

How technology-neutral are technology-neutral renewable energy auctions? A review of auction design elements and an LCOE model

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Abstract

The transition of the power sector from fossil fuel-based to renewable energy-based electricity generation is crucial mitigating climate change. In this transition, technology deployment policies play a key role and have been introduced in many countries to support innovation and diffusion of new technologies. Historically, technology-specific feed-in tariffs were the deployment policy instruments of choice in many countries in order to establish niches for renewable energy technologies. Yet more recently, with rapidly falling renewable energy prices, many governments are switching to renewable energy auctions as they are perceived to be more cost-effective. Additionally, auction designs are more and more technology-neutral meaning that different technologies compete for the same auction award. Yet, studies in the innovation literature suggest that technology-neutral policy designs may not necessarily offer the same level playing field to all technologies but specifically favour some technologies over others. To contribute to the growing literature on auction design, I build a framework to systematically analyse auction design elements and conduct a comprehensive literature review summarising the effects of the different design elements on auction outcomes. Then, I quantitatively analyse the influence of selected design elements on the cost competitiveness of different technologies. The results suggest that technology-neutral auction designs are not necessarily technology neutral.

1 Introduction

Auctions and tendering schemes enjoy rising popularity as instruments to support the deployment of renewable energy technologies with many jurisdictions switching to auctions for large-scale installations [1]. Technology deployment policies play a key role in transitioning from fossil fuel-based power supply to renewable energy technologies and have been widely introduced [2] to support innovation and diffusion of new technologies [3]–[5]. Historically, technology-specific feed-in tariffs were the deployment policy instrument of choice in many countries in order to establish niches for renewable energy technologies. Yet more recently, with rapidly falling renewable energy technology prices, many governments are now switching to more cost-efficient policy instruments, such as auctions [2].

Auctions have been successful in many jurisdictions in triggering renewable energy deployment and cost reductions. Yet, the success of auctions has been shown to be largely dependent on the auction design [6], [7]. Research has analysed the designs of auctions in various contexts and its role in triggering a specific policy outcome, such as low prices [8], [9], high effectiveness [9], [10], but also delays in commissioning [11] and project cancelation [12]. However, the main body of literature on auction design focuses on single-case studies, e.g. [6], [13]–[19], and only few studies apply a systematic comparative approach which encompasses various countries and design elements [7], [20]–[22].

An important design choice is the technology specificity of an auction. Auction have seen great changes in the past designs in terms of the included technologies. In frontrunner countries, such as Ireland and the UK, where the first auctions were introduced in the 1990s, they did not differentiate between technologies and were thus technology-neutral with the result that the then cheapest technology, wind power, was the only awarded technology [14], [17], [23], [24]. Later, policymakers started implementing technology-specific auctions that offered different so-called technology bands and prevented different technologies to compete with each other for policy support. In South Africa, for instance, individual calls for auctions specify which technology is eligible to bid for a given auction volume [25]–[28]. However recently, the cost of renewable electricity generation and particularly solar photovoltaics (PV) has seen steep declines [29]. Consequently, solar PV and wind onshore are now not only able to compete with each other, but they can also often match the cost of conventional power sources. In reaction to this, many policymakers are redirecting their focus on technology-neutral auctions where renewable energy technologies compete for support sometimes even including other power sources [1], [30], such as natural gas in Mexico [6].

With auction design being such an important factor, technology-neutral auctions may be designed in a way that unintendedly favours one or another technology. Offering the opportunity for various technologies to bid in one auction may not necessarily offer the same conditions to all technologies as they have different characteristics, such as cost structure, resource use, permit requirements, and learning rates. Thus, overall technology-neutral auctions may feature some design element that negatively affect the competitiveness and thus exclude a technology from being awarded even though it would be competitive in other circumstances. Generally, innovation literature shows that policy instruments can be more or less technology neutral [31] and, depending on the instrument design, seemingly technology-neutral instruments may still end up favouring one technology over others [5]. This is corroborated by empirical cases, such as Germany where a technology-neutral pilot auction aimed at solar PV and wind onshore resulted in all contracts awarded to solar PV even though the

technology-specific auctions resulted in similar winning bid prices for solar PV and wind onshore. So far, auction literature has not researched how technology-neutral auction designs really are.

This paper thus aims at answering the following research question: How technology-neutral are renewable energy auctions really? To answer these research questions, I build a framework of auction design elements and their influence on auction outcomes based on an extensive and systematic literature review. In a second step, I identify the design elements that may affect technologies differently and analyse their impact on the cost competitiveness measured by the levelised cost of electricity (LCOE) of two renewable energy generation technologies, i.e. solar PV and onshore wind.

2 Technology neutrality and technology specificity of auction design elements

An important design element of renewable energy deployment policies, in general, and auctions, in particular, is their technology specificity or technology neutrality. Technology specificity refers to policymakers specifically differentiating policy support for different technologies, while technology-neutral policy designs do not make this distinction [31]. The technology specificity or neutrality of a policy design is important as it determines which technologies are deployed. In technology-specific auctions, projects only compete with projects of the same technologies in specific technology bands. In France, for instance, only small-scale solar photovoltaics (PV) installations are eligible to participate in the auction and thus to compete [32], while in Brazil, some auctions are specifically designed for wind power only [11], [18], [33]–[35]. In technology-neutral auctions, on the other hand, different technologies compete for the same auction award. In Mexico, for instance, various renewable energy technologies as well as gas-fired power plants are qualified to participate in their Clean Energy Auction and compete with each other for policy support [6], [36], while in the Dutch SDE+ scheme, all renewable energy technologies compete in one technology-neutral auction for a sliding feed-in premium [37]. Advocates of technology-neutral policy designs argue that policymakers should sustain from picking the supported technologies but let the markets decide in which technologies to invest [38]. Technology-neutral policies result in markets picking the currently cheapest and mature technologies, which offer the highest short-term efficiency, excluding premature, more expensive technologies. Conversely, proponents of technology-specific policy designs argue that policymakers should offer differentiated support especially to early-stage technologies in order to create a niche for them to be deployed, achieve cost reductions through learning, and potentially be able to compete with mature technologies in the future [3], [5], [31], [39]. On the one hand, this may lead to higher (short-term) policy costs, as novel technologies may be more expensive than more mature ones. On the other hand, it may increase the diversity of future technology options and prevent lock-in of the energy system into few technologies only [5], [31], [40]–[42]. Thus, the energy system may be more resilient against external shocks and energy costs may be reduced in the long run in case the novel technologies offer superior learning rates and cost declines. It is important to note that policy designs are not either technology-neutral or technology-specific but are technology-specific to a lesser or greater extent [31].

While studies on how different design elements in general and how technology neutrality or technology specificity in particular influence auction outcomes and, specifically, bid prices are widely available, the differences in how these design elements influence different technologies has not been

analysed. However recently, Haelg et al. [5] have shown that not only the technology specificity of a policy design determines which technologies are deployed but that technology-neutral policy designs may be more conducive to some technologies and thus result in favouring one technology over the other. Renewable energy technologies differ largely in their premises: they have different risk and cost structures [43], need different permits, and use different resources. Hence, some design elements may exert different influence on the cost and consequently the bid prices for different technologies. In the next section, I summarises relevant auction design elements and their influence on auction outcomes as assessed by existing literature and derive which design elements may disproportionately affect different technologies.

3 Methodology

In the first, qualitative part of this study, I conduct an extensive and systematic literature review for three reasons: First, to develop a framework of auction design elements and their outcomes, second, to analyse how auction design elements influence these outcomes, and third, to identify design elements that may directly or indirectly influence which technologies get deployed. The literature review was conducted in a semi-structured way based on ‘Google Scholar’ and ‘Scopus’ searches. The search keys were broad terms, such as “renewable energy auctions”, and “auction design”. Additionally, I used existing literature reviews and empirical papers as well as snow-balling from their citations.

In the quantitative part of this study, I build an LCOE model for the two renewable energy technologies, solar PV and onshore wind, in Germany and analyse the sensitivity of the LCOE to changes in the input parameters that are directly related to auction design elements.

Germany is an interesting case for two reasons. First, solar PV and wind onshore currently exhibit similar average total cost per produced electricity in Germany [44] and thus offer a good starting point for the sensitivity analysis. Second, Germany holds regular renewable energy auctions for large installations since 2017. Initially, only technology-specific auctions were offered differentiating between solar PV, wind onshore, wind offshore, and biomass. However in 2018, the German government launched a pilot scheme with biannual technology-neutral auctions open for solar PV and wind onshore projects. Interestingly, even though solar PV and wind onshore currently produce electricity at very similar cost and the awarded prices in the technology-specific auctions are similar for solar PV and wind onshore, only solar PV projects have been awarded in the technology-neutral auctions as the wind onshore bids have been significantly higher. This suggests that the design of the technology-neutral auctions is conducive for solar PV but less so for wind onshore.

The LCOE quantifies the average cost of producing a unit of electricity in a given power plant and represents the average minimum price at which electricity needs to be sold to break even [45]. To do so, the total average cost of building and operating the power plant over its lifetime is divided by the total electricity production of the power plant over that lifetime. The LCOE allows for the comparison of the cost per unit of electricity of different technologies.

$$LCOE = \frac{\sum_{t=1}^n \frac{Expenditures_t}{(1+i)^t}}{\sum_{t=1}^n \frac{Electricity\ generated_t}{(1+i)^t}} \quad (1)$$

Where n the plant lifetime, t the year, and i the discount rate. The data used to calculate the LCOE for solar PV and wind onshore in Germany are summarised in Table 2, and the base case data and the calculated sensitivities in Table 3.

Table 1. Technology and financial data used in LCOE calculation.

	Solar PV	Wind onshore	Source
CAPEX (EUR/kW)	700	1700	[44]
Annual CAPEX reductions	5.6%	1.2%	Adapted from [46]
Fixed annual O&M (EUR/kW)	15	30	[44]
Annual fixed O&M cost reductions	20.6%	2.5%	Adapted from [47]
Variable annual O&M (EUR/kWh)		0.005	[44]
Degradation	0.25%		[44]
Full-load hours (kWh/kW·a)	1050	2700	[44]
Lifetime (a)	25	25	[44]
WACC real	2.1%	2.7%	[44]
WACC nominal	4.1%	4.8%	[44]
Inflation rate	2%	2%	[44]

Table 2. Base case data and sensitivities.

	Base case	Sensitivities
Lead time to build	-	2 years, 5 years
Contract duration	20 years	± 5 years
WACC real	See Table 2	± 1%
Bid bonds	0	5 EUR/kW, 30 EUR/kW

4 Results

4.1 Auction design elements and their influence on outcomes

Renewable energy auctions include many different design elements. I classified these design elements in a framework with five categories according to the stage of the auctioning process when they are important: Auction scope, qualification requirements, allocation process, contract design, and auxiliary policies (see Figure 1). First, design elements in the *auction scope* define what is actually being tendered. Besides the *auction volume* (i.e. how much is being auctioned) and *auction format* (i.e. single-item or multi-item auction), they include more specific information on the eligible installations in terms of technologies (*technology specificity*), location (*location specificity*), and installation size (*size specificity*). Finally, the auction scope also encompasses design elements with regard to a longer-term *auction schedule*, the time between the auction publication and the submission of bids (*lead time to bid*), as well as if the auctioneer offers some additional *physical information*, such as resource studies, and how the *communication* between auctioneer and bidders is organised. Second, *qualification requirements* encompass the requirements bidders have to fulfil to be able to compete in the auction. They are usually implemented to ensure the seriousness of the bids and define how advanced the submitted projects should be. Design elements in this category include *bidder requirements* (e.g. track records or proven technical capabilities), *financial requirements* (e.g. cash flow records), *equipment*

prequalifications as well as more specific *local content requirements*, *connection prequalifications* (e.g. grid access agreements), *permit prequalifications*, *physical prequalifications* (e.g. feasibility studies), and *financial guarantees and bid bonds*. Third, the *allocation process* includes all design elements that refer to how the auction winners are selected. The *auction type* defines if an auction is static or dynamic, i.e. if the bidders submit one bid in a sealed bid auction or if they adapt their bids throughout the process in a descending-clock auction. Other design elements in the allocation process include the *pricing rule*, i.e. if the price is the only criterion and how it is accounted for (e.g. uniform pricing or pay-as-bid pricing), *seller concentration rules* (e.g. restrictions to the number of projects that one bidder can be awarded to) and other evaluation criteria, such as a *technical evaluation*, an *environmental evaluation*, and an *economic development evaluation*. Fourth, the *contract design* represents the contract awarded to the auction winners. Its design elements are not exclusive to contracts awarded in auctions but are the same as in other policy schemes by which PPAs are issued. The contract defines the *remuneration unit* (e.g. per unit of energy or capacity), the *remuneration type* (e.g. fixed feed-in tariff or feed-in premium), the *contract duration* and the *lead time to build*, the *currency* including potential indexation of the currency, the *counterparty*, the *contract transferability* (i.e. if the contract can be transferred to another project developer), possible *penalties* in case of non-compliance, and *payment and sovereign risk guarantees*. Finally, the auction might be accompanied by *auxiliary policies* which are not directly linked to the auction process but may influence auction outcome. They include a simplification of the *permitting process* (i.e. in a one-stop shop), the provision of a *transmission line* to the chosen site, as well as low-cost *financing* or *financial guarantees*.

The auction outcomes are heavily influenced by the above auction design elements. Yet, the effects need to be differentiated according to the outcome as not all design elements equally influence all aspects of auction outcomes. These outcomes include the *bid and awarded prices*, the *bid and awarded volume*, the *on-time project realisation*, *actor diversity*, *technology diversity*, *geographic diversity*, *local content* in the bids and related *local industry development*, and finally *long-term generation cost* (see Figure 1).

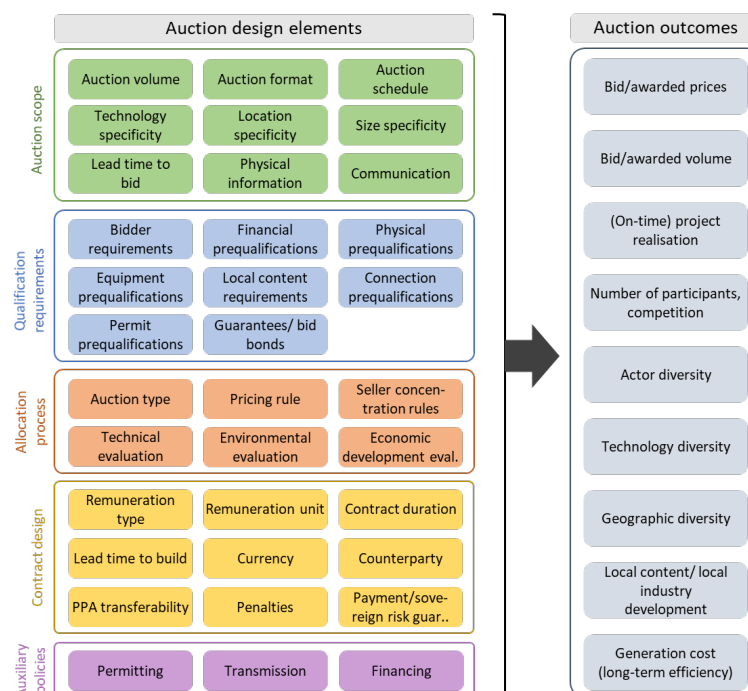


Figure 1. Framework of auction design elements and auction outcomes studied by literature.

An overview of the findings of existing literature regarding the influence of auction design elements on auction outcomes is given in Table 1. Most of the presented studies are qualitative country case studies, e.g. [11], [14], [16]–[19], [23], [24], [26], [28], [32]–[35], [37], [48]–[59], some are qualitative practical guides to auction design [6], [7], [10], [60], [61], and only few studies add a quantitative analysis, such as an agent-based model [62], [63], an econometric analysis [10], [64], or an LCOE or NPV model [8], [65], [66].

The reviewed literature suggests that only technology specificity directly influences technology diversity. However, all auction design elements influence the bid prices, either directly by acting on the transaction costs, the investment costs, the revenues, or risks and thus risk premiums or indirectly by fostering or impeding competition between the auction participants. Relatedly, all but one design element are found to have an effect on the number of participants in the auction or, more generally, the degree of competition. On-time project realisation seems to be influenced mainly by design elements related to qualification requirements and, to some extent, elements in the contract design. Finally, other auction outcomes, such as the bid volume, actor diversity, geographic diversity, local content and local industry development, and long-term generation cost have been less studied and are influenced by specific design elements only.

For the second step of this paper, I identified design elements that directly act on the bid prices and that indirectly influence the cost competitiveness of solar PV and wind onshore: lead time to build, contract duration, and bid bonds. First, the lead time to build refers to the period between the auction award and the actual plant commissioning. The literature review shows that long lead times may result in lower bid prices as project developers may speculate on technology price reductions [6], [7]. Therefore I expect this design element to be relevant in terms of how different its effect on different technologies is as past trends as well as future projections show that the technology prices evolve very differently [29], [46]. Second, the contract duration determines how many years the project developer can expect the generated electricity to be remunerated. Literature shows that long-term contracts directly impact the LCOE of projects [65], [67]. With different technologies exhibiting different cost structures in terms of investment cost and operation and maintenance (O&M) costs, this design element may differentially influence technologies. Finally, bid bonds are sometimes required to be able to participate in an auction as collateral in case of project delays or cancelation. Usually, they need to be paid per unit of capacity. Similarly to the previous design element, they may affect technologies differently depending on their cost structure.

Table 3. Influence of auction design elements on auction outcomes. The design elements are categorised according to auction scope (in green), qualification requirements (in blue), allocation process (in orange), contract design (in yellow), and auxiliary policies (in purple).

	Technology diversity	Bid prices and awarded prices	Bid volume and awarded volume	(On-time) project realisation	Number of participants, competition	Actor diversity	Geographic diversity	Local content, local industry development	Long-term generation cost
Auction volume		A high auction volume may attract more actors to participate and thus increase competition and achieve lower prices [1]. However, if the auction is too high, the lower competition leads to higher prices; conversely, lower auction volumes increase competition and reduce bid prices [6], [9], [10], [19], [20], [25], [26], [35], [50], [56], [68], [69]. Low auction volumes though may lead to aggressive bidding and underbidding as only few contracts are awarded [20].			High auction volumes may incentivize more actors to participate in the auction [1]. However, if the auction volumes are too high, competition is decreased since all bidders get awarded [6], [9], [10], [20], [25], [26], [50], [56], [69].			Lower auction volumes may increase competition and thus incentivise local content terms [26].	
Auction format		Single-item auctions may offer economies of scale and thus reduce bid prices [20].		Since generally only one project is awarded in single-item auctions, this may incentivise participants to underestimate their true cost and result in project delays and cancellation (winner's curse) [70]. Allocating the volume to be contracted to more than one project developer reduces non-compliance risk [20], [69].		Actor diversity increases with multi-item auctions as several participants are awarded a contract in contrast to single-item auctions where only one project can be awarded [20].			
Technology specificity	Technology-specific auction design can lead to technology diversity as policymakers can choose which technologies to include.	Technology neutrality favours cheap technologies and may thus lead to lower bid prices [6], [7], [20], [56], [60], [69]. Conversely, technology specificity may lead to supporting more expensive technologies and thus higher bid prices [6], [70].	Technology specificity and other demand bands may reduce the total submitted volume as some technologies may be excluded [7].		Technology-neutral auction designs encourages more actors to participate as more technologies are included [7], [20], [56], [58], [60], [71]. It may however also deter some participants as it increases insecurity with the risk of failure is hard to quantify [37]. Conversely, technology-specific auction designs reduces the number of eligible participants and thus competition [9].	In some cases, technology neutrality may impede small actors from participating [15], [20]. In other cases, such as offshore wind, technology specificity may only incentivise large actors to participate [72]. Generally, more technologies may be awarded with technology-specific auction designs and thus increase actor diversity [6].	Technology specificity may help to spread capacity across different regions [60], whereas technology neutrality may lead to deployment in a few regions only [9].	Technology-specific auction design may encourage local content in the bids [56] and local industrial value chain [6], [20], [60], [69].	Technology neutrality favours existing, cheap technologies and may thus impede long-term reductions in generation cost [7], [17], [20], [56], [58], [69], [70], [73] as it may not include technologies with the highest value for the total system [60].
Location specificity		Location specificity can lower investment cost thanks to reduction of site-specific risks, such as simplified permitting, present transmission line, etc., and lower development cost [1], [8], [20], [69], but also thanks to reducing the transaction cost of seeking for suitable sites [7], [20]. However, it may increase prices due to non-optimality of sites in terms of resources and market segmentation [20] and due to inflexibility [9].			Location-specific auctions may, on the one hand, discourage participation because of its limitation [9], but also lower participation costs and risks and thus encourage participation and competition [20] especially attracting new market entrants [60].			Location constraints or locational pricing may help to achieve greater geographic diversity [6], [7], [9], [20], [56], [60].	No location requirements may lead to concentration of installations in some areas preventing other regions from profiting from local industry development [7].
Installation size specificity		Lenient or no size restrictions will result in the project developers choosing the most cost-effective installation size and thus reduce bid prices [7]. Additionally, favouring small installations may increase bid prices by impeding economies of scale [1].	Restrictions to the installation size may lead to underserving of the auction [7] as many projects are excluded.		Size bands may deter the participation of actors [7], [56] if their projects do not match the required installation size. They may also incentivise participation of specific actors and competition within the bands [24].	Size caps may incentivise smaller actors to participate [56], [60].			

	Technology diversity	Bid prices and awarded prices	Bid volume and awarded volume	(On-time) project realisation	Number of participants, competition	Actor diversity	Geographic diversity	Local content, local industry development	Long-term generation cost
Auction schedule		Regular auctions decrease risks [6], [7], [20] and thus increase investor confidence [1], [6], [20], [56], [70] which reduces bid prices [6], [20]. Additionally, they may encourage technological progress and thus reduce technology prices [20]. Frequent auction rounds may prevent underbidding since bidders do not need to bid aggressively in a given round to secure a contract [20]. Intermittent auctions without long-term plan increase risks, reduce investor confidence and thus increase risk premiums [9], [14]. Finally, long time periods between auctions may limit competition [68] and thus raise bid prices, whereas unclear auction schedules may lead to underbidding [17].		Regular auctions may prevent underbidding and thus increase the likelihood of project realisation [20].	Regular auctions with a long-term schedule may encourage participation [9], [20], [60] by offering continuity in project development [7], [71], [74] and reducing investor risks [20], [70]. Conversely, intermittent auctions and long time periods between auctions provide insecurity, increase risks and discourage participation [9], [56], [63], [68].	Long time periods between auctions provide insecurity especially to small actors [63], [68].	Regular auctions with a long-term schedule and the resulting demand continuity help to build a local supplier industry [7], [20], [60].	Regular auctions may encourage technological progress [9], [20] and thus drive down long-term generation cost.	
Physical information		Physical information, such as resource studies and weather derivatives, helps predict future revenues better and reduce risk and related cost of capital [19]. Additionally, it may additionally lower bid prices by increasing participation and competition [20] and reducing transaction cost [1], [73]. On the other hand, lack of adequate information may lead to overly optimistic bidding and underbidding [20], [60].			Physical information, such as irradiation information, reduces information asymmetries, risks and costs to participation [20] and may specifically attract new market entrants [55], [60].	Information provision may benefit smaller actors who suffer most from information asymmetry [20].			
Lead time to bid		Short lead time may discourage participation, reduce competition, and thus result in high bid prices [20], [50].			Short lead time may reduce competition by discouraging participation [9], [20], [50], but also by resulting in flawed documents and the subsequent exclusion of bidders [8]. On the other hand, longer lead time may attract more participants [70].				
Communication with stakeholders		Open communication and dialog with stakeholders may reduce risks [20] but also competition [20] and may thus have ambiguous effects on bid prices. Yet, unclear auction procedure and requirements may reduce competition and thus increase prices [32].			Dialog between stakeholders encourages participation [74], especially of new entrants [60], by reducing risks and cost of participation [20]. Additionally, open and clear communication improves bid eligibility and thus competition [56], [58], whereas unclear auction procedures and criteria reduce eligibility of bids and thus competition [32].	Unclear auction procedure and requirements favour large players [32], and easy and transparent procedures may attract additional small bidders [60].			
Bidder requirements		Generally, prequalifications, such as track records, may help identify reasonably priced bids [60]. However, strict qualification requirements may exclude many potential bidders, reduce competition and thus increase bid prices [1], [20], while lenient requirements encourage more actors to participate, increase competition and thus reduce bid prices [68].		Stringent prequalification requirements, such as track records [11], ensure high rate of project realisation [7], [8], [11], [13], [20], [25], [55], as only participants with serious intent to realise the project may participate [68]. Conversely, lenient prequalification requirements increase the risk of delays and project cancellation [1].	Reasonable bidder requirements invite more actors to participate in the auction [8], [68], while strict bidder requirements may prevent actors from participating [1], [6], [7], [13], [58], [70], [74], [75], due to higher participation cost [20].	Strict bidder requirements, such as significant experience in similar projects, may favour large actors [72] and disincentivise small actors [13], [20], [58], [60].			

	Technology diversity	Bid prices and awarded prices	Bid volume and awarded volume	(On-time) project realisation	Number of participants, competition	Actor diversity	Geographic diversity	Local content, local industry development	Long-term generation cost
Financial prequalifications				Strict financial prequalifications, such as cash flow statements [20], ensure financial closure and viability of project [19] and thus decrease likelihood of project delays and cancelation [7], [68]. They may discourage speculators and financially insolvent companies from participating and thus increase the likelihood of project realisation [55], [60].	Strict financial requirements may deter potential participants [7], while low financial prequalifications incentivise more actors to participate and foster competition [60].	Strict financial prequalifications may deter small actors from participating as their financial resources and access to capital markets are limited [60].			
Equipment prequalifications		With lenient equipment prequalifications, bidders will choose cheaper technologies, incur lower investment cost and decrease bid prices [7], while narrow equipment prequalifications and additional requirements, such as building integration for PV [73], may force bidders to choose more expensive options and thus increase bid prices [20].			Strict equipment prequalifications may deter potential participants [7], while low technical prequalifications incentivise more actors to participate and thus foster competition [60].				
Local content requirements		Stringent local content requirements may increase bid prices as investment cost are high if local suppliers are not able to cover the demand and competition between suppliers is low [1], [7], [13], [20], [60], [76]. However, if the local industry is big enough to supply the local market, the effect on bid prices is small [1], [20].		If the local market is not able to cover demand, local content requirements may cause project delays [11], [13], [20]	Local content requirements may discourage actors from participating [20], [50], especially foreign project developers [8].			Local content requirements lead to local contents of bids [20], [60], [69], [77] and to the development of a local manufacturing industry [7], [61], [69].	
Connection prequalifications		Connection prequalifications may increase bid prices as they represent sunk costs [7], [68], [70] and shift risk to the bidder [11], [68] thus increasing risk premiums and cost of capital.		Grid connection prequalifications, such as grid access permits and access studies, decrease the likelihood of project delays and cancelation as delays in transmission construction and connection may be prevented [7], [11], [14], [19], [56], [70] and the proposed project are limited to advanced projects [68].	Connection prequalifications represent sunk costs and may thus disincentivise some actors from participating in the auction [7], [68].				
Permit prequalifications		Permit prequalifications may increase bid prices as they represent sunk costs and shift risks to the bidder [68], [70] thus increasing risk premiums and cost of capital.		Permit requirements may prevent project delays and cancelation as they prevent delays in permit issuance [19], [56], [70], limit bids to advanced projects [68], and discourages speculators [55]. Conversely, no permit requirements may lead to non-realisation [58].	Permit prequalifications represent sunk costs to the bidders and may thus deter potential participants [68], while low administrative prequalifications incentivise more actors to participate and thus foster competition [60].				
Physical prequalifications		Physical prequalifications, such as resource and feasibility studies and weather derivatives, may decrease bid prices as they help predict future revenues better and reduce risk [19], [78]. On the other hand, they represent sunk costs [25], [78] and may thus increase bid prices.		Physical prequalifications may improve realisation rates [56] as they increase certainty and thus reduce the chance of delays due to unexpected events [78] and to preparing the necessary documents [7]. Also they may discourage speculators from participating [55].	Physical prequalifications, such as feasibility studies, deter actors from participating and decrease competition [7], [78].				

	Technology diversity	Bid prices and awarded prices	Bid volume and awarded volume	(On-time) project realisation	Number of participants, competition	Actor diversity	Geographic diversity	Local content, local industry development	Long-term generation cost	
Financial guarantees, bid bonds		The deposition of financial securities, such as bid bonds, may increase bid prices [78] as they increase risks [6]. They reduce incentives for underbidding [69], [70] and help to identify reasonably priced bids [60].		Financial guarantees ensure the participants' intent to build the project and improves realisation rates [7], [10], [20], [56], [68]–[70], [73], [78].	Costly bid bonds or financial guarantees may exclude actors from participating [6], [18], [56], [68], [73]. However, [7] find that they impose only a slight burden on participants and thus do not restrict participation.	Costly bid bonds or financial guarantees may exclude small actors [6], [18], [58], [73] as it may pose a higher burden to them than to larger players and due to their insufficient credit-worthiness [56], [68].				
Auction type		Static auctions, such as sealed-bid auctions, may be less vulnerable to collusion than dynamic auctions, such as descending-clock auctions [6], [20], [73] and may thus result in lower prices [9], [19], [68], [69]. Yet, they bear the risk of overbidding and underbidding due to weak price discovery [6], [73]. Descending-clock auctions are transparent and may thus incentivise actors to lowering their bid prices [68], [69] and prevent underbidding as real prices are discovered [6], [9], [20]. Yet, other authors find that descending-clock auctions may incentivise actors to collude and offer higher prices [6], [68], [73] or to gambling and underbidding [79]. Other authors find that their transparency may actually prevent collusion [69]. Finally, hybrid auctions may allow for real price discovery (ceiling price) in a descending clock auction and prevent collusion thanks to a following sealed bid auction [9], [69].		Dynamic auctions may prevent underbidding and thus increase realisation rates [20].	Sealed-bid auctions are simpler and may thus reduce transaction costs and incentivise more actors to participate [6], [20], [69], [73]. Dynamic pricing may encourage participation in that participants do not need to bid their lowest price [69].	Sealed bid auctions are simpler and may thus reduce transaction costs and encourage small actors to participate [60], [73].				
Pricing rule		Price-only auctions lead to lower bid prices than multi-criteria auctions [20], [60]. They may however foster underbidding [80]. Literature is inconclusive on the effect of the pricing rule on bid prices. [70] find that the pricing rule has only a marginal effect on actual bid prices since other design options are much more important. Uniform pricing is reported to incentivise actors to reveal their real cost and therefore reduce bid prices [7], [20], [56], [60], [63], [68] but has, in practice, misled bidders to underbid [20], [56], [58], [62]. Conversely, [6], [60], [68] reason that pay-as-bid pricing may lead actors to guess the level of competition and not bid lowest possible price. Others find that pay-as-bid may prevent strategic behaviour [56] but that actors have incentive to submit similar prices [7]. Finally, [17] reports that pay-as-bid may incentivise underbidding.		Pay-as-bid pricing may favour more financially viable project with higher likelihood of on-time implementation [19], while uniform pricing may lead to underbidding and poor project realisation rates [20].	Price-only auctions may exclude many actors from participating and impede competition [23], [80]. Pay-as-bid is simple to understand and may thus incentivise various actors to participate [68].	Price-only auctions do not foster actor diversity [23] as they favour large actors [71]. Pay-as-bid pricing may disadvantage small participants as profits largely depend on the capability of the project developer to estimate the clearing price [6].		Price-only auctions may impede local industry development as international technology may be cheaper [23].		
Ceiling prices		Ceiling prices can prevent excessive prices [7], [68] and may prevent collusion and price manipulation [7]. However, high ceiling prices may lead to higher bid prices [50], [73] as actors may bid close to the ceiling price at low competition [1], [9], [60], [68], [70].	Ceiling prices may pose risk of undercontracting [7], [73].		Low ceiling prices may deter the participation of actors [7], [20], [60], [70], or if not communicated, exclude many bids and thus reduce competition [55], [69], [73]. Conversely, high ceiling prices attract more participants, though potentially weaker ones [20].	Low price ceilings may favour large players who can bid at such low prices [20]				
Technical evaluation		Technical evaluation criteria do not necessarily favour the lowest bids [20].								

	Technology diversity	Bid prices and awarded prices	Bid volume and awarded volume	(On-time) project realisation	Number of participants, competition	Actor diversity	Geographic diversity	Local content, local industry development	Long-term generation cost
Environmental evaluation						Additional evaluation criteria, such as environmental aspects, may disincentivise small bidders as their transaction cost are higher [73].			
Economic development evaluation		Local economic development criteria may lead to higher bid prices [50], [56], especially if the local industry cannot cover the demand [60], and do not necessarily favour the lowest bids [16].						Valuing economic development leads to development of local industry [56], [60].	
Seller concentration rules		Seller concentration rules may, on the one hand, increase bid prices as it may prevent economies of scale [7], but also reduce prices as it favours competition [9].			Seller concentration rules may incentivise more actors to participate [7], [9].	Seller concentration rules may incentivise small players to participate in the auction [7], [60] and mitigate market concentration [9], [56], [58], [70] thus increasing actor diversity.			
Remuneration unit		Remuneration per capacity reduces resource uncertainties and thus risk premiums and bid prices [7], [20] but does not encourage efficiency [20].							
Remuneration type		Feed-in tariffs may reduce bid prices as they provide stable revenues and thus reduce risk premiums and cost of capital [18], [20], [60] and encourage competition [20], [60]. Sliding feed-in premiums reduce risks somewhat compared to feed-in premiums and may thus result in lower bid prices [20].			Feed-in tariffs may encourage participation due to low revenue risks [20], [60].	Feed-in tariffs reduce risks and thus may attract more small players who cannot cover risks as well as large players [60].			
Contract duration		Long-term contracts may reduce bid prices as they directly reduce projects' LCOE [65], [67], reduce investment risks and thus cost of capital [7], [18], [56], [60], [67], and increase competition[60]. Short-term contracts, on the other hand, lead to more volatile revenues after contract termination [7] and thus increase risks. They may, however, lead to higher bid prices per unit electricity but not necessarily to higher overall policy cost [9].			Short contract durations may pose obstacle to financing and thus exclude actors from participating [7], while long contract durations reduce investment risks and may thus foster competition [60].	Short contract duration may affect smaller actors if their access to finance is more difficult [9] and their exposure to risks higher compared to large players [60].			
Lead time to build		Short lead times may increase bid prices by increasing sunk costs and risk premiums [9], [20], [68] and by hindering competition [20]. Long lead times, on the other hand, may lead to low bid prices since project developers can bet on reductions in technology prices and negotiate low-price forward contracts with manufacturers [8], as well as lower risks from delays and corresponding penalties [6], [7]. However, long lead times may also encourage speculation with falling technology prices and thus very optimistic bidding and underbidding [6], [7], [9], [20].		Short lead times increase the risk of delays [6], [7], [13], [68], e.g. because of longer than anticipated permitting processes [11]. They may however also push bidders to participate with advanced projects whose realisation is more certain [68]. Long lead times, on the other hand, may encourage speculation with equipment prices and thus lead to low realisation rates if prices do not drop as anticipated [6], [7], [9], [20].	Short lead times may exclude actors that are not ready to start right away [20], [52], [56], [73] and thus hinder competition.			Long lead times to build may incentivise investments in technology development and thus long-term technology price reductions [54].	

	Technology diversity	Bid prices and awarded prices	Bid volume and awarded volume	(On-time) project realisation	Number of participants, competition	Actor diversity	Geographic diversity	Local content, local industry development	Long-term generation cost
Currency		If the contract is issued in local currency, the bid prices may be higher as the currency may reduce the project developers' capability to raise debt [8] and fluctuating exchange rates increase risks and cost of capital [1], [7], [8]. Additionally, bid prices may be increased as the local currency influences investment cost for imported equipment pegged in US dollar [7], [8] and hedging against currency devaluation directly adds to LCOE [64]. Finally, if the local currency is prone to high inflation, the contract's value in real terms may considerably reduce in the future which may directly be factored into the bid prices [1]. Adjustments to inflation and indexation of the currency thus decrease investment risks and bid prices [18], [56].		Fluctuations in currency could affect the value of a bid post-auction and thus the ability of the developer to deliver projects in general or in a timely manner [8].	Local currency may discourage foreign bidders as risks may be too high [8].				
Counter-party		A credible counterparty increases investor confidence and thus reduces bid prices by reducing risk premiums [1], [7].			A credit-unworthy counterparty increases project risks and may deter bidders [7].				
Contract transferability		PPA transferability may lead to lower bid prices as it allows for hedging against general project risks and thus reduce cost of capital [52], [68]. Yet, it may also increase bid prices since some actors may choose to participate in the secondary market only and competition is thus reduced [68].		PPA transferability may ensure that non-implemented projects may be realised by other actors and thus increase general project realisation rates [68], [73].	PPA transferability may prevent some actors from participating in the auction process who speculate about better conditions on a secondary PPA market [68].				
Penalties		Penalties can increase bid prices as they increase risks and thus cost of capital [1], [6], [9], [60], [68], [70] and impede competition [9], [20], [52], [68]. However, high penalties may prevent underbidding [6], [11], [19], [61], [71], while low penalties may encourage underbidding [17], [24], [62], [76].		Costly penalties may prevent project delays and improve realisation rates [1], [7], [9]–[12], [20], [33], [56], [60], [68]–[70], [73]. Since they prevent underbidding, the financial viability of projects is increased which may increase the likelihood of on-time implementation [6], [19], [24], [25], [55], [61], [62], [69], [70], [77]. However, penalties alone may not be enough to increase project realisation rates [18].	High penalties may deter potential bidders and decrease competition [52], [56], [58], [60], [70], [73] as they increase sunk costs and risk premiums [68], [70]. Low penalties foster competition as the risk of failure after winning a bid is reduced [60].	High penalties may especially deter small actors from bidding [9], [20], [58] since their financial resources and access to capital markets are limited [60].			
Payment and sovereign risk guarantees		Payment and sovereign risk guarantees providing payment in case of counterparty default reduce bid prices by reducing risks and thus cost of capital [8], [19], [69].							
Transmission infrastructure		The provision of transmission line by the government or a utility reduces the risks and investment cost for project developers who may thus reduce bid prices [6], [65], [73]. However, the absence of transmission infrastructure to sites with good renewable energy resources may result in projects in suboptimal sites with lower capacity factors and thus higher bid prices [13], [16], [56].		The provision of transmission infrastructure may improve on-time connection of capacity to transmission network [19], [56], [60], but in case of delays in the expansion of the transmission network, also delay on-time connection [11], [18].	Previously settled grid connection terms for specific sites may attract new market entrants [60].				

	Technology diversity	Bid prices and awarded prices	Bid volume and awarded volume	(On-time) project realisation	Number of participants, competition	Actor diversity	Geographic diversity	Local content, local industry development	Long-term generation cost
Permitting		Burdensome administrative processes and difficulties in obtaining permits may lead to lower competition as well as higher risks and transaction costs and thus higher bid prices [9], [20]. Streamlined permitting reduces transaction cost and investment risks and thus bid prices [73].		Difficult permitting may cause delays or non-realisation [11], [14], [23], [24], while simplified permitting may prevent delays caused by a cumbersome administrative process [11], [20].	Burdensome administrative procedures may lead to low participation and competition [20], and difficulties in obtaining permits increase investor risks and may discourage participation [9]. Conversely, streamlined and centralised permitting may incentivize more actors to participate [1].	Difficulties in obtaining permits may impose higher risks on small players and discourage them from participating [9].			
Financing		Financing terms of international or local donors influence the cost of capital and thus bid prices [13], [25].		If funding is not disbursed as scheduled, projects may suffer delays [11].				Local donors may require local content and thus increase local content in the bids and local industry development [11].	

4.2 LCOE analysis

The LCOE analysis for solar PV and wind onshore in Germany resulted in base case values of 5.78 EUR/kWh and 5.73 EUR/kWh, respectively. The results of the sensitivity analyses are summarised in Figure 2.

Figure 2a displays how the lead time to build influences the LCOE of solar PV and wind onshore. For solar PV, waiting another 2 years or 5 years before building and commissioning the installation results in an LCOE reduction of 18.3% and 37.5%, respectively. The effect is substantially smaller for wind onshore which exhibits LCOE reductions of 3.1% and 7.7% for 2 and 5 years, respectively. These large differences can be attributed to the projected equipment and O&M costs which are estimated to decline much faster for solar PV than for wind onshore.

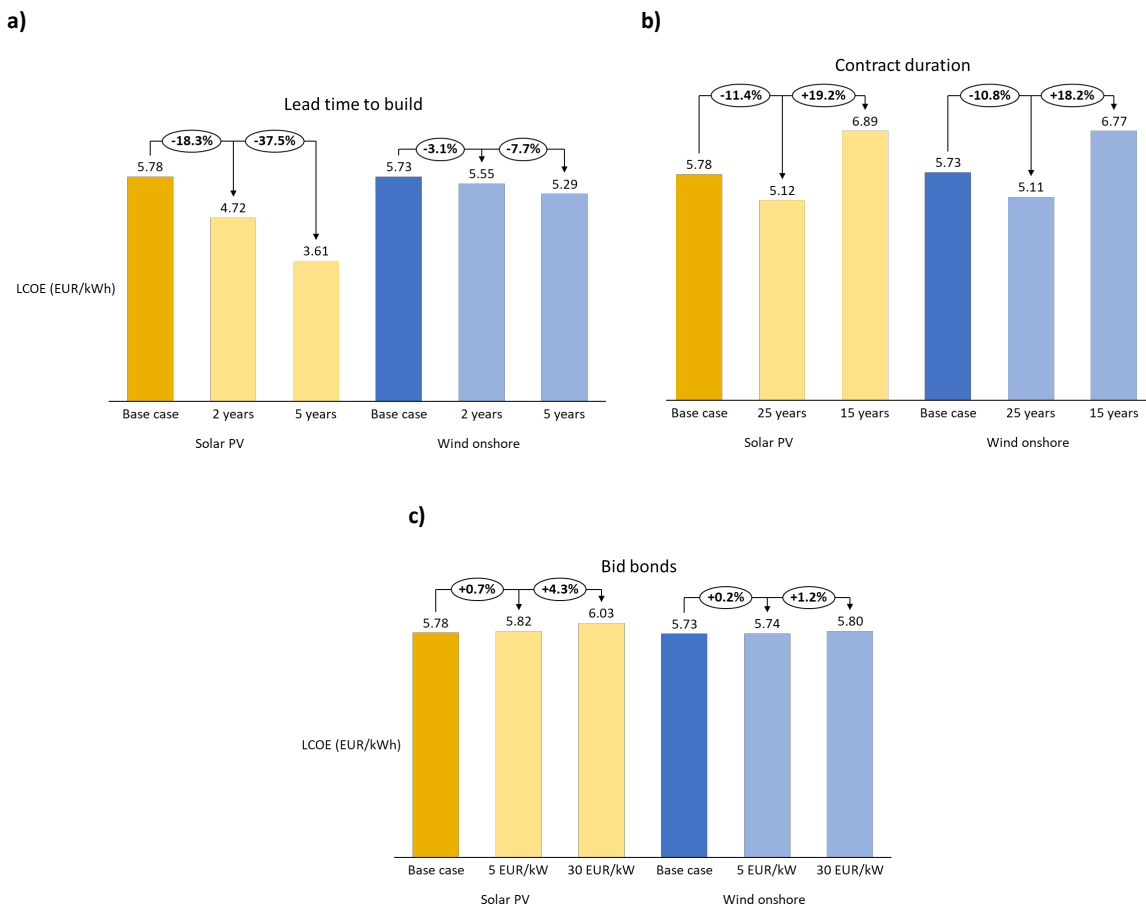


Figure 2. Results of LCOE analysis for solar PV (in yellow) and wind onshore (blue). The analysed sensitivities are a) lead time to build, b) contract duration, and c) bid bonds.

The sensitivities of the LCOEs for the contract duration are displayed in Figure 2b. Prolongation of the contract duration from 20 to 25 years results in declines of the LCOE by 11.4% and 10.8% for solar PV and wind onshore, respectively. Conversely, a reduction of the contract duration by 5 years to 15 years increases the LCOEs by 19.2% and 18.2% for solar PV and wind onshore, respectively. The contract duration thus does not influence the two technologies very differently. This is due to the fact that revenues in the far future are discounted in the LCOE model and consequently are less important than short-term investments and revenues. It is however important to note that the current model does not take into account potential reinvestments, such as the replacement of inverters or repowering of wind turbines, which may alter the results. Also, literature has shown that longer contract duration reduces future revenue risk and thus also risk premiums and WACC which is also not taken into account

in the current model. However, the results in Figure 2d (see below) show that the two technologies are similarly influenced by changes in WACC.

Finally, Figure 2c shows how the LCOEs react to bid bonds of 5 EUR/kW and 30 EUR/kW. These values correspond to the securities that the German government asks from solar PV and wind onshore, respectively. The results show that bid bonds of 5 EUR/kW increase the LCOEs by 0.7% and 0.2% for solar PV and wind onshore, respectively, and bid bonds of 30 EUR/kW increase the LCOEs by 4.3% and 1.2%, respectively. While bid bonds alter the LCOEs only marginally in absolute terms, they affect the two technologies quite differently. The results suggest that wind onshore is not as sensitive to such increases in CAPEX as solar PV because, generally, its CAPEX are higher and bid bonds have a relatively smaller influence.

5 Discussion and Conclusion

In this study, I conducted a comprehensive literature review summarising the effects of different design elements on auction outcomes. It has shown that all design elements affect bid prices and many affect competition and on-time project realisation. In the second part of the study, I quantitatively assessed how selected design elements influenced technologies differently. The results suggest that the lead time to build has not only a big influence on LCOE itself, it has also very different effects on the two analysed technologies as they exhibit different learning rates and thus their equipment and O&M prices reduce at different speed. The other analysed design elements do not offer such a clear picture. The contract duration influences the LCOE of both analysed technologies almost identically. While bid bonds have little influence on the LCOE itself, their relative impact on the technologies is very different because of technologies' different cost structure. Germany's technology-neutral auction pilot scheme actually differentiates between technologies by requiring different amounts of bid bonds of solar PV and wind onshore. Our results suggest that the 5 EUR/kW requested from solar PV do not increase its LCOE as much as the 30 EUR/kW requested from wind onshore, and this unequal differentiation may thus be one factor explaining the fact that exclusively solar PV projects were awarded in the technology-neutral auction scheme.

In line with recent literature on auction design, the results of this study suggest that policymakers need to be very careful when designing auctions especially considering the fact that low prices feature amongst the most important policy goals of auctions. With regard to technology-neutral auctions, this study shows that even seemingly technology-neutral design elements may have important consequences on the competitiveness of technologies and ultimately on which technologies are awarded in the auction.

This paper contributes to the auction literature threefold: First, it presents a framework of auction design elements which classifies these elements into five categories according to their prevalence in the auctioning process. Second, it offers a systematic and extensive literature review of auction design elements and their effects on the basis of the framework. Third, it adds to the scarce number of quantitative studies by analysing the cost competitiveness of two renewable energy technologies in the presence of different auction design elements. The paper also contributes to the debates about technology neutrality and technology specificity in the innovation literature [3], [31] in suggesting that technology-neutral policy designs may be more technology-specific as anticipated by policymakers.

The present study has many limitations especially regarding the quantitative analysis. The LCOE model is very simple omitting important elements such as future investments and repowering as well as

changes in cost of capital due to learning by the financing sector. Additionally, its focus on one country and two renewable energy technologies only is very limited. Yet, this offers interesting avenues for expanding this study in the future with a more sophisticated LCOE model as well as including more technologies, such as biomass, and countries with experience in technology-neutral auction designs, such as Mexico and the Netherlands.

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