile, the average full load hours are 2578.48, which is 90% of the reference yield of the turbine. The right panel of Figure 5 shows the geographical distribution of projects in the considered auctions. The distribution of projects is skewed to the North-West of Germany. The city-states of Hamburg and Berlin did not have any projects bidding in the relevant auctions.

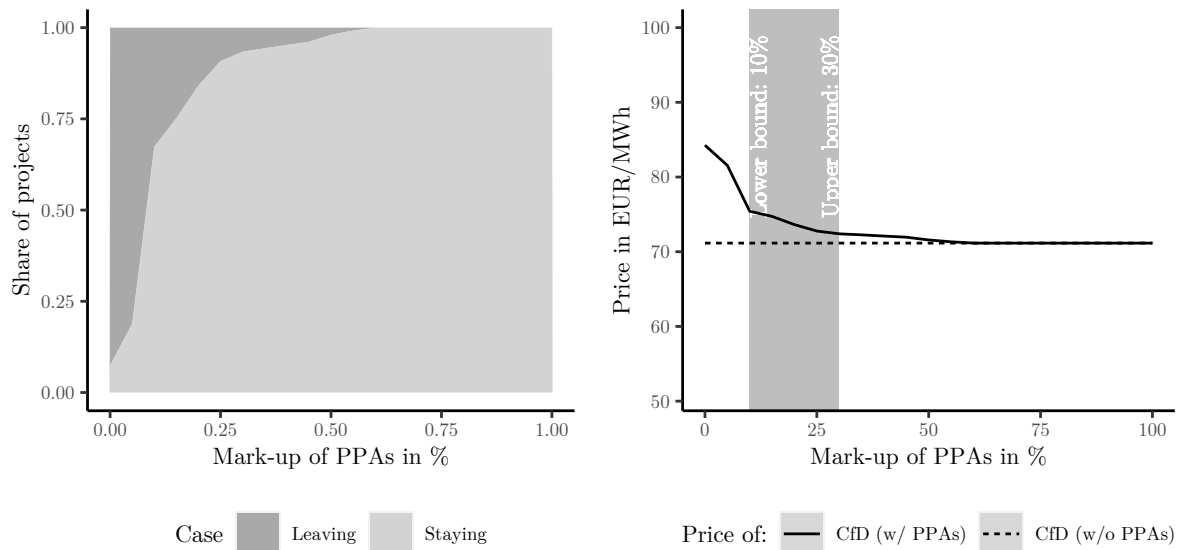
For the mark-up of bilateral contracts, I assume that the PPAs lead to a 10%-30% increase in costs of PPAs in comparison to a case where the electricity is sold under a government-backed CfD contract. At the lower bound, the 10% increase represents the increased counterparty risk from selling to a private off-taker instead of the government, assuming that all other contract modalities stay the same. At the upper bound, further PPA costs, such as the impact on off-takers credit-worthiness are considered as well.¹¹

5.3 Results

I find that an incentive exists under the reference yield model to deviate into PPAs. There is an average deviation into the PPAs of 33% of projects at the lower bound of mark-ups

Tröndle et al. (2019). While this is significantly smaller than the most recently built turbines, I use this turbine for consistency.

¹¹The assumption of a 10-30% mark-up due to the increased counterparty risk is taken from May and Neuhoff (2019). The authors argue that their estimates are in line with industry estimates such as Huneke and Claußner (2019).



The left panel shows the share of projects deviating into the PPAs at different mark-up levels. The dark grey area represents the share of projects leaving the public system, while the light grey area represents the share of projects remaining in the public system. The right panel shows the resulting cost increases. The solid line represents the pool price when companies deviate into the PPAs, while the dotted line shows the price without an outside option. The results in both panels are averaged over all auctions.

Figure 6: Output of the numerical model

and 7% at the upper bound of the mark-up. The left panel of Figure 6 shows the share of projects leaving the government system depending on the price mark-up of PPAs. The share of projects leaving the CfD decreases quite strongly with the mark-up. While, at a 5% mark-up, 81% of projects leave the CfD, this decreases to just 2% at a 50% mark-up.

The deviation of projects into the private contracts raises the price of the public renewable contracts, albeit in a moderate fashion. This effect is shown in the right panel of Figure 6. At a 10% mark-up, the option to deviate into PPAs increases the cost of the government contract pool by an average of 4.3 Euro per MWh (+6%). At a 30% mark-up up, the price increase is 1.2 Euro per MWh (+2%).

The cost difference depends on the distribution of projects in the auction. This can be seen in Figure 7 for the 10% and 30% mark-up. A complete overview of the auction results and the cost differences between projects can be found in Appendix A.7. At the 30% mark-up, most auctions have a cost increase from between 1-3% when the option to deviate into PPAs is introduced, while the auction in December 2022 does not have any auctions deviate towards the PPA. The reason for that is that the distribution of project costs differs between auctions. The spread between the highest and lowest bids varies from 51.1 to 26.8 Euros per MWh, with the auction in December 2022 having the lowest spread. Moreover, the auction in December 2022 was very undersubscribed, with only 29 projects bidding.

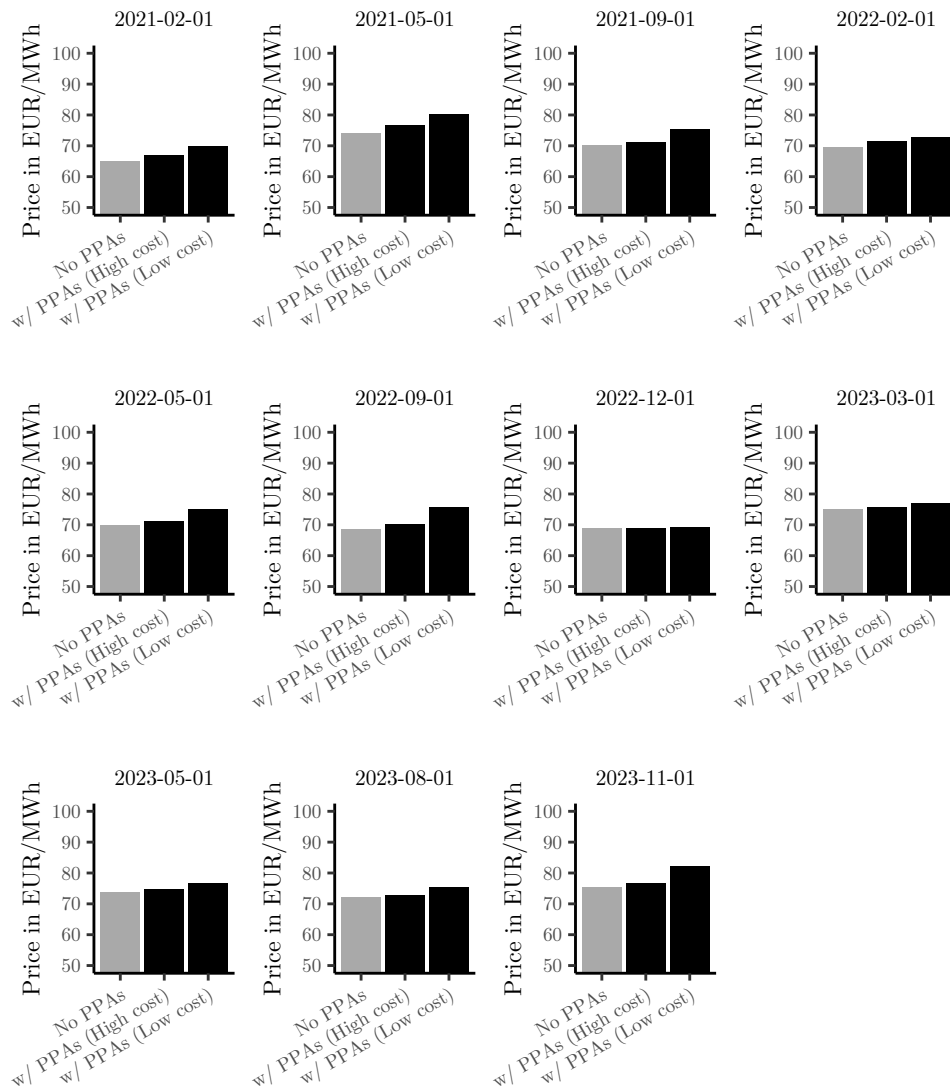


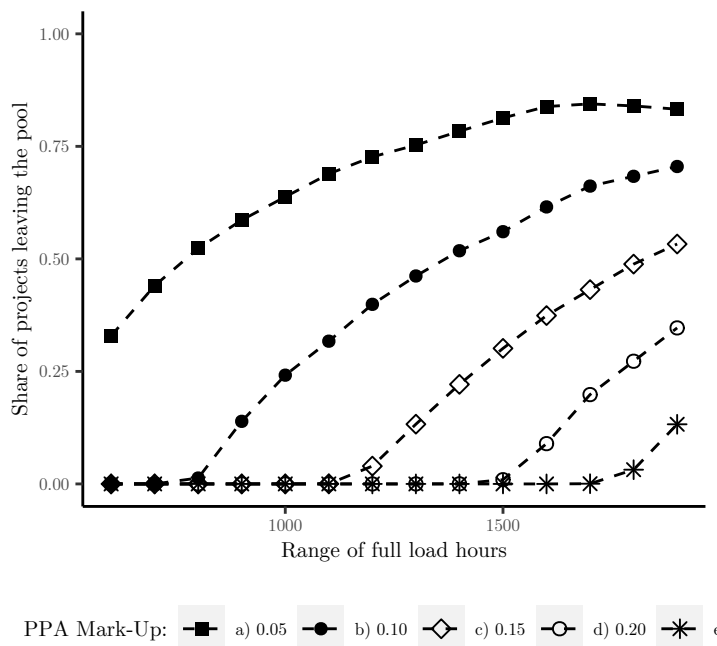
Figure shows the difference in CfD prices between the scenario with and without the option to deviate into PPAs for the different auctions conducted between 2021-2022. The left light grey bar represents the costs without the outside option, while the two dark grey bars represent the price with the outside option and a 10% and 30% mark-up for PPA projects, respectively.

Figure 7: Output of the numerical model

Another important reason why the difference is relatively small overall is that the projects are already able to subtract significant producer rent from the CfD auctions. This rent can be extracted because the reference yield model undercorrects for the cost differences between installations. As a consequence, the projects can extract an average producer rent of 21% from the projects. The most productive quarter of producers achieve an average producer rent of 24%. Thus, the prices are already relatively high in the government system even without the option of cream-skimming. Appendix A.8 shows the results for a case of perfect price discrimination. This change further increases the average share of projects deviating into private contracts to 50% (instead of 33%)

at a 10% mark-up and to 8% (instead of 7%) at a 30% mark-up. The perfect price discrimination leads to a price increase of the government contracts of 12% (instead of 6%) at a 10% mark-up and of 3% (instead of 2%) at a 30% mark-up.

5.4 Sensitivity analysis

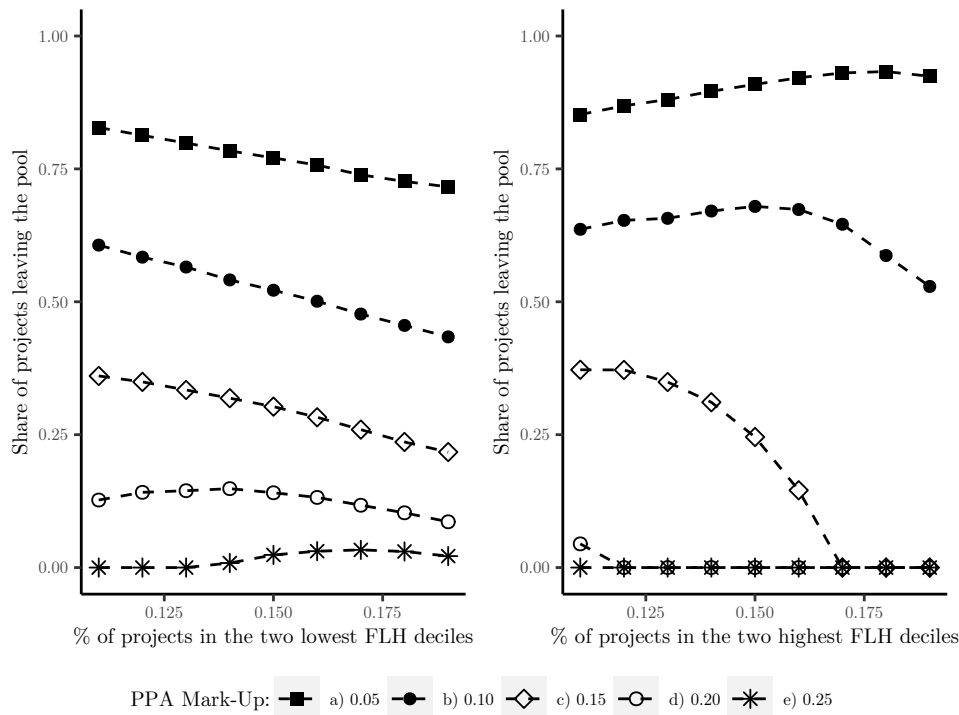


Graph shows the effect that a larger range of full load hours (i.e., a wider distribution) has on the share of firms leaving the public contract pool depending on the level of the mark-up of private contracts.

Figure 8: Impact of wider cost distribution on cream-skimming

The simulations in this section were done on a dataset of past auction participants from 2021 and 2022. In these past auctions, there was only a limited diversity in the geography of installations. One reason for this is that current support systems for renewable energy lead to a concentration of installations. Consequently, 77% of installations had between 2000 and 2999 full load hours, and 59% of installations had full load hours between 2200 and 2699 per year. With low-cost differences, cream-skimming becomes less beneficial for electricity consumers so that they remain in the contract pool. In addition, it can be seen in Appendix A.9 that the projects are approximately normally distributed with respect to their full load hours, i.e., there is a larger share of medium-cost installations. Thus, the question remains of how the effect of cream-skimming changes depending on the distribution of installations, both regarding the cost range of included projects and the shape of the distributions.

To analyze the sensitivity of the results to changes in the distribution of installations, I start with the assumption of a uniformly distributed wind energy potential that is located



Graph shows the effect that a larger share of firms in the two higher and lowest full load hours deciles (i.e., a more skewed distribution) has on the share of firms leaving the public contract pool depending on the level of the mark-up of private contracts.

Figure 9: Impact of more skewed cost distribution on cream-skimming

around the reference yield of the selected turbine. I assume that these installations bid in an auction that sells 1,000 MW. Firms can deviate into PPAs at an added cost between 5-30% of LCOE. The potential is then varied in two ways. First, the potential gets extended to cover installations along the entire spectrum of the reference yield model. This sensitivity analysis simulates the inclusion of a more diverse renewable energy supply, i.e., a wider cost distribution of projects. Second, I assume that there is a more skewed distribution toward high and low-cost installations. Appendix A.9 gives an overview of the distributions assumed for the sensitivity analysis.

The sensitivity analysis shows that cream-skimming might play a larger role in future scenarios with varying cost distributions. Figure 8 shows the effect of a wider cost distribution on the share of firms leaving the public contract system under the assumption of a uniform cost distribution. It shows that under any assumption of the mark-up the wider cost distribution leads to more firms leaving the system. For instance, at a 15% mark-up the share of firms leaving the pool increases from zero to over 50% as the distribution becomes wider. The reason behind this is that the difference in costs becomes larger such that more firms find it profitable to deviate for each level of mark-up. At the same time, the initial pool price remains stable when the distribution becomes wider.

Meanwhile, Figure 9 investigates the effect of a more skewed cost distribution holding the width of the distribution constant. A more skewed distribution has two counteracting effects. First, the more skewed distribution affects the pool price. When the distribution is more skewed toward projects with higher (lower) costs, the pool price increases (decreases) because the skewness affects the average price. Second, there is an effect on the number of projects that find a deviation profitable. When the distribution is more skewed towards higher (lower) cost projects, the number of low-cost projects that might want to deviate decreases (increases). It can be seen in the figure that it depends on the mark-up of PPAs, which effect prevails. The left panel of Figure 9 focuses on a distribution that is more skewed towards high-cost firms. It shows that in a scenario with low PPA mark-ups, the second effect prevails. The share of firms leaving the government system decreases since there are fewer firms with low costs for which a deviation into PPAs is profitable. However, at high mark-ups, the share of projects leaving then increases since the pool price incentivizes the lowest-cost firms to deviate into PPAs. Meanwhile, the right panel shows that, for higher shares of low-cost installations, the effect is less clear. At the lowest mark-up level of 5%, the increase in skewness leads to a higher share of projects leaving. The mechanism behind this is that there are more low-cost projects that find deviations favorable while the remaining high-cost projects keep the average price in the public contracts high and make a deviation interesting for consumers. At higher mark-ups, however, the second effect dominates: The increased skewness lowers the public contract price sufficiently such that fewer consumers want to deviate.

Overall, the sensitivity analysis shows that a wider distribution of projects leads to more cream-skimming, while the effect of a more skewed distribution depends on the PPA mark-up as well as the degree of skewness.

6 Conclusion and policy implicatons

There is no doubt that private capital will play an important role in delivering the capacity expansion of renewable energy needed for climate neutrality. McCollum et al. (2018) estimate that the necessary annual investment volume in the electricity sector to reach the 1.5-degree target in Europe will be 86 billion Euro. For Germany, an industry report by BDEW (2022) estimates that the investment volume required to reach the 2030 target of 65% renewable energy generation will be 351 billion Euro, and a report for the German public investment bank KfW estimated the required investment in renewable energy generation to achieve climate neutrality was at 502 billion Euro until 2050 (Prognos, 2021). Given the increasingly tight public budgets in times of multiple crises, PPAs can be an important way to realize renewable energy expansion without government involvement.

Nevertheless, it is important to consider the distributional aspects of this, especially when the public derisks the investment of renewable energy investors. Therefore, the use of CfDs and the passing on of the CfD conditions to electricity consumers can be an important tool to address the distributional concerns regarding derisking (Neuhoff et al., 2023). The EU Commission suggests combining such public CfDs with guarantees for private PPAs in the design of future European energy policy. This policy proposal raises the question of what interactions emerge between these two support systems. This paper focuses on the aspect of cream-skimming, i.e., the potential for low-cost projects to deviate into private contracts that could raise the costs of the public support system. The question is analyzed through a stylized microeconomic model and a numerical simulation using data from the German auctions for onshore wind energy between 2021-2023.

The study finds that there is an incentive for low-cost projects to deviate into private contracts. It analyzes a number of possible remedies, finding that taxing PPA revenues can reduce the incentive to leave the public contracts, thereby keeping their price low. An additional option would be to subsidize PPAs, for example, through a public guarantee. However, this could counteract one of the central motivations of PPAs, which is to remove renewable energy support from the public budgets. In a subsequent numerical analysis of the German auctions for renewable energy, I find that the effect of cream-skimming is relatively low. The reason for this is that the price differences of projects are relatively low, while the German auction design for onshore wind insufficiently corrects for differences in the wind resource. Despite the relatively modest increase of CfD prices in the standard model, the economic effects of a 2-6% increase in electricity costs are significant for the transition costs in the heavy industry. Fleiter et al. (2021) estimate that the electricity consumption of the German industry will double to 404 Twh in 2050 compared to its 2015 value. Thus, even the lower estimate of a 1.2 Euro increase in costs per MWh for the additional power demand would lead to 240 million Euro additional annual transition costs for the heavy industry resulting from an increase in electricity demand and prices. At lower mark-ups for PPAs, the increase in the public contract price can be larger. However, at these mark-ups, PPAs also become more affordable for a larger share of consumers, thus softening the blow of rising prices.

The paper offers important insights for regulators designing the future support system for renewable energy. The fact that an incentive for cream-skimming exists between the two systems emphasizes the importance of carefully considering the interactions in the policy design since it limits the government's ability to cross-subsidize the cost of electricity between different consumer groups. The fact that cream-skimming will have a limited effect at current expansion levels shows that the problem of cream-skimming might only become more pressing at a later stage of the energy transition when countries are building

more renewable energy at low-resource quality locations. A possible policy that reflects these two findings would be a tax on PPAs that is defined in relation to the strike price in the same year's CfD auction. That way, private investment into renewable energy is made possible, but excessive cream-skimming is prevented, thus allowing all electricity consumers to benefit from the low production costs of wind and solar energy. While the numerical model followed the example of the German reference yield model, the mechanism described would also be present in other cases in which the public support system employs price discrimination (e.g., Dutch and Austrian auctions for onshore wind energy).

Some caveats remain to the analysis that offer options for future research. First, this paper assumes a simple mark-up in percentage points for private PPAs. Further restrictions on electricity consumers' ability to sign PPAs are not considered. Therefore, an extension of the microeconomic modeling to the details of the investment case for an industrial company could be an interesting future project that should also consider how PPA and CfD contract structures differ from each other. Second, it should further be investigated which companies are able to sign PPAs, i.e., who benefits from the option to sign such contracts, especially since anecdotal evidence indicates that heavy industry, which needs to decarbonize in order for countries to reach their climate targets, struggles to sign such contracts. An important factor here could be the ability to charge the customers green premia. Third, the stylized microeconomic analysis builds on a number of assumptions that have to be kept in mind in the interpretation of results. For instance, I assume that the electricity demand is fixed in the short-run and that there is perfect price discrimination. However, the later analysis shows that the effect of cream-skimming exists regardless of the level of price discrimination. Likewise, the effect of cream-skimming of prices would exist when the quantity of PPAs is additional as well. However, these further interactions between private and public support schemes for renewable energy, which are out of the scope of this analysis, should be considered in future research. This includes, for example, the effect of PPAs on government budgets and the potential additionality of PPAs that lead to a faster energy transition. These should be weighed against potential price increases stemming from cream-skimming and the ability of governments to achieve additional policy goals through their renewable energy support. Overall, many interesting research questions arise in the design of PPAs and their interactions with government support schemes, which, as called for by Bichler et al. (2022), should become a stronger focus in social sciences, economics, and business research.

Data availability

All data and code used in this analysis can be made available upon request.

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A Appendix

A.1 Solving the microeconomic model

A.2 Base case

In order to solve the theoretical model, I first calculate the CfD price for a case in which all projects are part of the CfD. It is assumed that the projects are paid their marginal costs, i.e., that there is perfect price discrimination. The set-up then looks as follows:

$$\begin{aligned} \text{Supply: } S(Q) &= d * Q \\ \text{CfD-Quantity: } Q^{CfD} &= \bar{Q} \end{aligned}$$

The average cost of the projects, which equals the price of the CfD, is then:

$$\begin{aligned} \tilde{P} &= \frac{\int_0^{\bar{Q}} S(Q)}{\bar{Q} - 0} \\ \Leftrightarrow \tilde{P} &= \frac{d\bar{Q}^2}{2 * \bar{Q}} \\ \Leftrightarrow \tilde{P} &= \frac{d\bar{Q}}{2} \end{aligned}$$

A.3 Cream-skimming case

When there is the option to leave towards PPA, the pool costs can be redefined for the case that there is a quantity of products \hat{Q} that leave into the PPAs. The average cost of the CfD projects becomes:

$$\begin{aligned} \tilde{P}(\hat{Q}) &= \frac{\int_{\hat{Q}}^{\bar{Q}} S(Q)}{\bar{Q} - \hat{Q}} \\ \Leftrightarrow \tilde{P}(\hat{Q}) &= \frac{d\bar{Q}^2 - \hat{Q}^2}{2 * (\bar{Q} - \hat{Q})} \\ \Leftrightarrow \tilde{P}(\hat{Q}) &= \frac{d(\bar{Q} - \hat{Q})(\bar{Q} + \hat{Q})}{2 * (\bar{Q} - \hat{Q})} \\ \Leftrightarrow \tilde{P}(\hat{Q}) &= \frac{d(\bar{Q} + \hat{Q})}{2} \end{aligned}$$

Meanwhile, the cost of the PPA is:

$$\hat{P}(\hat{Q}) = R^{PPA}(Q) + e * \hat{Q}$$

The incentives for leaving the public contracts for the PPAs for producers is that the

revenue is larger in the PPAs:

$$\begin{aligned} \text{IC1: } & \hat{R}(Q) - e(Q) \geq \tilde{R}(Q) \\ \Leftrightarrow & \hat{R}(Q) - e\hat{Q} \geq d\hat{Q} \end{aligned}$$

For consumers, they want to leave the PPAs if:

$$\begin{aligned} \text{IC2: } & \hat{P}(Q) \leq \tilde{P}(Q) \\ \Leftrightarrow & \hat{R}(Q) \leq \frac{d\bar{Q} + d\hat{Q}}{2} \end{aligned}$$

I can combine the two equations, IC1 and IC2, to find the case in which both consumers and producers are indifferent between staying or leaving the public system. This yields the quantity of projects leaving the system:

$$\begin{aligned} d\hat{Q} + eQ &= \frac{d\bar{Q} + d\hat{Q}}{2} \\ \hat{Q} &= \frac{d\bar{Q}}{d + 2e} \end{aligned}$$

I can plug that into the price equation $\tilde{P}(\hat{Q})$ to find:

$$\tilde{P} = \frac{d(d + e)\bar{Q}}{d + 2e}$$

A.4 Share of firms benefiting from the PPA option

I can show that the share of firms leaving the CfD is larger than the share of firms that would benefit from doing so *ex-ante*. Additionally, some firms stay in the pool.

I can define these groups formally and solve the group sizes for the linear case.

- The marginal firm Q^* wants to leave the CfD if the pool price, given that all cheaper bilateral contracts have been made, is larger or equal to the bilateral contract offered to the firm: $\tilde{P}(Q^*) \geq \hat{P}(Q^*)$.
- The marginal firm benefits from the introduction of bilateral contracts *ex-ante*, if the bilateral contract offered to the firm is cheaper than the pool price given that all projects stay in the CfD: $\tilde{P}(\bar{Q}) \geq \hat{P}(Q^*)$.

Thus, the three options are:

- (a) Leave the CfD, benefit from PPA-option if: $\tilde{P}(Q^*) > \tilde{P}(\bar{Q}) \geq \hat{P}(Q^*)$
- (b) Leave the CfD, do not from PPA-option if: $\tilde{P}(Q^*) \geq \hat{P}(Q^*) > \tilde{P}(\bar{Q})$
- (c) Stay in CfD if: $\hat{P}(Q^*) > \tilde{P}(Q^*) \geq \tilde{P}(\bar{Q})$

For the linear case, the three equations can be solved to find the share corresponding to each of the groups. I can further solve for the marginal transaction costs at which customers do not benefit from the introduction of bilateral contracts (d).

(a) Share of firms leaving the CfD and benefiting from it

I have already previously solved that the quantity of firms leaving the CfD is $\hat{Q} = \frac{d\bar{Q}}{d+2e}$,

i.e., the share of firms leaving is $\frac{\hat{Q}}{\bar{Q}} = \frac{d}{d+2e}$.

The marginal firm Q^* benefits from leaving when $\tilde{P}(\bar{Q}) \geq \hat{P}(Q^*)$. Thus, the marginal firm Q^* and the share of firms benefiting is:

$$\begin{aligned} \frac{d\bar{Q}}{2} &= dQ^* + eQ^* \\ \Leftrightarrow Q^* &= \frac{d\bar{Q}}{2e+2d} \\ \Leftrightarrow \frac{Q^*}{\bar{Q}} &= \frac{d}{2e+2d} \end{aligned}$$

(b) Share of firms leaving the CfD and benefiting from it

From A3.1. it can be inferred that the share of firms that leave but do not benefit is:

$$\frac{\hat{Q}}{\bar{Q}} - \frac{Q^*}{\bar{Q}} = \frac{d}{d+2e} - \frac{d}{2d+2e} = \frac{d^2}{2(d+e)(d+2e)}$$

(c) Share of firms leaving the CfD and benefiting from it

The share of firms not leaving the CfD is:

$$1 - \frac{\hat{Q}}{\bar{Q}} = 1 - \frac{d}{d+2e} = \frac{2e}{d+2e}$$

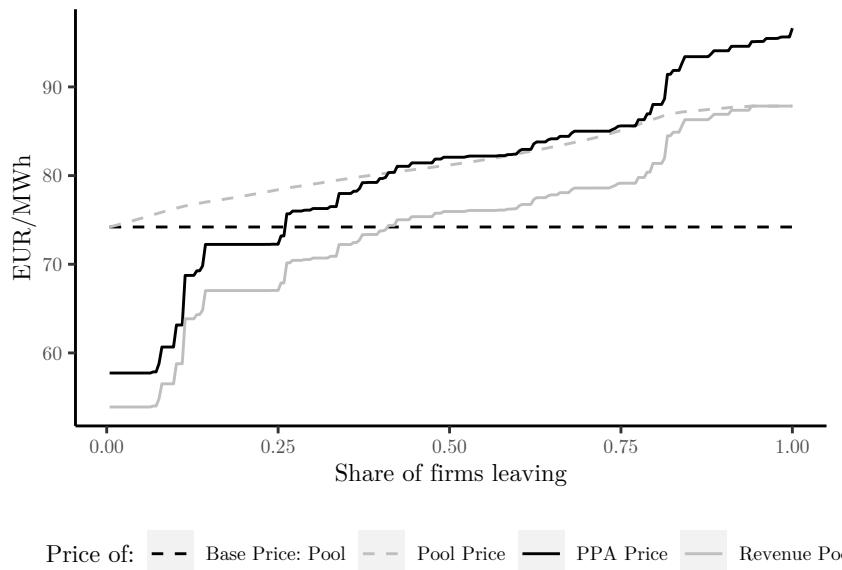
(d) Marginal transaction costs

Similarly, I can determine the transaction costs $e(Q^*)$ at which customers do not benefit

from the introduction of bilateral contracts *ex-ante*. They are:

$$\begin{aligned} \tilde{P}(\bar{Q}) &\geq \hat{P}(Q^*) \\ \Leftrightarrow \frac{d\bar{Q}}{2} &= dQ^* + eQ^* \\ \Leftrightarrow \frac{d\bar{Q} - 2dQ^*}{2} &= eQ^* \end{aligned}$$

A.5 Example of the theoretical model



Development of pool and PPA prices based on the example of an auction in May 2021

Figure 10: Example of the equilibrium from the analytical model in an exemplary auction

A.6 Data cleaning steps

I clean the data used for the analysis in multiple ways. Most importantly, to match them on the municipality level ("Gemeinden"), I need to clean the names of some municipalities. For instance, a number of municipalities have suffixes that only appear in one of the data (e.g., "Osterburg (Altmark)" and "Osterburg") or that are spelled differently in the two datasets. In a few other cases, a part of the municipality is incorrectly used to refer to the entire municipality (e.g., "Lohfeld" instead of "Porta Westfalica"). I make these corrections to be able to merge the dataset. In the potential data, there are some duplicate entries. In total, 191 (out of 11426) municipalities are duplicated. I sum them up to get the full potential in each municipality, which is equal to averaging the full load hours weighted by the production in each entry. Finally, 99 entries in the merged dataset have zero production due to zero full load hours being stated in the source data. I exclude

these observations from our analysis. Thereby, we end up with a dataset of 2,465 bids in the considered auctions.

A.7 Solution by auction

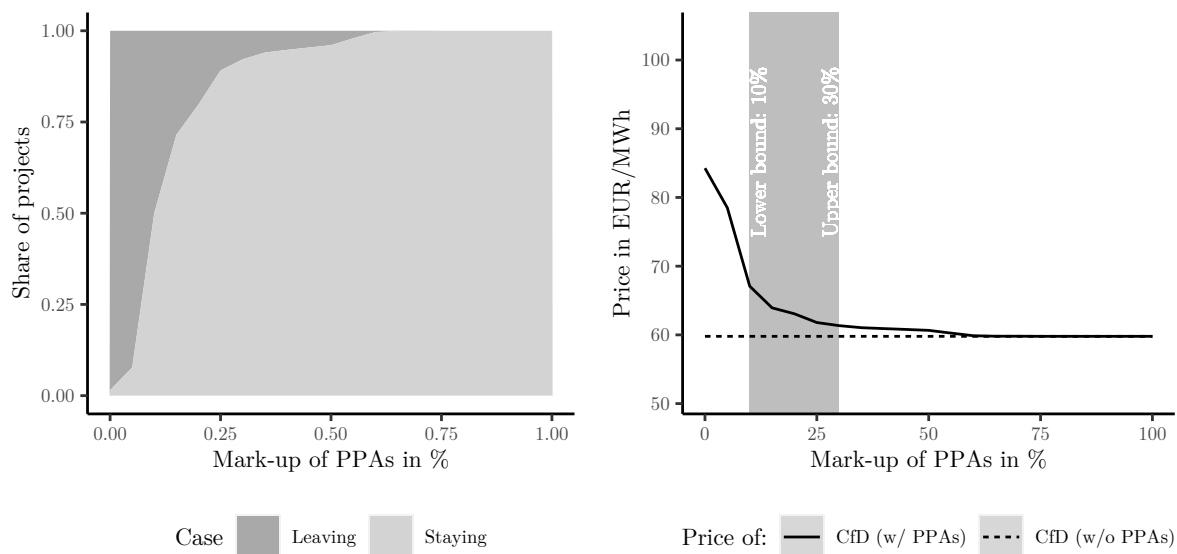
Auction	CfD-Price (w/ PPAs)	CfD-Price (w/o PPA)	Difference in Costs	Price Increase	Share leaving
	(EUR/MWh)	(EUR/MWh)	(EUR/MWh)	in %	in %
February 2021	69.9	65.1	40.5	7%	32%
May 2021	80.4	74.2	49.5	8%	42%
September 2021	75.5	70.3	45.8	8%	48%
February 2022	72.9	69.4	43.5	5%	23%
May 2022	74.9	69.8	45.9	7%	36%
September 2022	75.8	68.7	46.4	10%	52%
December 2022	69.2	68.9	26.8	0%	7%
March 2023	77.0	74.9	48.1	3%	16%
May 2023	76.5	73.9	50.8	4%	21%
August 2023	75.2	72.0	46.2	4%	30%
November 2023	82.2	75.5	51.1	9%	53%

Table 2: Overview of auction results for the base case mark-up of 10%

Auction	CfD-Price (w/ PPAs)	CfD-Price (w/o PPA)	Difference in Costs	Price Increase	Share leaving
	(EUR/MWh)	(EUR/MWh)	(EUR/MWh)	in %	in %
February 2021	66.8	65.1	40.5	3%	9%
May 2021	76.6	74.2	49.5	3%	11%
September 2021	71.1	70.3	45.8	1%	5%
February 2022	71.3	69.4	43.5	3%	10%
May 2022	71.3	69.8	45.9	2%	9%
September 2022	70.3	68.7	46.4	2%	10%
December 2022	68.9	68.9	26.8	0%	0%
March 2023	75.7	74.9	48.1	1%	4%
May 2023	74.8	73.9	50.8	1%	4%
August 2023	72.9	72.0	46.2	1%	4%
November 2023	76.6	75.5	51.1	1%	5%

Table 3: Overview of auction results for the base case mark-up of 30%

A.8 Perfect price discrimination



The left panel shows the share of projects deviating into the PPAs at different markup levels for the case of perfect price discrimination. The share of leaving projects is represented by the dark grey area, while the light grey areas represents the share of projects remaining in the public system. The right panel shows the resulting cost increases. The solid line represents the pool price when companies deviate into the PPAs, while the dotted line shows the price without an outside option. The results in both panels are averaged over all auctions.

Figure 11: Output of the numerical model

A.9 Project distribution for numerical analysis

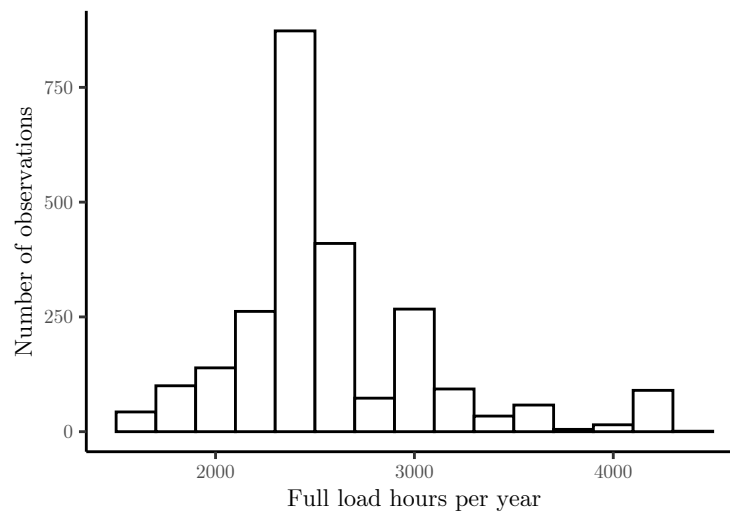


Figure shows the distribution of projects used in the numerical simulation based on the full load hours they achieve.

Figure 12: Histogram of projects in the dataset used for the numerical simulations

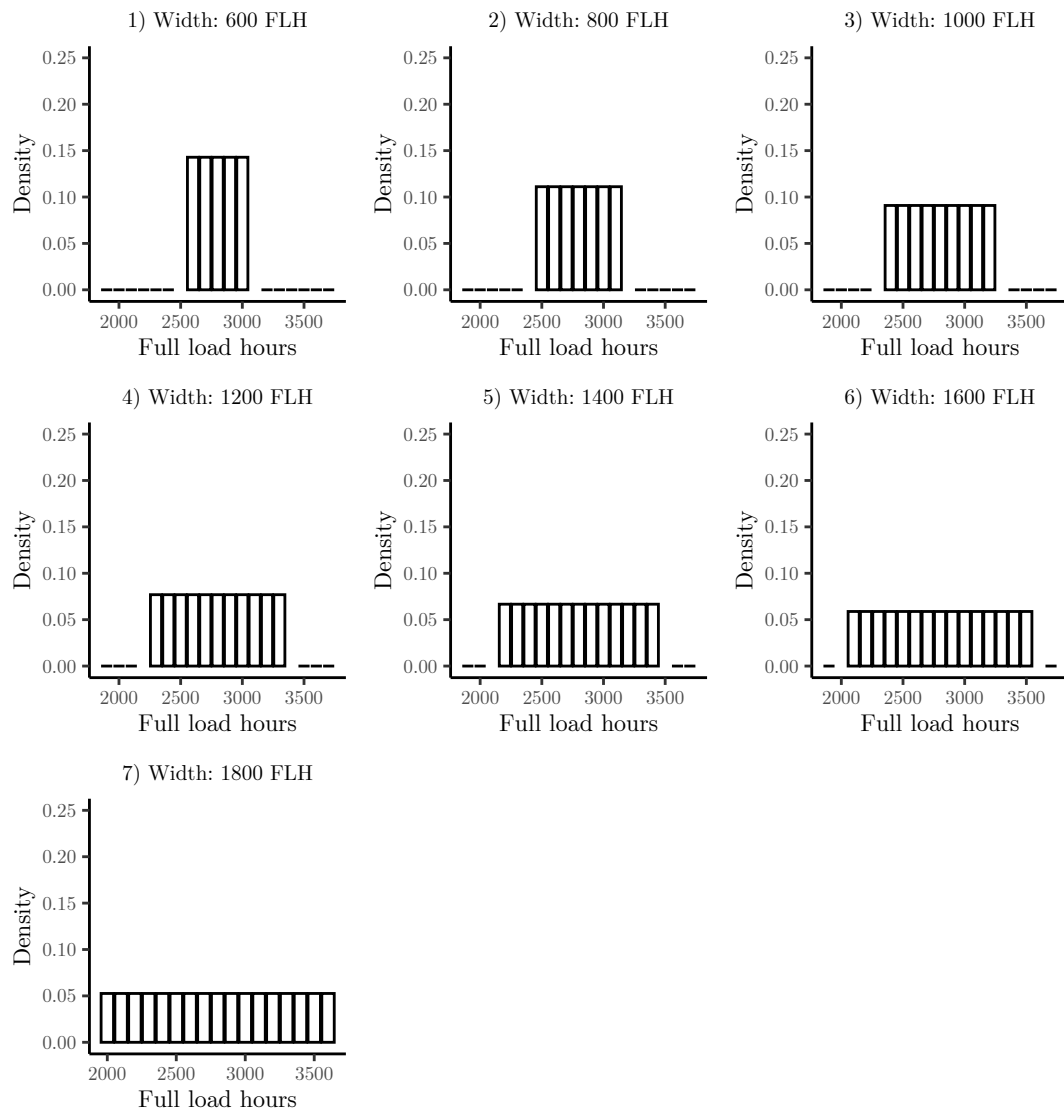


Figure shows the distribution of projects used for the sensitivity analysis with a wider distribution.

Figure 13: Histogram of project density used for the sensitivity analysis (wider distribution)

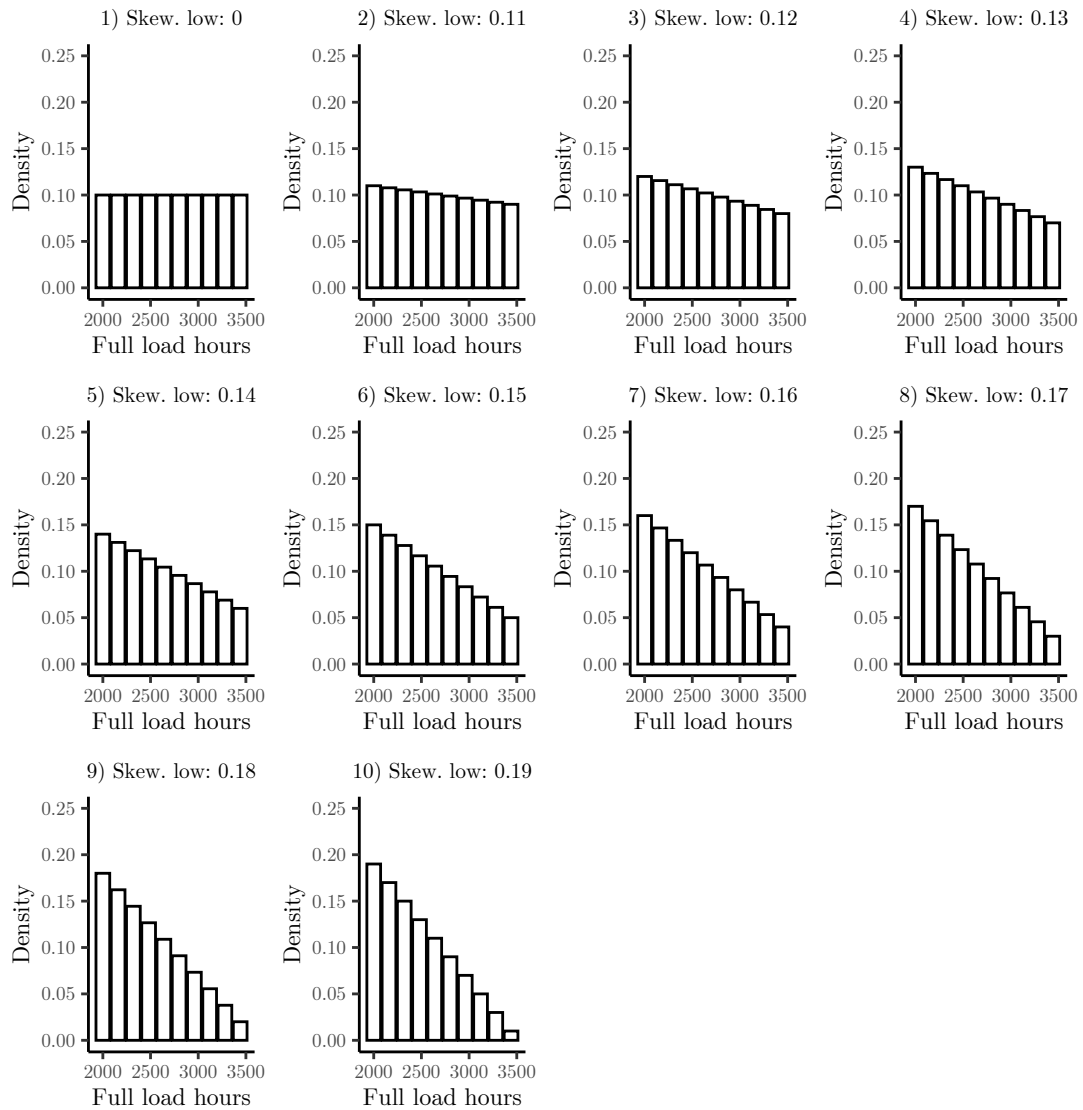


Figure shows the distribution of projects used for the sensitivity analysis with a more right-skewed distribution.

Figure 14: Histogram of project density used for the sensitivity analysis (distribution skewed towards high cost projects)

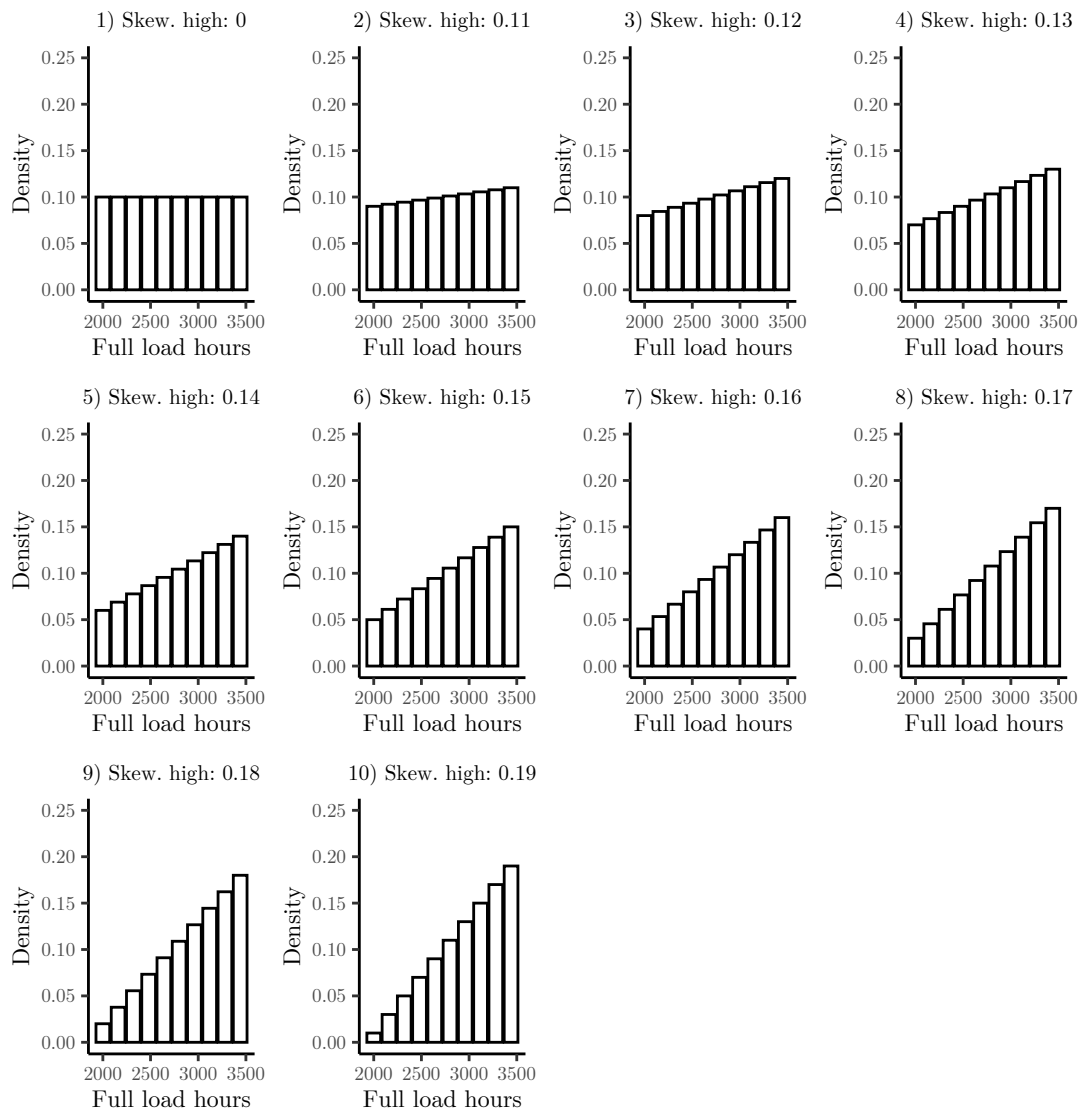


Figure shows the distribution of projects used for the sensitivity analysis with a more left-skewed distribution.

Figure 15: Histogram of project density used for the sensitivity analysis (distribution skewed towards low cost projects)