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Performance of Renewable Energy Policies – Evidence from Germany's Transition to Auctions

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Performance of Renewable Energy Policies – Evidence from Germany's Transition to Auctions

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Abstract

Government support for green technologies and renewable energy (RE) in particular has become an integral cornerstone of economic policy for most industrialized economies. Due to competitive price determination and supposedly higher efficiency, auctions have in recent years widely succeeded feed-in-tariffs (FITs) as the primary support instrument (del Rio & Linares, 2014; REN21, 2021). However, literature still struggles to produce causal evidence to validate mostly descriptive findings for efficiency gains. Yet, this evidence is needed as a foundation to provide robust recommendations to policy makers (Grashof et al., 2020). By utilizing a difference-in-differences (DiD) approach, this paper provides such evidence for a German photovoltaic (PV) auctioning program which came into effect in 2015. Results for this natural experiment confirm that cost-effectiveness improved significantly while previous literature shows that capacity expansion remained high. Results additionally show that falling prices for PV panels were the primary driver of cost reductions and wages also exert high influence on support price. Input cost development therefore indeed strongly influences support level which was the aim with introducing competitive auctions. Interest rate development cannot be linked to support level development, most probably due to the low interest environment in considered period.

Keywords: auctions, feed-in-tariffs, photovoltaic (PV), renewable energy policy, policy evaluation, difference-in-differences

JEL Codes: Q48, Q55, Q58

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1 Introduction

As one of the first countries to financially support the development of (RE) projects in a significant manner, Germany exhibits a long and insightful history of RE policy. Early on, Germany strongly pushed feed-in-tariffs as a policy instrument and gained success in capacity expansion as well as in the development of an extensive solar and wind industry.[1] Nevertheless, the European Union (EU) began to steer reform of administratively set FITs in 2011-2013 to leverage market-based elements which better align with competition principles (European Commission, 2011; Europ. Commission, 2012; Europ. Commission, 2013). Especially rapidly falling costs for solar components which led to surging installations, overcompensation of producers and high support costs, had previously clearly shown the weaknesses of administratively determined FITs (Fitch-Roy, Benson & Woodman, 2019. Also: Newbery et al., 2018). This prompted Germany to introduce auctions as its primary instrument in RE support and made this reform an intriguing case for analysis.

In the past, FITs were often deemed very successful in terms of installations development but also to be expensive (Newbery et al., 2018). Yet, they particularly outperformed in comparison to quota schemes (Butler & Neuhoff, 2008). Competitive auctions on the other hand make use of project developer's knowledge who determine their individual bids by discounting project costs and adding risk markups as well as margin (which according to economic theory depends on competitive intensity). Through competition, auctions are then supposed to drive down bids and thus support costs, while at the same time giving investors a chance to break even. This long-term financial security in turn also lowers risk premia (Fabra, 2021).[2]

The general aim of RE policy is to create demand for emerging RE technologies that would otherwise not exist or not exist in desired magnitude (Lesser & Su, 2018). Due to the pivotal role of such policy in combating climate change, several scholars contributed empirical evaluation of corresponding reforms as well as cross-country[3] comparisons. As will be shown, evidence in this regard points to well-designed auctions delivering positive results in terms of installations, decreasing costs, and further advantages. However, as Grashof et al. (2020) argue, many of these analyses are not suited to draw conclusions about appropriate support level as they only provide descriptive evidence on its development but do not account for other explanatory factors as for instance declining input costs which in the past were deemed to be the key contributor to support level reductions (e.g. Batz Linero & Müsgens, 2021). Even analyses that use econometric methods are in most cases designed for very specific issues and only deliver limited insight into support level development

[1] For PV see e.g. Karneyeva & Wüstenhagen, 2017.

[2] Even though, renewables are now often cheaper than conventional power sources, investors still price in risk premia in the absence of government support. This is due to marginal costs well below average costs which may imply future compensation that does not allow for amortization of initially high capital investment at increasing renewables shares (Fabra, 2021).

[3] Such comparisons are however difficult to undertake because auctions inherit many different design elements and countries differ in many individual-specific characteristics (del Rio & Kiefer, 2023).

(Quintana-Rojo et al., 2020). Moreover, due to difficulties in identifying suited counterfactuals, causal inference proves to be inherently difficult (Shrimali, Konda & Faroquee, 2016; Tiedemann et al., 2019).

To provide researchers and policymaker with more suitable evidence, this paper approaches described issue by identifying rooftop systems as a counterfactual for analysis of the German reform for ground mounted PV plants. While the latter were subjected to auctions from 2015 on, medium-size rooftop systems were not. As will be discussed, differences between ground mounted plants and rooftop systems can be assumed time invariant and make this case well-suited for DiD. By incorporating dedicated controls and demonstrating close similarities, parallel trends can be assumed. The resulting econometric model is of high quality and delivers unprecedented causal evidence for auctions' financial performance as well as further insights.

The remainder of this paper is structured as follows: first, it reviews existing theoretical and empirical research to describe channels of influence and past evidence. Second, reasons and aims behind analyzed case are discussed and previous evaluations for this specific framework reviewed. Third, the used method is presented with particular focus on validating assumptions and properties of the econometric model. The paper concludes with a discussion of found results and by outlining policy implications.

2 Literature review on support mechanisms

2.1 Theoretical predictions

When looking at theoretical properties of traditional RE support, such instruments are commonly distinct regarding their dimension of control into price- or quantity-based mechanisms. Historically, quantity mechanisms like quotas have often performed poorly due to high investment risks, as most RE investments require amortization periods of up to two decades and the perspective of short-term contracts with power providers rarely suffices for investors to realize such projects (Mitchell & Connor, 2004)[4]. This is even more the case in an environment where generating costs are expected to strongly decrease and therefore follow-up contracts would not allow for amortization. However, economists have often preferred quantity over price instruments due to lower amounts of information required and a higher degree of market integration.[5] Also, exposing producers to market prices allows for internalizing the costs of volatile and simultaneous production profiles (Fabra, 2021; Joskow, 2011).

Price instruments on the other hand provide investors with financial security to ensure amortization despite

[4] The authors show this was the case for UK policy until 2003. Del Rio & Linares (2014) also present evidence for quota underperformance in European RE policy.

[5] For Germany, many scholars and political consultancy institutions thus argued for introducing quotas, e.g.: Monopolies Commission, 2013; German Council of Economic Experts, 2012.

possible future energy market volatility (Newbery et al., 2018). Insulating against market forces in this fashion subsequently encourages investment into capacity expansion (Lesser & Su, 2008)[6]. However, this advantage in turn also implies disadvantages since decoupling from markets ultimately creates economic distortions via false incentives.[7] At the core of introducing effective price mechanisms therefore lie the administrative tasks of efficiently defining payment amount, duration and details of the policy design which may often include educated guesses about future events (Lesser & Su, 2008). In this regard, policymakers suffer from asymmetric information in the present as they do not possess sufficient knowledge about inherent costs, project challenges and risks in building RE plants (Fabra, 2021). Moreover, under uncertainty, determining suitable price levels is particularly inefficient when cost curves are rather flat (del Rio & Linares, 2014; Weitzman, 1974), especially if the legislator has limited information about the actual cost structures.

Some scholars and institutions like the European Commission therefore proposed in the beginning of the last decade to turn to auctions as an alternative which combines advantages of both solutions.[8] Similar to quotas, auctions are predominantly quantity-based mechanisms because they aim to fulfill clearly defined capacity targets.[9] Modus operandi for policymakers is thus directly capacity expansion unlike with price instruments which steer price in order to indirectly reach certain capacity goals. They also mitigate the aforementioned information asymmetry by making bidders reveal their true costs and therefore disclose the actual position of the supply curve (Bofinger, 2013; Haufe & Erhardt, 2018). Like pure price instruments, auctions provide investors with a reliable long-term means of income, the amount of which is known ex-ante (del Rio & Linares, 2014).[10] Payback periods can thus be calculated with a high degree of certainty before an investment decision is taken. Yet in comparison, auctions allocate these investments more efficiently (Klemperer, 2002) and clear the market in a manner which best satisfies supply and demand. In case of higher than anticipated demand for government support, this equilibrium price level would be lower or at least not higher compared to traditional FITs.[11] In case of target underachievement, auction mechanisms would enhance volume via increased market clearing price and still achieve set out targets at higher costs – if there are no price ceilings in place.

[6]Abolhosseini & Heshmati (2014) also show by literature review that FITs are for these reasons being preferred when investors require a low level of risk.

[7]In particular it entails e.g. volatility in capacity expansion or missing market signals with regard to market-based supply management.

[8]See e.g. Bofinger, 2013; del Rio & Linares, 2014; European Commission, 2013.

[9]For auctions, capacity targets represent more of a cap, which is often not quite reached. With quotas, capacity growth is achieved indirectly since e.g. electricity providers must ensure the quota, but built-up is a decision for RE-investors who can still under- or overdeliver. This would induce strong ex-post price movements.

[10]In case of auctions, the applicable tariff equals an investor's bid value if the bid is accepted. Otherwise, the project will not be realized.

[11]By instead applying caps in price mechanisms, one would introduce distortions which would ultimately require discriminatory allocation, e.g. first come, first serve (Winkler, Magosch & Ragwitz, 2018). One legitimate reason for such caps would however be to limit costs to society incurred by the support scheme and therefore not harm social acceptance.

On the other hand, auctions introduce higher transaction costs due to complex procedures and may reduce innovativeness (Finon & Menanteau, 2004).[12] Especially detailed planning and the necessity to precisely calculate costs in advance may result in prohibitive upfront effort when final project allocation is uncertain. This is even more the case for smaller project developers (Alvarez & del Rio, 2022; Anatolitis & Welisch, 2017; del Rio & Kiefer, 2023).[13] Since regional developers are often also smaller firms or citizen cooperatives, such progression could then harm social acceptance (Fell, 2017). Moreover, some auction designs, as for instance high penalties in combination with short realization periods, impose additional risks on project developers, which further intensify these effects and reduce participation (Côté et al., 2022; Gephart, Klessmann & Wiegand, 2017). It is therefore particularly important for policymakers to provide certainty and predictability (Kruger, Nygaard & Kitzing, 2021).

2.2 Competitive price determination

Auctions function by determining support levels fairly and efficiently through competitive bidding. Sufficient competition amongst bidders is therefore a basic precondition for them to perform well (del Rio, 2017).[14] As the example of German onshore wind, where lacking competition persistently led auctions to result in price outcomes at the ceiling level, has shown,[15] this is however not naturally the case. Policymakers are therefore required to intervene if things develop adversely. Other such obstacles, as for instance decreasing competition from smaller players, can nevertheless be mitigated ex-ante via specific policy design.[16] Additionally, while certain preconditions and penalties may increase realization rates,[17] those measures must likewise be carefully considered regarding trade-offs which induce diminishing competition by favoring large and established players (Côté, et al., 2022; Gephart et al., 2017).[18]

Further implications to competitive bidding processes are determined by an auction design's final price discovery method. For instance, in situations where costs of a certain technology are prohibitively high without governmental support, the state is in essence the only demander in a monopsony market. This was and predominantly still is the case for most RE technologies. In such a monopsony and under an auction regime, policymakers can make use of their market power to price discriminate and subsequently

[12] Del Rio & Linares (2014) indicate that these higher costs are probably passed through and increase the overall level of support payments. Del Rio & Kiefer (2022) find that literature mostly determines auctions to reduce innovation due to high competition and lower profits.

[13] Côté et al. (2022) even postulate a trade-off between actor diversity and low cost RE deployment.

[14] Haufe & Erhardt (2018) therefore stress the importance of reliable and long-term oriented framework as well as sustained and transparent conditions.

[15] See e.g. Batz Lineiro & Müsgens, 2023; Grashof et al., 2020.

[16] Lower prequalification requirements and penalties could increase small bidder's competitiveness (del Rio, 2017). Alvarez & del Rio (2022) however show that ensuring high participation of small bidders in auctions not always adds to increased auction efficiency.

[17] See e.g. Kitzing et al., 2022; Kreiss, Ehrhart & Haufe, 2017; Toke, 2015.

[18] Fell (2017) voices concerns about favoring established energy oligopolies.

lower support payments (Bofinger, 2013).[19] Sealed pay-as-bid auctions for example enable governments to price discriminate by awarding only bid-amounts, while uniform pricing guarantees support payments to all accepted bidders for the amount of the highest accepted bid (Haufe & Erhardt, 2018).[20]

This relation may however be undermined by strategic behavior. As many scholars show, bidders will maximize expected profits by bidding above marginal costs while considering the diminishing probability of a bid's success with increasing margin such that they must solve a profit optimization problem under uncertainty (Anatolitis & Welisch, 2017; McAfee & McMillan, 1987; Samuelson, 1986). Theory nevertheless predicts pay-as-bid auctions to deliver at least as well as uniform pricing (Samuelson, 1986), while modelling forecasts outcomes only to be slightly superior if bidders possess insight into market conditions and use this knowledge to maximize own profits (Anatolitis & Welisch, 2017). Still, literature sometimes suggests that heated competition in auctions may induce unsustainably low bids which would lead to low margins of error, increased sensitivity to risk or decreased realization rates (Stetter et al., 2020). This again is less likely the case for pay-as-bid, as underbidding is not rational when awarded payments equal bid price.[21] Also, the risk of strategic supply reductions and collusion is lower for multi-project developers in pay-as-bid with repeated interactions (Haufe & Erhardt, 2018).

Another important parameter for competitive intensity is whether auctions are designed technology-specific or -neutral. While especially German economists used to call for strict technology neutrality to achieve stronger competition,[22] such design is now mostly believed to oversupport (del Rio & Linares, 2014; Fabra, 2021; Newbery et al., 2018; Verbruggen & Lauber, 2009) mature technologies and fall short in considerations of diversification among power sources (del Rio, 2017). This issue is particularly important as different technologies stabilize grids via deviating production profiles that reduce supply peaks and thus the costs for grid interventions. It also benefits energy security if production technologies do not depend on the same naturally occurring phenomenon. Moreover, technology neutrality encourages the deployment of technologies that can be built cheapest, not considering arguments of actor diversity or fostering infant technologies that do not yet scale sufficiently. Technology-neutral auctions thus only partially optimize competition regarding static efficiency. Yet, as they fail to incorporate aspects of technological and therefore individual cost advancement, they are also not dynamically efficient (Winkler et al., 2018). Segmenting auctions by technology therefore increases social welfare as well as it reduces business risk such that project developers

[19]Bofinger (2013) also argues that policy could differentiate price in case of FITs, if differentiation depending on expected specific yield is possible (as with German onshore wind).

[20]Uniform pricing can as well be determined by the value of the lowest rejected bid (del Rio, 2017).

[21]Haufe & Erhardt (2018) argue that irrational underbidding is more likely to occur for uniform pricing when project developers want to be accepted, but hope for higher support payments in the end.

[22]E.g.: Monopolies Commission, 2013; German Council of Economic Experts, 2012. Botta (2019) stresses this is only true for static efficiency regarding cost considerations.

accept lower risk premia (Botta, 2019).

2.3 Empirical evidence

The two most important overall indicators of auction success are arguably low support levels and simultaneously a high degree of installation target achievement, including high realization rates (obviously, achieving these goals must also not result in high insolvency rates, monopolization tendencies, diminishing social acceptance or similar damages). Regarding support price development (usually referred to as cost-efficiency), there is extensive literature which points to a price decreasing effect of auctions in comparison to FITs.[23] Similar results are shown in literature that compares auctions against other benchmarks such as administrative ceiling prices or cost measures.[24] However, most of these studies do not consider effects of decreasing input costs for key components such as PV panels which are naturally very significant as these costs decreased substantially over the observed period and represent a major determinant of overall installation costs (Grashof et al., 2020).[25] Not including these measures would therefore falsely attribute price decreases to be an effect of the support scheme and as such overestimate a policy's influence.

As already mentioned, a more suited option would be to make use of econometrics. This would allow for a more systematic analysis, including control variables like technology specific cost reductions. To date, this has to the best of knowledge not been done in a very broad manner. According to Quintana-Rojo et al., who reviewed econometric literature on RE support policy, econometric analysis regarding effectiveness and efficiency of competitive mechanisms is lacking (Quintana-Rojo et al., 2020). Most publications that indeed employ econometrics do furthermore not analyze financial efficiency in relation to different policies or geographies.[26] Cassetta et al. (2017) seem to come closest by regressing base tariffs on different determinants and comparing auction outcomes to administratively set ceiling prices.

On the other hand, these analyses present more significant evidence for the performance of auction regarding capacity expansion (usually referred to as effectiveness). Bento et al. show that auctions exhibit the strongest positive effect on RE capacity growth compared to other support instruments (Bento et al., 2020). According to Kilinc-Ata, the effect of auctions is positive but smaller than for FITs (Kilinc-Ata, 2016). Bersalli et al.

[23] E.g., for within one geography: del Rio & Linares, 2014; Newbery, 2016; Sach, Lotz & Blücher, 2019; between geographies: Menanteau, Finon & Lamy, 2003; or both: Shrimali, et al., 2016; Winkler, et al., 2018. Del Rio & Kiefer (2023) recently confirm that there is consensus in literature. Butler & Neuhoff (2008) add that FITs yield lower prices than quota systems. Less successful transition from FIT to auctions however: Förster, 2016.

[24] E.g. Anatolitis, 2020; Cassetta et al., 2017; Eberhard & Kaberger, 2016; Elizondo Azuela et al., 2014; Kitzing et al., 2022; Sach, et al., 2019; Tiedemann et al., 2019. Bayer, Schäuble & Ferrari (2018) compare auction results to price levels in previous rounds. Yet, this analysis does not indicate effects of the introduction of auctions and developments are predominantly driven by underlying cost factors and competitive intensity.

[25] Toke (2015) even doubts for Denmark and South Africa that there is any price decreasing effect of auctions which goes beyond of what can be attributed to falling technology costs.

[26] E.g. Batz Lineiro & Müsgens, 2021; Bento, Borello & Gianfrate, 2020; Bersalli, Menanteau & El-Methni, 2020; Kilinc-Ata, 2016.

find FITs to outperform auctions in European countries with both schemes exhibiting significant positive performance, while they only find such evidence in Latin American countries for auctions (Bersalli et al., 2020). Realization rates though predominantly depend on the details of auction design and differ substantially among countries.[27] Carefully designed auction schemes therefore seem to not fall behind in terms of new installations. Empirical literature further provides clear evidence that the most important factor for auctions to deliver efficient pricing is that there is sufficient competition which means that there must be noticeably more supply in the market than auctioned capacity.[28] Such connections are for instance visible for South Africa or Germany.[29] These Findings are also consistent with predictions of the competition theory mentioned above.

3 Germany's policy transition

To evaluate success for the German introduction of auctions, one must first acknowledge the reasons and goals for which the new policy was adopted. This chapter therefore briefly outlines the circumstances and objectives for the German policy transition.

3.1 Feed-in-tariffs during the early energy transition

In 1991, Germany introduced its first law to strategically support RE producers with technology-neutral feed-in-premia.[30] In order to increase investment security and to allow for technologies other than onshore wind to materially benefit, technology-specific FITs were introduced in 2000.[31] Under this new regime of the first renewable-energy-act (EEG), Germany experienced well-known success in expanding its installed capacity of RE plants (Leiren & Reimer, 2018).

However, this success in capacity expansion resulted in an increased cost burden for German electricity consumers who financed support to plant developers via a RE levy as a surcharge on electricity price. This development counteracted public acceptance (Lesser & Su, 2008) such that FIT levels were decreased rapidly and capacity expansion slowed significantly from 2011 (Leiren & Reimer, 2018).[32] From May 2012, FIT development became rule-based but continued.[33] Such instance clearly shows theoretically predicted volatility

[27] E.g. Anatolitis, Azanbayev & Fleck, 2022; del Rio & Kiefer, 2023; Kitzing et al., 2022.
[28] E.g. Shrimali, et al., 2016; Tiedemann et al., 2019; Wrede, 2022.
[29] For South Africa see: Eberhard & Kaberger, 2016; for Germany: Tiedemann et al., 2019; lacking competition in German onshore wind: Batz Lineiro & Müsgens, 2023; Grashof et al., 2020.
[30] See §§ 2 f. Stromeinspeisungsgesetz (StrEG).
[31] The aim with FIT was to decouple support from electricity market price (Raabe & Mayer, 2000). Solar-PV and other technologies did not profit under the StrEG due to higher production costs, (Steingrüber, 2021). See §§ 3 ff. EEG 2000.
[32] Karakaya, Hidalgo & Nuur (2015) identify rapid FIT reduction in a case study for south Germany as the main cause for decreased capacity expansion.
[33] See § 20b EEG 2012, § 31 EEG 2014 and § 49 EEG 2017.

in capacity expansion with price side mechanisms. The early 2010s were inter alia therefore characterized by a lively discussion amongst German economists about introducing quantity-based instruments like quotas.[34]

3.2 The EU's push towards competition

Beginning with a first communication in 2011, the European Commission stated that RE technology had left an initial phase of technological uncertainty and could therefore increasingly be subjected to market forces (European Commission, 2011). To reduce disturbances to competition within the internal market, the Commission communicated its intention to adapt state aid guidelines accordingly (European Commission, 2012). Accompanied by determinations that auctions would fare at least as well as FITs and if well-designed lead to lower support costs (European Commission, Impact assessment, 2014), the Commission in 2014 passed renewed state aid guidelines on energy and environmental aid (European Commission, Communication, 2014) which effectively required member states to adopt auctions as their primary instrument for RE support to furthermore comply with state aid law.[35]

From a legal perspective, critics remarked previously guaranteed member state independence in selecting their own support schemes as well as the inappropriateness of commission-issued state aid guidelines as a vessel to deliver such substantial provisions.[36] Criticism from economists on the other hand predominantly aimed at in contradiction to the Commission statements' not too unambiguous evidence at that time for auction superiority and a poor level of conclusive prior experiences (Fitch-Roy et al., 2019). Nevertheless, the guidelines achieved strong adoption to a level at which auctions became the prevalent support instrument in the EU (CEER, 2018; Fitch-Roy et al., 2019). Merely smaller systems and innovative demonstration projects were exempted and could still be supported via FITs due to concerns about prohibitively high transaction costs.[37]

3.3 Germany's switch to auctions

In light of these developments and increasing belief that the German RE law had to comply with state aid law,[38] Germany developed its revised EEG 2014 in close coordination with the European Commission. With

[34] See footnote 5.

[35] Guidelines do not represent applicable law but as the Commission commits itself in the context of Art. 107 subs. 3 TFEU, they are often called de-facto legislation.

[36] E.g. Ekardt & Wieding, 2019; Kahl, 2015. Art. 3 subs. 3 letter a) in conjunction with Art. 2 letter k) Directive 2009/28/EC (European Communities) gave member states sovereignty of selecting their support schemes and as a directive (secondary EU-law) represents law of higher rank than guidelines.

[37] See rec. 19 Directive (EU) 2018/2001 in conjunction with the threshold values for PV and wind plants in: European Commission, Communication, 2014, rec. 125.

[38] Via *PreussenElektra* case law established non-applicability of EU state aid law regarding the EEG was later restricted via *Essent* and *Vent de Colère* decisions by the Court of Justice such that it was believed that the EEG had to comply at this point (Ludwigs, 2014). Germany thus filed an application for state aid compliance for the EEG 2014 which was later granted (see European Commission, State Aid, 2014, rec. 323). Later, in its *EEG 2012* decision (rec. 69 ff.), the Court of Justice however

this EU influence and additional public pressure to reduce support costs (Leiren & Reimer, 2018), Germany introduced a pilot auctioning scheme for ground mounted PV with the goal of achieving capacity expansion within a clearly defined corridor and thereby limiting expenditures (Hake et al., 2015). The intention with the pilot was also to gain experience and eventually roll out auctions as a general support instrument for all renewables by the end of the Commission-determined transition phase in 2017 (Kohls & Wustlich, 2015).[39]

While starting off with a design of pay-as-bid, the legislator then utilized uniform pricing before ultimately reverting to sealed static pay-as-bid auctions (Bundesnetzagentur, 2023).[40] With the subsequent EEG 2017 and after positive pilot experiences, auctions were introduced for all RE technologies and designed in accordance with state aid guidelines (Mohr, 2018). Due to arguments of grid stability and technological diversity, the Commission approved an exemption for Germany's technology specific design despite the guideline's principle of technology neutrality (European Commission, 2016 (rec. 225)). Germany additionally adopted the guideline's provided exemption for smaller plants which were furthermore entitled to FITs (Leiren & Reimer, 2018).[41]

3.4 Empirical analyses for the German PV auctions scheme

Meanwhile, sufficient time has passed to draw meaningful conclusions about the success of described reform. Few scholars have already empirically evaluated aspects of the German auctioning program's performance. Batz Lineiro & Müsgens (2021) determine that German PV auctions deployed capacities effectively with realization rates for auctions until December 2018 being solid with 83 % of awarded projects realized. Further evaluations also point to capacity build-up above set expansion path (Sach et al., 2019; Tiedemann et al., 2019). However, there is a substantial divergence for projects that participated in auctions before and after late summer of 2017 with realization rates being on average at 97 % and 56 % respectively. The authors hypothesize the reason to be anticipation by project developers of strongly falling technology costs which later did not materialize to expected extend (Batz Lineiro & Müsgens, 2021).

In an evaluation for the German government, Tiedemann et al. have further shown that actor concentration does not raise particular concern about market power and that competition was sufficient (Tiedemann et al., 2019). Especially early auction rounds exhibited positive results since bidding was heavily oversubscribed and awarded levels indicate competition to be effective (Voss & Madlener, 2017). Research additionally confirms that competition indeed exerts significant influence on bids in a sense that intensified competition

decided that the EEG did not meet the criteria to fall under state aid rules at this time.

[39]The EEG 2014 rules were therefore only approved by the Commission until 2017, European Commission, State Aid, 2014, rec. 323.

[40]Auction rounds 2 and 3 therefore by design yield a relatively higher value despite a lower accepted bid average.

[41]See exemption in European Commission, Communication, 2014, rec. 126.

led to decreasing bid values in an environment of falling costs (Batz Lineiro & Müsgens, 2021). These results are in line with evidence from other geographies as shown in chapter 2.3.

Welisch & Kreiss (2019) determine that the first few rounds of the German ground mounted PV auction program yielded higher than expected prices which were not caused by correspondingly higher input costs. They hypothesize that these discrepancies compared to predictions might be caused by uncertainty and unrealistic expectations of bidders regarding competition as well as necessary learning effects in handling such a new regime. After this transition phase, competitive pressure increased, and participants bid more aggressively such that resulting auction prices and realized margins declined sustainably. Empirical evaluation however shows technology costs reductions to be the most significant influence on bid values and the driving force behind the support cost reductions (Batz Lineiro & Müsgens, 2021). Tiedemann et al. (2019) also confirm effective cost reductions through the introduction of auctions despite inherently higher transaction costs. Due to this decline in accordance with input cost development and strong competition, Batz Linero & Müsgens (2019) conclude that German PV auctions exhibit the true level of marginal costs. Observed increase (Tiedemann et al., 2019) in the variance of accepted bid prices adds further substance to this conclusion.

Since mid-2019, PV auction levels are stagnating, which Sach et al. (2019) attribute to an ease in competition due to higher auction volume without an equal increase in bid volume. Yet, as technology costs have also been stagnating, this effect could just as well contribute to an explanation. Overall, most scholars still determine ground mounted PV auctions in Germany to have sufficiently achieved price reductions and capacity expansion (Batz Lineiro & Müsgens, 2021; Sach et al., 2019; Tiedemann et al., 2019). Additionally, data show there to be no significant downside for smaller or inexperienced bidders in the auction process as they do not face higher entry barriers, construction delays, or are more likely to underbid than large or experienced players (Batz Lineiro & Müsgens, 2021)[42].

4 Evaluation method and data

The aim of this paper is to perform econometric analysis that provides evidence for the case of German ground mounted solar PV[43] into support cost reducing effects due to the introduction of RE auctions. The following section therefore discusses the setup of analysis for this natural experiment. First, the selection

[42]The authors however find that large players earn higher profits which suggests that they are better at estimating the marginal bid such that they can bid strategically.

[43]Analyzing wind auctions would not yield worthwhile results since offshore wind auctions have not been in operation for a sufficiently long time and onshore wind auctions suffer from very low competition such that the introduction of these auctions is widely considered unsuccessful (Batz Lineiro & Müsgens, 2023; Grashof et al., 2020; Sach et al., 2016). Independent auctions for large rooftop PV systems have only been conducted since 2021 (Bundesnetzagentur, 2023).

of a suited counterfactual and its comparability towards the treated group are outlined. Subsequently, the methodology and its assumptions are carefully considered before the econometric model is presented.

4.1 Selection of a counterfactual

As shown before, many aspects other than introducing auctions can influence the achieved support level. Gaining insights therefore requires referring to regression analysis which makes use of a wide range of variables simultaneously. Yet, such a setting could never be fully determined and would suffer from unobserved variable bias. One must therefore draw on a counterfactual scenario to account for developments which are not modelled to enable causal inference. This would require comparing outcomes within the same jurisdiction under auctions with a scenario in which treatment (introduction of auctions) did not occur. At the same time, RE projects would need to be randomly assigned to either group to avoid selection bias (Angrist & Pischke, 2009). Literature thus describes causal inference in such settings to be inherently difficult or impossible due to the challenge of producing suited counterfactuals (Shrimali et al., 2016; Tiedemann et al., 2019).

DiD-methods can however mitigate certain types of selection bias if preconditions apply. By providing the grounds to incorporate a counterfactual scenario where time-invariant distinctions can be canceled out through differencing, one can mitigate the effects of nonrandom program placement at the policy level (Khandker, Koolwal & Samad, 2010). Like this, both groups are then not required to be balanced in every aspect without impeding causal inference. Still, DiD analysis' most critical requirement lies in identifying a comparable control group that has not been subjected to the intervention or was subjected at a different time[44]. For Germany, auctions were first introduced in 2015 simultaneously for all ground mounted PV in the entire country, such that geographically distinct counterfactuals can only be identified in other countries. General comparability and parallel trends assumption would however be difficult to uphold in these cases.

Yet, Germany did not introduce auctions on all PV types and project sizes. Especially small and medium-size rooftop systems remained under the FIT scheme and therefore constitute particularly suited counterfactuals. This is even more the case as they are being influenced by similar price drivers as the treated group and were not subjected to auctions to this day. Among rooftop systems, Germany distinguishes support level by size (installed capacity) but subjected these groups to changes in categorization. While groups of 0-10 kWp and 10-40 kWp only remain unchanged since April 2012, larger systems of 40-100 kWp were recategorized even after 2012 and are thus difficult to analyze consistently. With these restrictions, analysis is effectively limited to April 2012 and later and to system sizes below 40 kWp.

[44]See Roth et al., 2023: Staggered DiD.

The smaller PV systems get though, the more they exhibit electricity self-consumption and as such experience variation in underlying economic drivers compared to large ground mounted plants. Such effect could violate the parallel trends assumption. Also, professionalism and economies of scale are more closely related if control and treated group are more similar. Both reasons thus suggest selecting the 10-40 kWp category as a closer substitute to large solar plants and correspondingly better counterfactual.

4.2 Group comparability and control variables

A DiD approach's credibility hinges very strongly on the counterfactual's comparability. Besides quantitatively validating parallel trends pre-treatment, which exhibits perfect correlation,[45] qualitative criteria should also confirm similar attributes and drivers. It is therefore particularly important that treated and control group are affected by the same underlying mechanisms and that there were no policy interventions or singular events other than the introduction of auctions. Furthermore, both support frameworks must function properly to not introduce bias from poor policy execution.

Validating the comparability of cost components among both groups is critical in this context. Studies show PV panel prices, wages and debt (interest payments) to be highly relevant contributors to costs with their respective shares differing between large plants and smaller systems (Chung et al., 2015; Kost et al, 2018). Yet, smaller systems specifically exhibit higher relative shares of wage related costs as for instance increased overhead, such as planning effort, per capacity unit (Chung et al., 2015)[46]. Due to panel prices strongly declining and wages moderately increasing, it is obvious that relative cost shares may shift along observed timeframe and result in time-dependent divergence between both groups. It is therefore vital to account for changes in these input price factors via dedicated control variables. Consequently, I incorporate variables for panel prices, wages and interest rates into the regression.[47] One could further add inverters and other input cost components, but these three represent key determinants of different type and are thus taken as exemplary to avoid correlations between controls.

In many other aspects, rooftop systems and ground mounted plants in Germany are alike. As can be seen in table 1, this is for instance the case regarding system lifetime or efficiency. With sunshine intensity also being approximately equally determined by average German weather and climate conditions, electricity production per installed capacity unit yields very comparable results. Likewise, revenue channels for all PV system sizes

[45] Own correlation analysis of the support level for ground mounted plants and medium-size rooftop systems equals 1.00.

[46] This study analyzes the US, but since Germany and the US are both high wage countries and raw material prices are world market prices, findings are transferrable.

[47] Time-series data for wages and interest rates were obtained via Deutsche Bundesbank (2023). Different wage categories are being represented by an average for the construction sector. Data for panel prices in Germany are publicly accessible on the website of pv magazine (Schachtinger, 2021. Data are however not perfectly continuous as they were first published by source country and later by efficiency. Due to overlap, both time series are therefore adapted to transition frictionless from June to July 2016).

are very similar as they generate revenue predominantly through support payments per electricity unit produced. Being required to sell on electricity exchanges and thus being subjected to market prices and additional effort, larger plants are compensated via market and management premia.[48] Additionally, while larger plants are more often subjected to shut-offs, these lost revenues are compensated by grid operators.[49] Strong increases in forced shut-offs in the past years do accordingly not cause differences between groups. Both groups also benefit equally from prioritized dispatch.[50]

	Ground mounted PV	**Medium-size rooftop PV**
Cost development	same components, different shares: thus control variables	
System lifetime (Kost et al., 2018)	approx. 25 years	approx. 25 years
Sunshine intens. (Kost et al., 2018)	approx. 1.120 kWh/m^{2}a	approx. 1.120 kWh/m^{2}a
Efficiency (Kost et al., 2018)	not dependent on size of plant or system (75 - 90 %)	
Revenue source	support payment per kWh	support payment per kWh
Reliability of revenue source	less, but compensation	high
Prioritized dispatch	yes	yes
Self-consumption	extend unclear; minimization by group selection; rationally no influence on determination of support level	
Profit orientation	yes	yes
Further reform or events	import tariff for panels	import tariff for panels
Functioning scheme	yes	yes

Table 1: Comparability of ground mounted PV and medium-sized rooftop systems.

Slight divergence between the groups can by contrast arise as a result of electricity self-consumption. This can be the case for residential systems or PV on manufacturing site roofs, where shares of the generated electricity can immediately be used as a substitute for electricity from the grid. This is especially true if support reaches or falls below the price of electricity from the grid such that the share of self-consumption may increase more drastically than before and shift business cases in a divergent fashion compared to the treated group.[51] Lacking data to indicate such shares within analyzed groups, the magnitude of this effect is however difficult to determine. As described above, groups have been selected in a manner to minimize this effect, but

[48] See e.g. §§ 19, 20 EEG 2017 for market premium. For management premium see attachment 4 EEG 2012. It was later and still is paid implicitly, see e.g. § 21 sec. 1 no. 1 with § 53 sec. 1 EEG 2017.

[49] See Art. 13 sec. 7 Regulation (EU) 2019/943 (the EEG did not always define full compensation of lost revenues, e.g. §§ 14, 15 EEG 2021 guaranteed 95 %. This divergence is however only marginal).

[50] See § 11 sec. 1 EEG 2017 and earlier versions.

[51] Karakaya et al. (2015) provide evidence that in situations of grid parity and beyond, FIT level was no longer perceived as the main determinant for investing in PV for the case of south Germany. Arnold, Jeddi & Sitzmann (2022) also show that self-consumption in Germany increased in recent years and might be further strengthened by availability of lower-priced battery storage solutions.

it is still very probable to be present. On the other hand, being determined uniformly, support level would need to be adjusted for a group's average PV system. Lowering support for this reason would consequently be irrational for the state as only a fraction of systems benefit from self-consumption. Additionally, data do not show a strong relative increase in capacity build-up from smaller residential PV (Peper, Längle & Kost, 2020). Noticeable influence from self-consumption towards the validity of the counterfactual is therefore unlikely.

Further, systematic differences could also arise from decisions regarding smaller PV systems being taken less profit oriented because owners are more frequently citizens. This concern is nonetheless mitigated by the fact that studies have shown profit considerations to be the most important reason even in building residential PV systems (Schelly, 2014). Particularly in analyzed timeframe of this research project, environmental concerns did not suffice to convince potential builders without a perspective for sufficient profits (Palm, 2018). Additionally, such effects are again less relevant in chosen 10-40 kWp category as systems of this size are to a smaller extend residential.

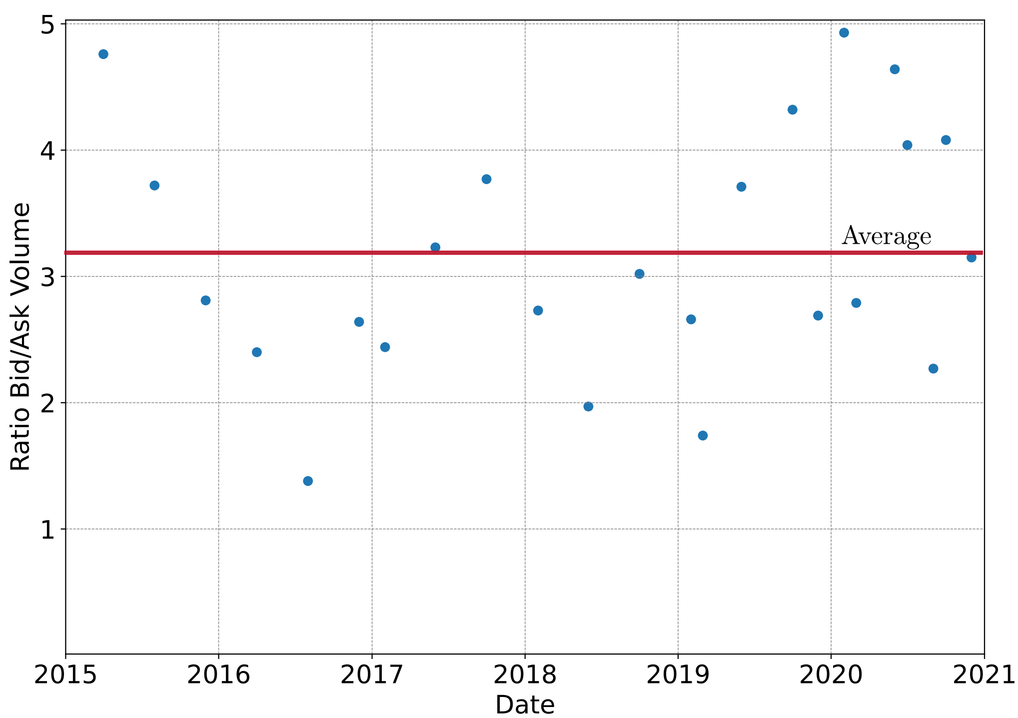

Figure 1: Competitive intensity as a ratio of bid/ask (Data: Bundesnetzagentur, 2023).

Another very relevant fact for comparability is that the introduction of auctions represents the only policy intervention in this period with implications for the two groups. Except for the introduction and termination of tariffs on Chinese PV modules[52] this is to the best of knowledge the case. The effect of these tariffs,

[52]See Regulation (EU) 513/2013 (in force June 6^{th} 2013 - September 3^{rd} 2018).

which affected input prices for both groups, is captured via mentioned control variable for panel price. Moreover, both support schemes must function properly for the evaluation to deliver valid results. For a single auction in March 2019 (see figure 2), auctioned quantity was raised and a large bid was unexpectedly excluded (Tiedemann et al., 2019). The removal of this outlier is tested (estimate 4 of table 2), but does not materially change results. Apart from this, auctions functioned properly and consistently delivered sufficient competition – a clear indicator of functioning price determination (see figure 1).

4.3 Assumptions and limitations

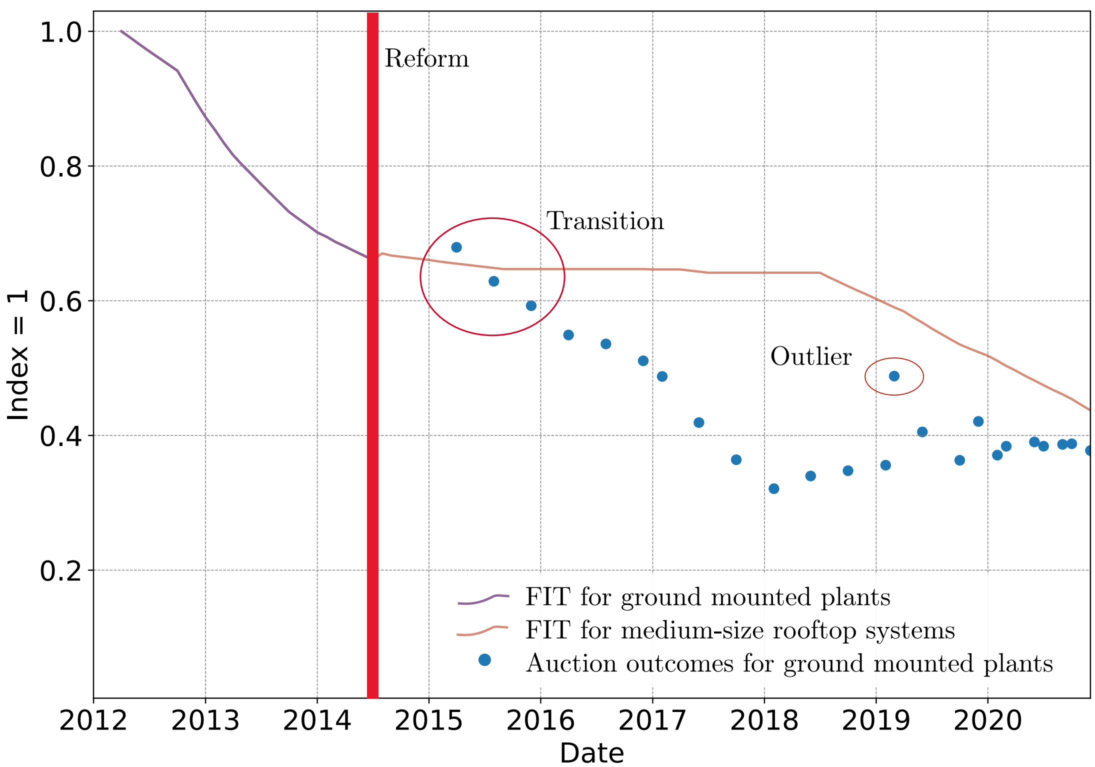

Figure 2: Development of FIT and auction outcomes (Data: Bundesnetzagentur, 2023; SFV, 2022).

In order for a DiD-approach to deliver valid results, three core assumptions must hold: (1) parallel trends, (2) no anticipation and (3) stable unit treatment value (SUTVA) (Roth et al., 2023). Parallel trends assumption for treated and non-treated groups arguably holds in this context as the previous chapter already established group comparability and dedicated controls have been introduced to mitigate shifting input cost shares.[53] This is additionally supported by parallel trends in both groups pre-intervention, which represents essentially an outcome by definition due to the determination of FIT levels via the EEG (see figure 2: pre-reform, both lines are congruent; also, see above: perfect correlation). As FIT development was rule-based, ground

[53]"Conditional parallel trends assumption", see Roth et al., 2023.

mounted plants would have also experienced the stagnating price development of rooftop systems in a counterfactual scenario. The visible decline from mid-2018 was caused by increasing capacity growth.[54]

The second assumption that needs to be valid is no anticipation, meaning that acting entities should not deviate in their behavior due to anticipating the intervention. In this circumstance, analyzed policy intervention was discussed and communicated by the legislator early on to allow actors to adapt to upcoming changes. Allowing anticipation has thus been a firm goal for policy makers. However, since FITs hold support levels fixed and economic entities cannot act within the price-dimension, they could only increase or reduce capacity build-up (i. e. quantity) which is not subject to analysis here. Still, one cannot forgo the possibility of temporary spillover by this behavior within the treatment group into early auction rounds after the intervention where quantity decisions indeed influence price-related outcomes. As this would only be short-term, implications of said effect would be small in evaluating the overall impact.

Yet thus, and due to an in any case detectable adjustment phase for bidders in the first rounds of auctioning,[55] following model will include a control-dummy for such possible transition period in the first three auctions (see figure 2). This is especially necessary as the second and third auction were held under uniform-pricing-regime and then changed to pay-as-bid from the fourth auction on.[56] Introducing this dummy therefore eliminates thereby caused disturbances and is supported by economic theory which suggests uniform pricing to deliver higher or at least not lower prices (see chapter 2.2). Furthermore relevant in this context is also more generally, that self-selection out of treatment is only marginally possible due to the fact that plant size is determined by project specifics. Escaping treatment would therefore at most be rational for a limited number of plants at the margin and thus represents a limited effect.

Third, one must exclude knowledge spillover to sufficiently satisfy SUTVA in a sense that policymakers may realize through auction outcomes that FIT levels could be adjusted downwards. Due to auction results being publicly available after closing of the bidding process, such information spillover must be considered highly plausible. Yet, it is legitimate to assume that its finding, adaption, and translation into applicable law would take time. One could therefore analyze a sufficiently short time after the reform and reasonably reject such feedback; particularly if the legislator did not steer support. Beginning with the EEG 2012, FITs were determined by a fixed mechanism which raised or decreased support depending on capacity growth.[57] In the post-intervention period, reduction rate did not change until the introduction of the EEG 2021 on

[54]This growth was according to Peper et al. mainly caused by large rooftop plants, which are often build on commercial buildings. Reasons were in particular rising environmental requirements and more generally for all system or plant sizes: decreased costs and higher electricity price (Peper et al., 2020).

[55]Welisch & Kreiss (2019) show theoretically and empirically that price discovery in the first 2-4 auction rounds was distorted with higher price outcomes due to reasons discussed in section 3.4.

[56]See § 13 FFAV. This effect is also presented in detail by Welisch & Kreiss, 2019.

[57]See mechanism in § 20b EEG 2012.

January 1^{st}, 2021.[58] Information spillover from auctions to FITs could therefore not have translated to the scheme until this time such that this analysis only covers outcomes until the end of 2020.

More generally in this context, exogeneity of the covariates must also be ensured. Representing on average below 50.000 employees in Germany for the analyzed timeframe,[59] dependencies of wage or overall economic development (interest rate) on the PV-sector are unlikely. However, as an early adopter in PV, Germany accounted for a very significant proportion of global demand for PV panels of up to 60 %. From 2012, this share nevertheless never exceeded 8 % and remained mostly below 4 %,[60] such that exogeneity can again be assumed. Furthermore, this analysis is subject to the limitation that official data in Germany do not provide evidence on which projects were ultimately realized. This can introduce systematic bias as it might be the case that low-bid-price-projects are not realized with a higher probability than higher priced competition (Grashof et al., 2020). Due to this fact, such bias is unavoidable – yet, as realization rates were altogether at robust levels, influence can be assumed limited.

4.4 The econometric model

Performed econometric analysis aims at unveiling the effect of introducing auctions into PV support policy on realized support level. It therefore regresses a DiD design and further covariates such that the resulting model appears as follows:

$$support_{it} = \beta_0 + \beta_1 reform_t + \beta_2 treat_i + \beta_3 interact_{it} + \beta_4 transition_{it} + \sum \beta_j control_t + u_{it} \tag{1}$$

The dummy for treatment timing, $reform_t$, represents the group-specific dummy and equals 1 for the treated group or 0 for the control group. $treat_i$ takes the value of 1 in the post-reform period or 0 for the pre-reform period. $interact_{it}$ expresses the interaction of both previous dummies $reform_t$ and $treat_i$ and therefore gives 1 for the treated group in the post-reform period and 0 otherwise.[61] Additionally, I introduce the dummy $transition_{it}$ to control for possible disturbances from uniform pricing scheme as the alternative price discovery method and actors adapting to the new scheme in the first three auctions. This additionally relaxes the no anticipation assumption as mentioned above. It therefore takes the value 1 for the first three auctions in the treated group and 0 otherwise.

The term $control_t$ in above equation substitutes three further control variables: $panels_t$ which is a time-series for PV panel prices, $wage_t$, which is a time-series of the sector specific tariff wage development, and $interest_t$, which represents the interest rate development of securitized long-term business loans. Subscript

[58]See § 31 EEG 2014, § 49 EEG 2017 and change in degression rate in § 49 sec. 1 EEG 2021.

[59]Data source: Federal Ministry of Economic Affairs and Climate Action, 2022.

[60]Data source: Fraunhofer ISE, 2022; SolarPower Europe, 2022.

[61]Subscripts t depict that a variable changes over time, while subscripts i represent variation among groups.

j can therefore take the values 5, 6, and 7. A more detailed description of these variables, including each data source, is presented in table 3 in the appendix. This includes $support_{it}$, which is the dependent variable and contains a time-series for all achieved support payment levels for ground mounted and rooftop PV. For ground mounted plants, these support levels are first FITs and after the reform they represent the outcomes of each auction. u_{it} captures the error term.

5 Discussion of results

This section discusses the results of proposed regression model. First, gained evidence is presented and assessed before its implications vis-à-vis existing literature are discussed.

5.1 Empirical evidence

Shown below are six different estimates for the econometric model. Columns (1-5) represent OLS-based estimates while (6) leverages a fixed effects estimation. Estimate (1) depicts the basic DiD design which is supplemented in (2) by additional controls for input cost development to satisfy conditional parallel trends. Data for both estimations omit observations for each group starting with the introduction of the treatment until including the third auction round (8/2014 - 12/2015) in order to mitigate disturbances from uniform pricing and validate the no anticipation assumption. Estimate (3) approaches the same issue by including all observations and introducing a dummy to control for this transition period as explained in the previous section. Estimate (4) differs from (3) only in the fact that an outlier (see chapter 4.2) has been removed from the data. Estimate (5) represents a sensitivity test in which the analysis ends in August 2018. All further observations are omitted. This is to validate that changes in the form of increased capacity growth, which led to decreasing FITs, do not impede the general outcome of the analysis. Estimate (6) includes the full data set as in (3) but uses a fixed-effects panel estimation method due to which the group indicator *treat* is omitted. Furthermore, standard errors for all estimates have been determined heteroscedasticity robust and are clustered on time period.

Results for the estimates show that the reform leads to lower support payments for the treated group (subjected to auctions) compared to the control group (continued FITs). The resulting coefficient for the key impact indicator $interact_{it}$ is negative for all six estimates and statistically highly significant. Testing for time-dependence by including separate interaction terms for each year post-reform also reveals that this result is robust and remains significant over the course of the analysis (see table 3). These outcomes suggest that the introduction of auctions causally lowered support costs in German PV compared to continued FITs.

The coefficient for $treat_i$ gives the value 0 for all estimates due to perfectly parallel pre-treatment trends.

Variables	(1) support	(2) support	(3) support	(4) support	(5) support	(6) support
reform	-0.221***	0.007	-0.029	-0.030	-0.028	-0.029
	(0.023)	(0.026)	(0.019)	(0.019)	(0.025)	(0.019)
treat	0.000	0.000	0.000	0.000	0.000	
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	
interact	-0.184***	-0.162***	-0.158***	-0.163***	-0.187***	-0.156***
	(0.015)	(0.015)	(0.015)	(0.015)	(0.023)	(0.015)
transition			0.101***	0.104***	0.123***	0.124***
			(0.028)	(0.028)	(0.034)	(0.021)
panels		1.259***	1.267***	1.268***	1.320***	1.284***
		(0.131)	(0.110)	(0.109)	(0.110)	(0.107)
wage		1.982***	2.167***	2.148***	2.037***	2.186***
		(0.411)	(0.286)	(0.282)	(0.306)	(0.284)
interest		0.015	0.011	0.008	-0.011	0.008
		(0.023)	(0.018)	(0.017)	(0.021)	(0.017)
Constant	0.814***	-2.281***	-2.472***	-2.443***	-2.311***	-2.496***
	(0.022)	(0.533)	(0.384)	(0.379)	(0.392)	(0.380)
Observations	137	137	157	156	115	157
R-squared	0.730	0.921	0.912	0.914	0.884	0.912
Adj. clusters	88	88	105	105	76	105

Robust standard errors in parentheses; *** p<0.01, ** p<0.05, * p<0.1

Table 2: Results of different estimation methods for the DiD model.

Variable	2016	2017	2018	2019	2020
interact_t*year	-0.133***	-0.205***	-0.251***	-0.129***	-0.124***
	(0.010)	(0.035)	(0.024)	(0.021)	(0.013)

Robust standard errors in parentheses; *** p<0.01, ** p<0.05, * p<0.1

Table 3: Yearly interaction terms (full estimate in the appendix (table 5)).

Figure 3 additionally visualizes how the treatment effect evolved over time. It depicts separate interaction terms for each conducted auction since the inception of the auctioning program in 2015. The first three data points represent auctions from the transition period and clearly show an increasing treatment effect, respectively an initially diminished effect. Beyond that, the treatment effect for the very first auction is even statistically insignificant (see appendix: Table 6). While the value of the indicator is subsequently rather volatile, the general effect remains negative and significant over the further course of the analysis. The depicted value and weak treatment effect for auction 14 constitutes mentioned outlier from March 2019.

In line with theory and above assumptions, the dummy $transition_{it}$ for the transition period is positive and also highly significant. Estimates including $transition_{it}$ and omitting the entire period lead to similar

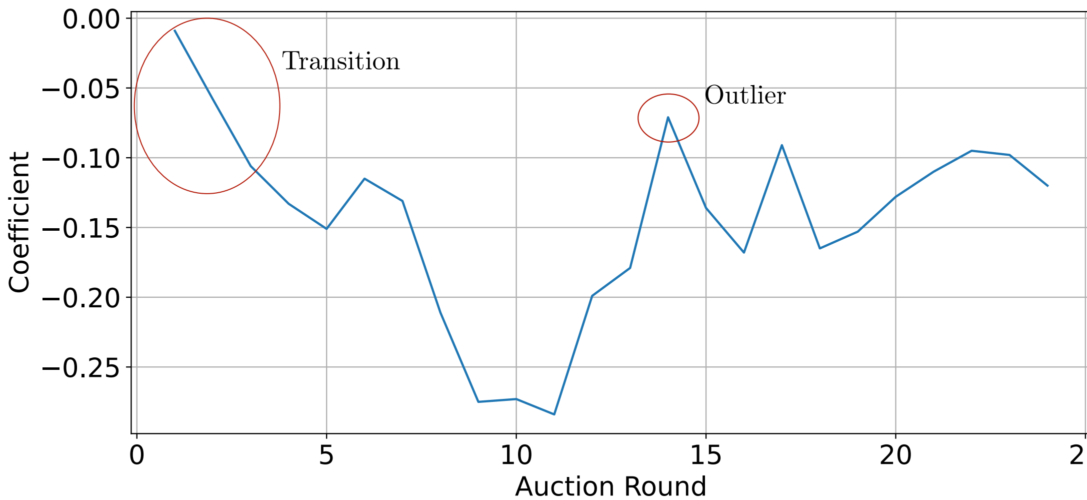

Figure 3: Development of the treatment effect over time (see table 6).

results (see estimates (2) and (3)) but the indicator additionally suggests that auctions within the transition period lead to higher support payments. These elevated levels might thereby be due to the uniform pricing scheme, the need for actors to adapt to the new regime and/or lower bid volume caused by e.g. anticipation. While including controls for input cost development is necessary to maintain the parallel trends assumption, they also strongly raise the model's efficiency and further visualize drivers of auction outcomes. PV panel costs ($panels_t$) as well as $wage_t$ evidently exert a particularly high influence on support and thus cost level development. Since panel costs have been declining strongly (in analyzed period: 77 %, Data: Schachtinger, 2021.[62]) the estimation also suggests that their price development indeed was the key contributor to falling support costs in the past. For high wage countries like Germany and in labor-intensive industries like solar installations, it is moreover to be expected that wage development represents a significant contributor to costs. However, as wages have only been developing gradually, their impact on support has in reality not been as strong as that of panel prices.

$Interest_t$ to the contrary is the only statistically insignificant variable. Additionally, its influence is also marginal. This outcome could very probably be explained by the fact that the European Central Bank kept interest mostly unchanged and on consistently low levels in observed timeframe.[63] Especially being perceptible only lagged and indirectly, a variable behaving this way would not give econometric models much opportunity for isolating its effect. Analysis with a longer timeframe could solve this issue if it incorporated periods of medium to higher interest rates. This topic would also be interesting for further research as its implications might be relevant beyond RE support policy in many investment-related contexts.

[62]See also Kost et al., 2018.
[63]The key interest rate has never exceeded 1 % in this period (see European Central Bank, 2022).

5.2 Implications vis-a-vis literature

Results of this econometric analysis are predominantly in line with theory and confirm most empirical publications which determined auctions to be superior to FITs in a cost perspective. Adding to existing literature, this paper determines German PV auctions to represent a successful policy which led to increased competition and lower cost. As the employed DiD analysis incorporates control variables and an untreated control group, it shows that lower support levels are in fact due to the change in scheme. However, the influence of input prices such as panel costs is much higher than the one of the reform.

What this analysis cannot fully answer is if lower support can be appointed to truthfully revealed costs plus a decent margin or rather strategic underbidding as described by Anatolitis & Welisch (2017) and remains to be seen in the longer term. Until today, possible strategic underbidding at least did not lead to strongly declining participation or high levels of concentration which would be expected with predatory pricing or frequent miscalculation by small bidders.[64] Furthermore, Batz Linero & Müsgens (2021) found a realization rate of 97 % for the first eight auction rounds and on average 82 % which points to a clear majority of awarded projects being realized in the end. The authors also attribute the apparent decline in realization rate to stagnating prices for PV panels and not to effects of underbidding.[65] Additionally, they previously confirmed high levels of competition for these auctions by using different methodology which further validates this papers results (Batz Liñeiro & Müsgens, 2019).

6 Conclusion and policy implications

This paper examines the performance of RE auctions in comparison to FITs regarding financial support efficiency. Evidence in previous research has only been descriptive and seldomly controlled for other explanatory factors such as input price development or made use of counterfactuals to allow for causal inference. Insights from this paper contribute to painting a clearer picture of auctions' outperformance compared to alternative RE support instruments. To this end, it analyzes the introduction of auctions for large ground mounted PV plants in Germany via a DiD design and by taking medium-size rooftop systems as a counterfactual. The main contribution lies in for the first time providing causal evidence that support level reductions are due to the switch from FITs to auctions. Incorporating further covariates, the model reaches a high level of explanatory power and delivers additional insights.

Gained insights confirm a support level reducing effect caused by auctions. Since the model controls for

[64] See Batz Linero & Müsgens, 2021.

[65] Additionally, the author's results show that competitive intensity was especially high for the first auctions where realization rate was the highest.

input price movements and risk premia can be assumed approximately constant,[66] what one can observe in essence is a confirmation of competition theory such that the introduction of competition leads to decreasing margins. Estimates moreover confirm that support level outcomes predominantly follow price development of major input factors such as wages or panel costs, whereas price reductions in panels represent the main reason for strong support level reductions in recent years. Furthermore, results hint that auction levels experienced unusually high outcomes for the first three rounds, probably due to actors adapting to the change in scheme, anticipation effects and/or the use of uniform pricing.

Results of this regression are subject to certain limitations. First, performed DiD analysis rests on certain preconditions required to be true. In this context, minor constraints due to real-life conditions and how they were considered within the model were discussed. Second, concrete inferences are not generally transferrable to other policy designs or geographies. This is due to a high number of possible implications from different design elements. And third, results of this analysis cannot be perpetuated to assume this kind of design generally leads to reported outcomes. Subsequent need for additional research remains in a sense that similar analysis could be performed in other cases where diverging conditions apply to further validate findings. Outcomes for German PV might also not remain constant in the future and should be followed closely.

Another interesting object for further study is the influence of interest rates. As RE investments are usually highly leveraged with debt, economic theory would suggest a high sensitivity to rate development. Yet, and probably due to the low interest environment in the past decade, performed analysis does not exhibit any significant influence to rate changes. With currently rapidly rising interest however, this factor becomes very relevant again. Policy and research would therefore greatly benefit from further insights.

Learnings from this paper can aid policymakers in better assessing RE support policy. This analysis complements existing indications by providing further insights into financial efficiency and drivers of bid prices. It moreover highlights phenomena in context of auction introduction and hints further benefits from reduced information asymmetry. Lastly, auctions represent an intriguing support policy framework for more than just RE technologies and could be applied in further instances. Close implementations would lie in similar technologies in the zero-carbon environment as for instance batteries and hydrogen. But also, specific goals in industrial policy might be achieved more efficiently by leveraging on gained experiences with RE auctions.

[66] In General, bids in this context are comprised of a plant's cost components, risk premia and margin. Since installers still have income security for 20 years, project risk increases only slightly relative to FITs.

7 Appendix

Variable	**Source**	**Time**	**Description**
$\mathbf{support}_{it}$	Bundesnetzagentur, 2023	2015-22	Resulting indicators for ground-mounted PV auctions of Bundesnetzagentur in Germany
	SFV, 2022	2000-22	Historical FITs for Germany by month of commissioning and installed capacity
$\mathbf{panels}_{t}$	Schachtinger, 2021	2011-23	Monthly average panel cost in the German market by country of origin or panel efficiency
$\mathbf{wage}_{t}$	Deutsche Bundesbank, 2023b	1991-2023	Industry tariff wage incl. the construction sector, excluding extraordinary items or bonus payments
$\mathbf{interest}_{t}$	Deutsche Bundesbank, 2023a	2010-23	Effective interest for securitized loans EUR >1 mn to non-financial corporations (10 years fixed rate)

Table 4: Sources and description of data used in the regressions.

Variables	(1) support
reform	-0.011
	(0.021)
treat	0.000
	(0.000)
transition	-0.058**
	(0.024)
panels	1.246***
	(0.113)
wage	2.153***
	(0.286)
interest	0.030
	(0.021)
interact16	-0.133***
	(0.010)
interact17	-0.205***
	(0.035)
interact18	-0.251***
	(0.024)
interact19	-0.129***
	(0.021)
interact20	-0.124***
	(0.013)
Constant	-2.494***
	(0.384)
Observations	157
R-squared	0.923
Adj. clusters	105

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table 5: Results for year-specific treatment effects.

Variables	(1) support
reform	-0.012
	(0.023)
treat	0.000
	(0.000)
panels	1.292***
	(0.122)
wage	2.283***
	(0.312)
interest	0.030
	(0.023)
1.auct_round	-0.009
	(0.010)
2.auct_round	-0.058***
	(0.008)
3.auct_round	-0.106***
	(0.012)
4.auct_round	-0.133***
	(0.009)
5.auct_round	-0.151***
	(0.008)
6.auct_round	-0.115***
	(0.007)
7.auct_round	-0.131***
	(0.005)
8.auct_round	-0.211***
	(0.005)
9.auct_round	-0.275***
	(0.008)
10.auct_round	-0.273***
	(0.013)
11.auct_round	-0.284***
	(0.015)
12.auct_round	-0.199***
	(0.013)
13.auct_round	-0.179***
	(0.009)
14.auct_round	-0.071***
	(0.012)
15.auct_round	-0.136***
	(0.008)
16.auct_round	-0.168***
	(0.007)
17.auct_round	-0.091***
	(0.008)
18.auct_round	-0.165***
	(0.010)
19.auct_round	-0.153***
	(0.010)
20.auct_round	-0.128***
	(0.008)
21.auct_round	-0.110***
	(0.009)
22.auct_round	-0.095***
	(0.010)
23.auct_round	-0.098***
	(0.009)
24.auct_round	-0.120***
	(0.009)
Constant	-2.667***
	(0.420)
Observations	157
R-squared	0.931
Adj. clusters	105

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table 6: Results for auction-round-specific treatment effects.

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