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Designing renewable energy auctions for high realization probability — CfD and payment-only auctions

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ABSTRACT

In recent years, different instruments for renewable energy expansion have been debated. Among support and hedging instruments, two-sided contracts for difference (CfDs) have become the default in many countries and are promoted by the European Commission. At the same time, payment-only auctions (e.g., seabed lease auction for offshore wind) have also become established, where electricity sales are unregulated, but winners pay for the right to build and operate energy plants. Considering both cost uncertainty in the form of post-auction shocks and revenue uncertainty, we compare two-sided CfDs with payment-only auctions. Contrary to conventional wisdom, the non-realization risk is higher with auctioned CfDs than with payment-only auctions and is exacerbated by risk aversion, when developers can cope with both options. This result is reinforced when payments are due before the implementation decision. It can be altered in either direction by information updates about the future electricity market during the implementation period. Auctioneer's expected costs are higher in payment-only auctions if the bidders are risk-averse or risk-neutral and have higher costs. Thus, there is a trade-off for the auctioneer between realization and revenue. CfDs are particularly useful when developers need support or hedging for project implementation. Against this backdrop and considering asymmetric information, i.e., developers know best the economic conditions of their projects, we propose a design in which developers decide competitively between a CfD auction and a payment-only auction and which enhances the realization probability.

1. Introduction

Since the competitive allocation – typically by auctions – of rights for the construction and operation of renewable energy (RE) plants began more than 10 years ago, different approaches have been discussed and implemented (e.g., Anatolitis et al., 2022). In recent years, RE auctions have polarized between two trends, particularly in Europe: toward two-sided contracts for difference (CfDs), which serve as a hedging instrument for electricity sales, and toward payment-only auctions, in which auction winners make payments to the auctioneer for the right to build and operate a RE plant, while electricity sales remain unregulated. For this reason, we also refer to the latter as the market solution. Payment-only auctions have become particularly established for offshore wind, for example, seabed lease auctions in the UK (Laido and Kitzing, 2022; Laido et al., 2024). We use the term "payment-only" instead of "lease", for example, because our model also allows for payments from the auctioneer to the auction winner. The tension between these two trends became particularly apparent after the German offshore wind auction in 2023 (e.g., Ehrhart et al., 2024). In this auction, two winners submitted unexpectedly high payment bids of 12.6 billion euros for the leases of four wind sites with a combined capacity of 7 GW. This result prompted stronger calls for two-sided CfDs, as the payment-only auction was seen to drive excessive bidding competition, increase financing costs, and put pressure on supply chains (e.g., BDEW, 2025; WindEurope, 2024). Even the European Commission has expressed its support for CfDs (European Commission, 2023; European Parliament and Council, 2024). In this context, the increased non-realization risk of projects has also been emphasized, along with how CfDs could mitigate this risk.

The risk of RE projects not being realized is a key issue, as it could jeopardize politically determined RE expansion targets. This is particularly relevant for offshore wind: If the decision not to proceed with the project is made several years after the auction, it can cause delays of many years and may require the auctioneer to schedule a new auction for the site. Such delays result in welfare losses that can be reflected in the value of foregone greenhouse gas emission reductions (based on the emission permit price), higher electricity prices, sunk costs, health impacts, and other factors. While much of the literature emphasizes the benefits of integrating RE into power systems (e.g.,

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Lynch and Curtis, 2016; Koecklin et al., 2021), these benefits also underscore the opportunity costs in case of delayed realization. Using hypothetical projects, Longoria et al. (2024) show that without delay, wholesale electricity prices could be up to 10% lower in a given year, and CO_2 emissions up to 3.4% lower. Shawhan et al. (2025) demonstrate in simulations that delays in clean energy infrastructure hinder RE deployment, prolong fossil fuel use, and generate billions of dollars in annual welfare losses through higher emissions, health damages, and inequitable burdens on low-income households. This is further backed by empirical evidence. A Lawrence Berkeley National Laboratory survey (Nilson et al., 2024) finds that roughly one-third of U.S. wind and solar projects were canceled and half experienced delays of six months or more; cancellations led to average non-recoverable sunk costs of over $2 million per solar project and $7.5 million per wind project, and delays cost around $200,000 per MW.

A CfD is a financial agreement in which a buyer and a seller settle the difference between a pre-agreed strike price and the market price of an underlying asset at the time of delivery. In electricity markets, CfDs are long-term contracts between an electricity generator and the government, with payments linked to the actual electricity produced or the reference energy quantity (see Section 2 and Schlecht et al., 2024). CfDs are particularly useful when developers cannot realize projects solely with expected revenues from the electricity market and thus require government support. In this case, a CfD strike price (hereafter referred to as "CfD price") above the expected electricity price contributes to the expansion of RE. When projects are viable without government support, CfDs are still argued to reduce risks for developers, thereby supporting cost-effective and reliable RE expansion (e.g., Neuhoff et al., 2022; Fabra, 2023; Khodadadi and Poudineh, 2024; Đukan et al., 2025). In line with this, CfDs are associated by their advocates with a higher realization probability, especially for risk-averse developers (e.g., Neuhoff et al., 2022). Although many studies highlight the advantages of CfDs, their disadvantages are often understated or even overlooked, including the decoupling of the electricity market and potential barriers to market integration (e.g., Schlecht et al., 2024), which contradicts the European Commission guidelines that explicitly require the integration of RE into the electricity market.[1] While developments such as generation-independent CfDs address some of these weaknesses, these new CfD types have their own weaknesses (see Section 2.2).

Another often overlooked aspect is that CfDs are typically determined through auctions. In a CfD-allocating auction (hereafter referred to as a "CfD auction"), the bidder(s) with the lowest bid(s) win. It can be assumed that a developer who is willing to pay a high amount to the government in a payment-only auction (hereafter referred to as a "payment auction") would submit a low bid in a CfD-allocating auction, possibly even much lower than the expected electricity price.[2] Consequently, arguments in favor of CfDs, particularly regarding higher realization probability, should not be assessed in isolation but rather in relative comparison with payment auctions under the same conditions. This is where our analysis comes in: focusing on the non-realization risk, we compare a CfD auction with a payment auction under the same conditions. These conditions include the same bidders with the same projects as well as the same uncertainty regarding investment costs. Our model incorporates private investment cost of developers, overlaid with common investment cost uncertainty. In addition, the payment auction involves uncertainty regarding the electricity market prices (i.e., market revenue), whereas CfDs hedge against market price risk. Besides, developers' private investment costs may vary further between the two auctions due to different financing conditions and other factors.

Theoretical models typically assume that actors are either risk-neutral or risk-averse, with risk aversion being more common in analyses of companies or investors (e.g., Wüstenhagen and Teppo, 2006; Haering et al., 2020). This is also the case in analyses of the electricity market (e.g., Abate et al., 2022; Möbius et al., 2023). Some studies implicitly assume risk aversion by arguing that bidders add a risk premium to their bids in payment auctions relative to CfD bids (see Section 2, Neuhoff et al., 2022; Khodadadi and Poudineh, 2024). In policy debates, advocates of CfDs point to their role in reducing non-realization risk (i.e., increasing realization probability), arguing that risk-averse developers benefit from the reduced electricity price risk due to CfDs (e.g., Neuhoff et al., 2022). However, our results contradict this argument. We show that CfD auctions are not superior to payment auctions in terms of project realization. When projects are viable without government support, the non-realization risk is in fact higher for a CfD auction than for a payment auction under risk neutrality, and this effect is enforced by risk aversion. At first glance, these results appear somewhat paradoxical, since CfDs hedge market price risk, which would normally benefit risk-averse developers. As our analysis shows, CfDs induce more aggressive bidding behavior of risk-averse bidders due to their derisking effect, which implies less "bidding buffer" against cost uncertainty compared to payment auctions and thereby lowering realization probability (see Section 4). We also consider three extensions of the basic model. We show that the main result is robust to pay-as-bid pricing and is reinforced when payments are due before the implementation decision. However, it can be altered in either direction by information updates regarding the future electricity market during the implementation period.

Based on our analysis and observations of RE auctions and the development of relevant markets, we also examine whether it would be advisable to allow participating developers to decide whether to allocate a CfD in the auction. This idea is supported by asymmetric information, i.e., developers know more about the factors that determine the value of a project than the auctioneer, particularly under the constantly changing conditions in recent years, as well as the varying conditions of locations, such as those for offshore wind projects. To this end, we propose a mechanism in which developers competitively choose between a CfD auction and a payment auction, thereby achieving a high realization probability. This mechanism prioritizes payment auctions where feasible, while providing CfDs "as a safety net" when required for offshore wind expansion.

The remainder of this paper is structured as follows. Section 2 discusses different forms of support and hedging instruments as well as the payment auction. This provides the background for the formal analysis. Section 3 lays the foundation for the theoretical analysis presented in Section 4. Model extensions are presented in Section 5. Section 6 describes practical examples that highlight the weaknesses of the selected auction designs. Section 7 proposes a mechanism to address these weaknesses. Section 8 concludes with policy recommendations. Proofs of the lemmas and propositions are provided in the appendix.

2. Support and hedging instruments and the payment auction

This section briefly describes different forms of support and hedging instruments and the payment auction, which form the basis of the auction-theoretic analysis in Section 4. It serves as a short introduction, while the theoretical model applies more generally to CfD variants that substantially eliminate electricity price risk.

[1] European Commission (2018, Article 4): (2) "Support schemes for electricity from RE sources shall provide incentives for the integration of electricity from renewable sources in the electricity market in a market-based and market-responsive way, while avoiding unnecessary distortions of electricity markets as well as taking into account possible system integration costs and grid stability." (3) "Support schemes for electricity from renewable sources shall be designed so as to maximize the integration of electricity from renewable sources in the electricity market and to ensure that RE producers are responding to market price signals and maximize their market revenues."

[2] Although the payment bid and the CfD bid are expressed in different units (lump-sum vs. Euro/MWh), once both are converted to net present value over the CfD contract years, a higher payment corresponds to a lower CfD bid. See Section 6.1 for an example.

2.1. One-sided floating FIP (oFIP) and traditional CfD (tCfD)

The main support and hedging instruments for RE projects are directly linked to the amount of energy fed into the grid (generation-based) and take the form of a subsidy per unit of energy, kWh or MWh (e.g., Gephart et al., 2017). A central class of instruments is CfDs, also known as feed-in premiums (FIPs) (e.g., Anatolitis et al., 2022). Two variants are commonly distinguished: the one-sided floating feed-in premium (oFIP) and the two-sided traditional contract for difference (tCfD).[3] Both forms require operators to sell the energy they generate on the electricity market.[4] Payments to or from the operator are determined as the difference between a fixed premium and a reference price derived from the electricity price, e.g., the monthly average of the so-called technology specific market value (e.g., Hirth, 2013). Under a oFIP, if the reference price is lower than the premium, the operator receives the difference between the premium and the reference price for the quantity marketed; if the reference price is higher than the premium, no payment is made. A tCfD provides the same downside protection, but differs in that the operator must pay the difference back when the reference price is higher than the premium.

Consequently, by definition, while oFIPs function both as a support and a hedging instrument, tCfDs are a hedging instrument rather than a support instrument.[5] Both oFIPs and tCfDs protect the operator from low electricity prices. While oFIPs allow the operator to keep the excess revenue above the premium, tCfDs require the excess revenue to be paid to the government. Due to this design difference, the operator's indifference price – the award price at which the operator is indifferent about winning the auction or not – is higher for the tCfD than for the oFIP and thus also the bid prices and award prices.

In recent years, the scope of the application of tCfDs has steadily increased (Schlecht et al., 2024). This is also related to a forward-looking reform of the electricity markets (Fabra, 2023). An overview of the advantages associated with tCfDs is provided by Neuhoff et al. (2022). One of the main advantages of tCfDs over the oFIP and particularly over the payment auction (see Section 2.3) is that they reduce the developers' uncertainty regarding future revenue by eliminating exposure to electricity price risk. CfDs thereby lower financing costs for developers. This, in turn, reduces the overall cost of RE procurement and provides consumers with more stable prices (e.g., Steffen and Waidelich, 2022; Fabra, 2023; Kröger et al., 2022; Gohdes et al., 2022). Moreover, due to the absence of electricity price risk, it is also claimed that CfDs generally offer better protection against the non-realization risk than the oFIP or the market solution (e.g., May et al., 2018; Kell et al., 2022; Neuhoff et al., 2022; Stiftung Offshore Windenergie, 2025).

Despite these advantages, tCfDs have some drawbacks related to induced investment, production, and market distortions. A key concern is a weak incentive for market integration. Under a tCfD, operators tend to maximize output whenever the electricity price is positive ("produce-and-forget"), with limited adjustment of production to price variations, i.e., producing more (less) at high (low) prices (e.g., Khodadadi and Poudineh, 2024; Schlecht et al., 2024). This affects investment incentives for system-friendly RE facilities that smooth the RE generation profile with its typical fluctuations. In addition, tCfDs dampen fluctuations in the electricity market, which alters scarcity signals as the share of CfD-hedged plants increases. On the other hand, several design options, such as CfDs with a cap-and-floor system, longer reference periods, alternative settlement designs, and payout limitations at negative prices create, at least in part, incentives for market-oriented behavior and system integration (Kitzing et al., 2024).

oFIPs, in comparison, provide stronger incentives for market-compliant behavior and thus allowing a better integration of RE into the market. While a tCfD price must remain positive, at least in the long term, the oFIP price can be zero. This was first observed in an RE auction for offshore wind in Germany in 2017 (BNetzA, 2017). oFIP price at zero is equivalent to the market solution with zero payment (Section 2.3). The main criticisms of oFIPs are based on this. Their structure causes bidders to either forgo hedging, exposing themselves completely to market price risk, and benefit fully from possible high electricity market prices. Due to the negligible variable costs of RE, critics view high profits from high electricity prices as undesirable windfall profits (e.g., Khodadadi and Poudineh, 2024). Consequently, oFIPs are being phased out in practice. The European Commission explicitly supports the use of CfDs in these contexts.[6]

Finally, both oFIPs and tCfDs shift electricity price risks from the operators to the public. This raises the political debate of how risks can or should be distributed within society (Beiter et al., 2024). This aspect is more relevant for tCfDs because, when determined competitively, a tCfD price will be higher than a oFIP price.

2.2. Generation-independent CfDs

To address the weaknesses of generation-based tCfDs, several generation-independent CfD designs have been proposed in the literature (e.g., Newbery, 2023; Schlecht et al., 2024; Kitzing et al., 2024). One strand includes capability-based CfDs (cCfDs), proposed by the Belgian TSO Elia (Kitzing et al., 2024), where payments are linked to plant-specific generation capability (production potential) based on real-time measurements. Another discussed proposal is financial CfDs (fCfDs), in which operators receive a fixed (capacity) remuneration determined in advance and settlement payments based on a reference generator that closely reflects the production profile of the contracted assets (Schlecht et al., 2024). Beside these two proposals, different approaches have been proposed for determining the reference volume (Kitzing et al., 2024).

The common feature of generation-independent CfDs is that hedging payments are linked to production potential or reference volumes rather than actual energy generation. Operators can sell the energy they actually produced on the electricity market without any restrictions. Since they cannot influence the payments to or from the auctioneer during the operating period, they are incentivized to align their sales behavior with market conditions. As a result, the scarcity signals in the market are not disturbed, operators have an incentive to follow them, and market integration is promoted.

However, this only works effectively if the reference energy volume closely reflects actual production. Deviations between the reference and actual generation create basis risk. While more granular or plant-specific reference designs may reduce this risk, they complicate the concept, increase its cost, and weaken its generation independence and the positive effects associated with it.

[3] The oFIP is also referred to as the one-sided CfD. The tCfD is also known as the two-sided floating FIP. For clarity and better differentiation, this paper consistently uses the abbreviations oFIP and tCfD.

[4] The operator of a project is typically also its developer. In the following, both terms are used synonymously. The term operator is more common in the context of selling energy on the market, whereas developer is more frequently used in the context of auctions (where they are also referred to as bidders) and project implementation.

[5] Here, we follow the convention that an instrument is labeled "support" only if payments can flow solely from the government to the operator, whereas any two-sided contract – such as a tCfD with potential payments in both directions – is classified as a hedge, even if it can provide positive expected revenue when the strike price is set above the expected market price.

[6] Recital (35) of European Parliament and Council (2024): "Where Member States decide to support publicly financed investment by direct price support schemes in new low carbon, non-fossil fuel power-generating facilities to achieve the Union's decarbonization objectives, those schemes should be structured as two-way contracts for difference or equivalent schemes with the same effects such as to include, in addition to a revenue guarantee, an upward limitation of the market revenues of the generation assets concerned".

In addition, fCfDs shift weather-related volume risks from operators to the public sector (Schlecht et al., 2024). As with tCfDs, this raises the political issue of risk distribution (Beiter et al., 2024).

Another critical consideration is that generation-independent CfDs may create incentives for operators to optimize plant design to exploit the determination of the reference quantity. This is because deviations between actual and reference energy quantities are unavoidable, partly due to the excessive effort required for greater accuracy. These CfDs may even encourage the development of installations specifically tailored to this purpose. The creativity of market participants in this regard should not be underestimated. Such incentives can conflict with the objective of efficient, system-friendly energy production. This relates to the recommendation that support or hedging schemes should be designed as simply as possible because each additional rule or adjusting screw increases the risk of creating uncontrollable and undesirable incentives.

2.3. Payment auction

Since the first occurrence of zero-cent bids in a oFIP auction (see Section 2.1), many countries have switched to auctions in which the winners do not receive support or hedging but instead must make a payment to the auctioneer for the right to build and operate energy plants. In the context of offshore wind, this is also called a seabed lease. For consistency, in our model, we refer to these as negative payments, meaning that more negative numbers correspond to higher absolute payments from the auction winner to the auctioneer. Therefore, the auctions award the lowest payment bids (see Section 3.1). Auction winners participate in the electricity market and can decide whether to equip themselves with privately negotiated hedges, such as PPA or OREC.[7] This is also referred to as the market solution. Payment auctions, for example, are used for offshore wind in Germany, the US, and the UK (EEG, 2023; BOEM, 2022; Crown Estate, 2025).

3. Framework and setup of the analysis

The analysis compares auction designs for RE that eliminate electricity price risk for bidders with those that do not. For this purpose, the term CfD is used to cover different concepts of CfDs without distinguishing between them, as the concepts share the principle of excluding electricity price risk. The comparison focuses on the realization probability. The decision whether to implement a project (i.e., realization) becomes relevant, if the auction winner receives information after the auction indicating that the project's economic viability is lower than expected. In such cases, the decision then depends on penalties for non-realization.

3.1. Two scenarios

We consider two scenarios, C and N. Scenario C covers all types of CfDs that eliminate the electricity price risk. In the auction in C, bidders submit bids indicating the CfD price. The bidder with the lowest bid wins. Scenario N refers to payment auctions with electricity price risk (i.e., no hedging or support). The bidder with the lowest bid wins. The payment auction (i.e., the market solution) in Section 2.3 is captured by only allowing non-positive bids in N. To enable a general comparison with C, we also permit positive bids in N that represent a one-time payment from the auctioneer to the developers, which correspond to lump sum capex subsidies. The submitted bids determine whether a payment is made to or from the auctioneer, depending on whether the bids are negative or positive. We assume this initially so that all bidders can participate in N in any case. The case in which positive bids are not feasible in N is discussed in Section 7.

If winning bidders fail to implement the project in C or N, they must pay a penalty, for example by forfeiting a bid bond, which must be submitted before the auction. Bidders who did not win receive their bond back after the auction.

3.2. Timeline and uncertainties

Fig. 1 illustrates the timeline of the whole process on which the analysis in Section 4 is based. As assumed in Section 3.1, all bidders have an incentive to participate in either auction. First, the auction is conducted among all participants. This is followed by the implementation decision period, which typically lasts up to a few years. During this period, the winning bidder must decide whether to implement (realize) the project. If the project is implemented, the operating period starts. Our analysis focuses on the pre-operation phases.

There are two categories of uncertainty in different periods. The first category includes uncertainties that developers face regarding material and installation costs, administrative processes (e.g., obtaining permits), environmental factors, and other installation-related issues (cost uncertainty). These uncertainties exist at the time of the auction and are resolved during the implementation decision period when information about the uncertain factors is revealed. This applies equally to C and N. The non-realization risk refers to the implementation decision period: If the winning bidder learns during this period that the project's value is lower than initially expected, non-realization may occur, depending on the severity of the deviation and penalties. The second category refers to uncertainties about electricity price and generated quantities (revenue uncertainty). In N, these uncertainties fully apply to the market solution. In C, we assume that these uncertainties are fully excluded.[8] Revenue uncertainty is resolved only after the plant becomes operational. Thus, it can no longer trigger a project non-realization. If the winning bidder discovers during the operational period that the project's value is lower than expected, the winning bidder will likely incur an unavoidable loss. Fig. 2 in Section 4 illustrates the evolution of information and uncertainty over the entire timeline.

Given the timeline, uncertainties in the first category are more relevant for non-realization risk, as they materialize during the implementation decision period (the post-auction shock). While new information about uncertainties in the second category (e.g., electricity price expectations) may also emerge in this period, these uncertainties unfold over the long operational period in the future. We therefore disregard such updates in the first step of our analysis and focus solely on resolved uncertainties in the first category. In a second step, we account for updated information on uncertainties in the second category during the implementation decision period (see Section 5.2).

4. Basic model

This section presents our basic model. To make our analysis tractable, we use the second-price auction format. This includes dynamic auctions, such as English auctions (i.e., ascending or descending clock auctions), in which the second-best bidder ends the auction and sets the winning price with their bid limit. These formats have been used, for example, in offshore wind auctions in the US and Germany (e.g., BOEM, 2018; WindSeeG, 2023, §21 et seqq.). In Section 5.1, we show that our findings also apply to first-price auctions (pay-as-bid auctions).

Consider n a priori symmetric bidders, $n \geq 2$, each with wealth w and the von Neumann–Morgenstern utility function u. We consider cases in which all bidders are risk-averse, risk-neutral or, for the sake of completeness, risk-seeking.[9]

[7] Similar to tCfDs, both PPA and OREC contracts set a fixed price for the supply of energy services (e.g., Jansen et al., 2022).

[8] The volume risk only applies to the tCfD, while cCfDs and fCfDs involve the so-called basis risk (Section 2.2).

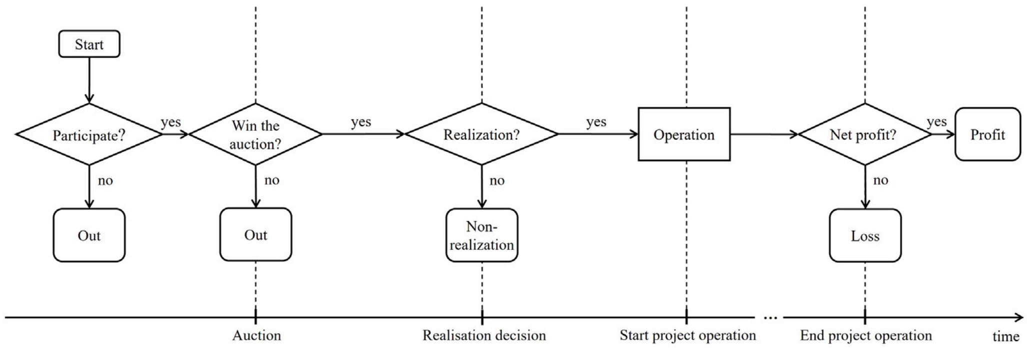

Fig. 1. Timeline of the whole process.

Bidders are characterized by private cost signals $\theta_i \in [\underline{\theta}, \bar{\theta}]$, which are realizations of n independent and identically distributed random variables Θ_i with the distribution function F and density function f. f is assumed to be log-concave.[10] For simplicity, we omit the index i for Θ. In scenario C, each bidder i's private costs are equal to θ_i, i.e., $\theta_i^C = \theta_i, \forall i \in \{1, \dots, n\}$. The private costs of the bidders in scenario N differ from that in C by a parameter τ. This accounts for additional costs incurred due to the higher uncertainty in N caused by revenue uncertainty (see below). For example, a positive τ accounts for higher financing costs in N (see Section 2.1). Assuming that the bidders are subject to different conditions relevant in N, such as internal or external financing, τ may vary among bidders (e.g., Kröger et al., 2022; Gohdes et al., 2022). This is modeled by the random variable T, which is independent of Θ. Thus, in scenario N, the random variable is given by $\Theta^N = \Theta + T$, and its distribution function is denoted by F^N. For simplicity, we assume there are two types of realization of T: τ_h with probability λ and τ_ℓ with probability $1-\lambda$, $\tau_h > \tau_\ell$.[11] Although higher financing costs are a prominent example, we allow T to be negative. Bidder i's private costs at the time of the auction are $\theta_i^N = \theta_i + \tau_i$, $\tau_i \in \{\tau_\ell, \tau_h\}$. Let $\Theta_{(i)}$ and $\Theta_{(i)}^N$ denote the ith order statistics of the random variables of the private cost signals Θ and Θ^N.

At the time of the auction, there is common uncertainty regarding the investment costs (first category of uncertainty). This uncertainty is related to factors that affect all bidders equally, such as material or installation costs. We use the post-auction shock approach as employed by Board (2007) to analyze strategic bankruptcy behavior and determine the exact valuation of the auction winner by resolving a common uncertainty after the auction. In our model, the post-auction shock is linked to the resolution of a common uncertainty regarding investment costs. This is modeled by a random variable Y with the distribution function G and density function g on the support $[\underline{y}, \bar{y}]$, and $\mathbb{E}[Y] = 0$. Y realizes y in the implementation decision period. Therefore, the a priori implementation costs of each bidder are $\Theta + Y$ in C and $\Theta^N + Y$ in N. Bidder i's implementation costs at the time of the auction are $\theta_i^C + Y$ in C and $\theta_i^N + Y$ in N. We assume that the common cost uncertainty is significant compared to the variation of the private costs, which is captured by the assumption $\text{std.dev}(Y) \geq \text{std.dev}(\Theta)$.

The future revenue in C is a constant, which is determined by the auction price for the CfD. In N, the future revenue is modeled by the random variable Z (second category of uncertainty) with distribution function H and density function h on the support $[\underline{z}, \bar{z}]$. Random variable Z realizes z in the operation period. For a basic comparison of the two scenarios, we assume that this uncertainty is the same for all bidders in N. Private hedging instruments such as PPAs and their possible differences are not taken into account.

The distributions of all random variables Θ, T, Y and Z are common knowledge. For simplicity's sake, we omit the discounting of monetary values, which is without loss of generality when assuming a uniform discount rate for all bidders. In other words, all monetary values are already expressed in discounted terms and thus interpreted as net present values. We also assume that the CfD is effective throughout the entire operating period.

Consider a representative bidder i. For simplicity, we omit the index i. Let b_C^* and b_N^* denote the bidder's indifference bids under scenarios C and N, respectively. At the indifference bids, the bidder is indifferent between winning and not winning the auction, i.e., the expected utility from winning the auction equals the utility of the current wealth $u(w)$. In second-price auctions (including English auctions), bidding the indifference price is a weakly dominant strategy. Suppose that if the bidder wins, they get the awarded price p_C or p_N, determined by the next best bidder, where $p_C \geq b_C^*$ and $p_N \geq b_N^*$. In scenario C, only the first uncertainty category is relevant, so the bidder's utility from implementation is $u(w + p_C - \theta - Y)$. In scenario N, both uncertainty categories are relevant, so the bidder's utility from implementation is $u(w + p_N - \theta - \tau - Y + Z)$. Z could be updated during the implementation decision period, see Section 5.2 for model extension. Information, uncertainties, and cash flows throughout the whole process are illustrated in Fig. 2.

In both scenarios, if the project is not implemented (non-realization), the bidder must pay a penalty $s \geq 0$, where $w \geq s$ ensuring the bidder can cover the penalty. The bidder's ex-ante expected utilities conditional on winning at the awarded price p_C or p_N in both scenarios are given by

$$U_C(p_C) = \int_{\underline{y}}^{y_C^*(p_C)} u(w + p_C - \theta - y) g(y) dy + \int_{y_C^*(p_C)}^{\bar{y}} u(w - s) g(y) dy \tag{1}$$

and

$$U_N(p_N) = \int_{\underline{y}}^{y_N^*(p_N)} \int_{\underline{z}}^{\bar{z}} u(w + p_N - \theta - \tau - y + z) h(z) dz g(y) dy + \int_{y_N^*(p_N)}^{\bar{y}} u(w - s) g(y) dy, \tag{2}$$

where $y_C^*(p_C)$ and $y_N^*(p_N)$ denote the threshold of the realization of Y (hereafter referred to as the implementation cost threshold), at which the bidder is indifferent as to whether or not to implement the project,

[9] Risk aversion is modeled by $u' > 0$ and $u'' < 0$, i.e., a strictly increasing and concave utility function u. We assume a non-increasing Arrow–Pratt measure of absolute risk aversion, which is defined as $-u''/u'$ (Arrow, 1971). If this measure is non-increasing, the risk premium of a risky investment decreases in the wealth level (Pratt, 1978; Kimball, 1993; Mas-Colell et al., 1995).

[10] A density function f is log-concave on the support Ω if, for any $x_1, x_2 \in \Omega$ and $\rho \in [0, 1]$, $f(\rho x_1 + (1-\rho)x_2) \geq f(x_1)^\rho f(x_1)^{1-\rho}$ (e.g., An, 1998). Many common probability distributions are log-concave, e.g., normal distribution, exponential distribution, or uniform distribution (e.g., Bagnoli and Bergstrom, 2005).

[11] Our results would be the same if T were continuously distributed on $[\underline{\tau}, \bar{\tau}]$. Then there would be a cutoff τ^*, such that all $\tau \leq \tau^*$ would be considered as low τ, and all $\tau > \tau^*$ would be considered as high τ. The same applies when assuming that T and Θ are positively correlated.

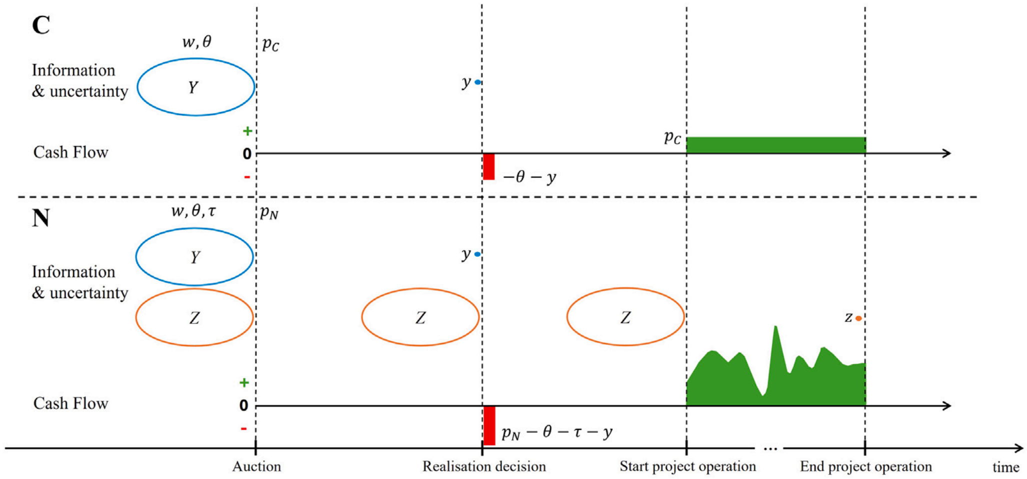

Fig. 2. Information, uncertainty, and cash flow over the entire timeline for an exemplary auction winner under realization in scenarios C and N.

depending on the awarded prices p_C or p_N. Thus, the probability that the project will be implemented is given by $G(y^*_C(p_C))$ or $G(y^*_N(p_N))$ and increases in $y^*_C(p_C)$ or $y^*_N(p_N)$. The implementation cost thresholds are determined by equating the bidder's (expected) utility from implementation at the given awarded price and the utility from paying the penalty s:

$$u(w + p_C - \theta - y^*_C(p_C)) = u(w - s), \tag{3}$$

$$\int_{\underline{z}}^{\bar{z}} u(w + p_N - \theta - \tau - y^*_N(p_N) + z)h(z)dz = u(w - s). \tag{4}$$

After y is realized, the winner will implement the project if and only if y does not exceed the corresponding threshold.

At the indifference bids b^*_C and b^*_N, we have

$$U_C(b^*_C) = U_N(b^*_N) = u(w), \tag{5}$$

$$u(w + b^*_C - \theta - y^*_C(b^*_C)) = u(w - s), \tag{6}$$

$$\int_{\underline{z}}^{\bar{z}} u(w + b^*_N - \theta - \tau - y^*_N(b^*_N) + z)h(z)dz = u(w - s). \tag{7}$$

Due to their different references, the indifference bids b^*_C and b^*_N cannot be compared directly. Instead, the expected electricity market revenues and the cost parameter τ in N must also be taken into account, so that b^*_C and $b^*_N + \mathbb{E}[Z] - \tau$ can be compared.

Lemma 1. *The following relationships hold for different risk preferences:*

- *Risk-averse bidders:* $b^*_C < b^*_N + \mathbb{E}[Z] - \tau$ *and* $y^*_C(b^*_C) < y^*_N(b^*_N)$.
- *Risk-neutral bidders:* $b^*_C = b^*_N + \mathbb{E}[Z] - \tau$ *and* $y^*_C(b^*_C) = y^*_N(b^*_N)$.
- *Risk-seeking bidders:* $b^*_C > b^*_N + \mathbb{E}[Z] - \tau$ *and* $y^*_C(b^*_C) > y^*_N(b^*_N)$.

Under risk-neutrality, the indifference price and the implementation decision only depend on the expected values of the investment costs and the electricity market revenue. Thus, b^*_C and $b^*_N + \mathbb{E}[Z] - \tau$ are equal for C and N as are $y^*_C(b^*_C)$ and $y^*_N(b^*_N)$ and thus also the realization probability at the indifference bids b^*_C and b^*_N. This changes once bidders exhibit non-neutral risk preferences. For risk-averse bidders, $b^*_C < b^*_N + E[Z] - \tau$ indicates a more aggressive indifference bid in C, and $y^*_C(b^*_C) < y^*_N(b^*_N)$ indicates a lower realization probability in C at the indifference bid. This result arises because scenario C eliminates more risk than scenario N. Consequently, risk-averse bidders require a higher risk premium in scenario N to compensate for the additional uncertainty, resulting in a higher expected revenue at the same expected utility level. Furthermore, since the implementation cost threshold is positively correlated with the indifference price, the threshold at the indifference bid is higher in N than in C. This implies a higher realization probability in scenario N. The opposite holds for risk-seeking bidders. Since both scenarios involve risk, they require a negative risk premium in both scenarios, where the risk premium is lower (more negative) in N due to the additional uncertainty in Z. This results in a lower indifference bid and a lower realization probability at the indifference bid in N.

Consider now two bidders with the same utility function u, Bidder i with θ_i and τ_i, and Bidder j with θ_j and τ_j. We use the subscripts C, N, i, and j to denote indifference prices and implementation cost thresholds, referring to the respective scenarios and bidders.

Lemma 2. *For any two bidders i and j, it holds that* $b^*_{C,j} - b^*_{C,i} = \theta^C_j - \theta^C_i$ *and* $y^*_{C,j}(b^*_{C,j}) = y^*_{C,i}(b^*_{C,i})$; $b^*_{N,j} - b^*_{N,i} = \theta^N_j - \theta^N_i$ *and* $y^*_{N,j}(b^*_{N,j}) = y^*_{N,i}(b^*_{N,i})$.

Lemma 2 states that the difference between the indifference bids of any two bidders exactly equals the difference of their private costs in each scenario, i.e., $\Delta\theta = \theta^C_j - \theta^C_i$ in C and $\Delta\theta^N = \theta^N_j - \theta^N_i$ in N. As a result, in the equilibrium with weakly dominant strategy, bidders' indifference bids increase monotonically in their private cost in the respective auction. Consequently, the bidder with the lowest θ^C wins in C, whereas the bidder with the lowest θ^N wins in N, which may lead to different winners due to the independence between T and Θ. This result holds for any two bidders with the same utility function, regardless of what that risk preference is. Besides, the realization probability at each bidder's own indifference price is the same across all bidders. This is because at the implementation cost threshold, all bidders have the same expected utility, and bidders with higher private cost take this into account and price this into their indifference price accordingly.

Lemma 3. *For any two bidders i and j, it holds that* $y^*_{C,i}(b^*_{C,j}) = y^*_{C,i}(b^*_{C,i}) + \theta^C_j - \theta^C_i$ *and* $y^*_{N,i}(b^*_{N,j}) = y^*_{N,i}(b^*_{N,i}) + \theta^N_j - \theta^N_i$.

If a bidder wins the auction at the indifference bid of another bidder with a higher private cost (and thus a higher indifference bid), the realization probability increases relative to that at its own indifference bid. Lemma 3 shows that this increase is exactly equal to the difference in their private costs $\Delta\theta$ and $\Delta\theta^N$. This result holds in both scenarios C and N regardless of bidders' risk preferences.

Due to the additional dispersion from T, the expected difference in private cost between the price setter and the winner is larger in N than in C.

Lemma 4. $\mathbb{E}[\Theta^N_{(2)}] - \mathbb{E}[\Theta^N_{(1)}] \geq \mathbb{E}[\Theta_{(2)}] - \mathbb{E}[\Theta_{(1)}]$.

Regarding the realization probability, the following holds.

Proposition 1. *If all bidders are either risk-averse or risk-neutral, each with either τ_ℓ or τ_h, then the realization probability from the auctioneer's point of view is higher in N than in C. If all bidders are risk-seeking, the result is ambiguous.*

According to Lemma 4, the winner in N benefits in expectation more from the additional dispersion introduced by different τ. In addition, as shown in Lemma 1, the implementation cost threshold is higher in scenario N for risk-averse bidders, which further increases the realization probability. Therefore, from the auctioneer's perspective, scenario N yields a higher realization probability.

To compare this result with the auctioneer's expected costs, which are equal to the expected award price minus $\mathbb{E}[Z]$ in C and equal to the expected award price in N, we apply Lemma 1. When $\tau > 0$, as is usually assumed, and bidders are risk-neutral, scenario N leads to higher expected costs (or lower expected revenues). This also holds for risk-averse bidders, even when $\tau \geq 0$. From this perspective, the auctioneer would prefer scenario C over N. Thus, the objectives of minimizing cost (maximizing revenue) and achieving a higher realization probability conflict with each other and thus cannot be achieved simultaneously. In our context, the primary objective of the auctioneer is to achieve a high realization probability and thereby promote the targeted expansion of RE.

Regarding the penalty for non-realization s, we treat it as exogenous and identical across both scenarios. In practice, the auctioneer might choose a higher penalty for CfD-backed projects, reflecting that the public absorbs the project's revenue uncertainty. While a higher s increases the realization probability in both scenarios, it also raises bidders' indifference bids, particularly for risk-averse bidders. Consequently, adjusting s in either scenario involves a trade-off between realization probability and the auctioneer's revenue or cost, which must be carefully weighed in practice.

Now let us take the perspective of the bidders. For risk-neutral bidders, according to Lemmas 1 and 3, the expected utility conditional on winning at prices p_C and p_N are equal, i.e., $U_C(p_C) = U_N(p_N)$ if and only if $p_C - b_C^* = p_N - b_N^*$. For risk-averse or risk-seeking bidders, this is ambiguous and depends on the specific form of the utility function. However, the impact of the utility function is very small, mainly because the uncertain price p only slightly exceeds the bid b^* in comparison to the uncertainty caused by Y. For this reason, we assume equivalence for all forms of risk preference.

Assumption 1. $U_C(p_C) \gtreqless U_N(p_N)$ iff $p_C - b_C^* \gtreqless p_N - b_N^*$.

Let $EU_C(b_C^*)$ and $EU_N(b_N^*)$ denote the expected utilities, accounting for the winning probability. It follows that

$$EU_C(b_C^*) = \int_{b_C^*}^{\bar{b}_C} U_C(p_C) f_C(p_C) dp_C + F_C(b_C^*) u(w),$$

$$EU_N(b_N^*) = \int_{b_N^*}^{\bar{b}_N} U_N(p_N) f_N(p_N) dp_N + F_N(b_N^*) u(w).$$

The density functions f_C and f_N correspond to the distribution functions F_C and F_N. The expressions $1 - F_C(b_C^*)$ and $1 - F_N(b_N^*)$ denote the winning probabilities of the bidder with indifference bids b_C^* and b_N^* in C and N, respectively. For C, the winning probability can be expressed in terms of the underlying cost θ because the indifference bid b_C^* is strictly increasing in θ (Lemma 2). Specifically, the event that the winning price exceeds b_C^* is equivalent to all competitors having private costs higher than θ, which occurs with probability $(1 - F(\theta))^{n-1}$. Thus, for C it holds that $1 - F_C(b_C^*) = (1 - F(\theta))^{n-1}$. Similarly, for N it holds that $1 - F_N(b_N^*) = (1 - F^N(\theta^N))^{n-1}$. The upper bounds $\bar{b}_C$ and $\bar{b}_N$ denote the maximum prices in both scenarios. Since our model does not initially implement an upper limit, $\bar{b}_C$ and $\bar{b}_N$ are set to infinity (see Section 7 for finite maximum prices). As a result, following (5), $EU_C(b_C^*) \geq u(w)$ and $EU_N(b_N^*) \geq u(w)$ for all b_C^* and b_N^*, so bidders with all private costs have an incentive to participate in either auction.

Assume that Assumption 1 applies. The following applies to the winning probability, the expected utility, and the realization probability in C and N.

Proposition 2. *If all bidders are either risk-averse or risk-neutral, then the following holds:*

- *For bidders with τ_ℓ: $1 - F_C(b_C^*) < 1 - F_N(b_N^*)$, $\mathbb{E}[y_C^*(P_C)] < \mathbb{E}[y_N^*(P_N)]$, and $EU_C(b_C^*) < EU_N(b_N^*)$.*
- *For bidders with τ_h: $1 - F_C(b_C^*) > 1 - F_N(b_N^*)$, $EU_C(b_C^*) > EU_N(b_N^*)$, and, for risk-neutral bidders, $\mathbb{E}[y_C^*(P_C)] > \mathbb{E}[y_N^*(P_N)]$.*

That is, regardless of risk preference, bidders with τ_ℓ prefer N while bidders with τ_h prefer C. It is the relative level of τ, not its absolute value, that determines this preference. Lower τ increases both the winning and realization probability in N relative to C, while higher τ has the opposite effect.

In our model, it is assumed that bidders have the same beliefs about cost and revenue uncertainty (modeled by Y and Z with distribution functions G and H, which are common knowledge). Bidders are differentiated by their private costs. In the absence of a common prior, such as when some bidders are more optimistic than others, this can be captured in a common-value model in which bidders have different signals regarding uncertainties (e.g., Milgrom and Weber, 1982). Assuming the same risk preference, May et al. (2018) argue that the market solution favors the most optimistic bidder with regard to revenue uncertainty, which reduces the probability of project realization. This is because downward revisions of price expectations after the auction can result in cancellations despite penalties. Our approach, however, does not yield the same conclusion. Since revenue uncertainty Z is not resolved at the time of the implementation decision, optimism or pessimism regarding revenue uncertainty has no impact on the implementation decision. By contrast, an optimistic prior regarding cost uncertainty can indeed reduce the realization probability, an effect that applies equally to both scenarios C and N (with the opposite effect for pessimism). In other words, despite different prior beliefs, our main result that the expected realization probability is higher in N than in C for either risk-averse or risk-neutral bidders, remains unchanged.

The following can be stated with regard to efficiency. The auctions in C and N are incentive compatible, i.e., bidders submit their indifference bids, which, as assumed, are not limited by maximum prices. Therefore, each of the two auctions in C and N is efficient when viewed separately. Efficiency means that the project is awarded to the bidder with the lowest private cost θ in C, and to the bidder with the lowest total cost $\theta + \tau$ in N. This changes when the two auctions are considered together. Since τ differs between the bidders in N, there may be different winners in N and C, with the probability of a winner with τ_ℓ in N being higher than that of a winner with τ_h. According to Proposition 1, the realization probability in N is higher than in C in case of risk-neutral or risk-averse bidders. Thus, if $\tau_\ell > 0$, as argued, no statement about efficiency can be made without further specifications. Even if $\tau_\ell \leq 0$, there is no clear result, although the probability of the efficient outcome in N is higher than in C. If $\tau_h \leq 0$, the N auction is the efficient one. For risk-seeking bidders, the results are ambiguous. On the one hand, the bids in N are relatively higher than in C, which reduces the realization probability. On the other hand, the bids in N are more widely scattered than in C, which increases the realization probability. Therefore, as in the previous case, the model must be specified in more detail in order to make a clear statement about efficiency.

5. Model extensions

This section presents extensions to our basic model.

5.1. Pay-as-bid pricing

Under the assumptions of symmetric bidders, as specified in the basic model in Section 3, and that F and F^N satisfy the strictly increasing failure rate (IFR) property, i.e., their hazard rates are increasing, monotone symmetric Bayes–Nash equilibria exist in the first-price (pay-as-bid) auctions in C and N (Riley and Samuelson, 1981; Board, 2007; Maskin and Riley, 1984, adaptation of the results for value signals to cost signals). For risk-neutral bidders, the equilibrium is unique under the standard IFR conditions (Riley and Samuelson, 1981; Board, 2007). For risk-averse bidders, we maintain the baseline assumptions of strictly increasing and concave utility functions with non-increasing Arrow–Pratt measures of absolute risk aversion. In equilibrium, the bidder with the lowest CfD bid in C or the lowest payment bid in N wins the auction.

Proposition 3. *In a first-price auction, if all bidders are either risk-averse or risk-neutral, each with either τ_ℓ or τ_h, then the realization probability from the auctioneer's point of view is higher in N than in C. If all bidders are risk-seeking, the result is ambiguous.*

The same intuition applies as in Proposition 1 for the second-price auction. First, risk-averse bidders require a higher risk premium in scenario N to compensate for the additional uncertainty. This leads to a higher expected award price, a larger buffer against cost uncertainty, and therefore a higher realization probability. Second, when τ is non-constant, the additional dispersion in scenario N weakens competitive pressure relative to scenario C, as depicted in Lemma 4. As a result, the winning bidder in N earns a higher expected profit, which further increases the project's realization probability.

To compare the realization probability in the first-price and second-price auctions within the same scenario C or N, we can apply the results from Parlane (2003) and Board (2007), adapted by Kreiss et al. (2017) to RE auctions: For risk-neutral bidders, the expected award price, and thus the realization probability, is higher in a first-price auction than in a second-price auction. Thus, revenue equivalence does not apply. We will not delve deeper into this discussion for the following reasons. While most RE auctions are first-price or pay-as-bid (PaB) auctions, conducted as single-round, sealed-bid auctions (e.g., IRENA and CEM, 2015; Jansen et al., 2022), the second-price rule is primarily used in dynamic, multi-round auctions. One reason for this is that, during the auction, bidders can gain insights into the assessment of uncertain variables by other bidders by observing and tracking the competition and other bidders' bidding behavior (e.g., BMWE, 2025). However, unlike our model and the previously mentioned theoretical studies, which assume that there is only common information about the uncertain post-auction shock variables, this approach requires that bidders have private information about these variables and can learn from each other and thus from other bidders' bids in a multi-round auction (Milgrom and Weber, 1982). This allows bidders to adjust their estimates during the auction, which reduces "the winner's curse" risk and, thus, increases the realization probability, compared to single-round, sealed-bid auctions. This applies to both the C and N scenarios. However, further analysis of this topic is beyond the scope of this paper, not least because the private-information approach is feasible only for risk-neutral bidders and not for risk-averse ones. In conclusion, it should be emphasized that this paper focuses on comparing CfDs and payment auctions, and that neither the pricing rule nor the above considerations affect the main results.

5.2. Information update during the implementation decision period

Suppose that the distribution of Z is updated during the implementation decision period. This may reflect developments in forward markets or structural changes in long-term revenue forecasts. At the time of the implementation decision, the bidder faces the random variable Z_1 with distribution function H_1 and density h_1, which is a update of Z with H and h. The implementation cost threshold in scenario C remains unchanged, as Z plays no role in C. The updated threshold in scenario N, denoted with $\hat{y}^*_N$, is determined by

$$\int_{\underline{z}}^{\bar{z}} u(w + p_N - \theta - \tau - y^*_N(p_N) + z)h(z)dz = u(w - s)$$

$$= \int_{\underline{z}}^{\bar{z}} u(w + p_N - \theta - \tau - \hat{y}^*_N + z)h_1(z)dz.$$

For the update, we consider first-order stochastic dominance in both directions: $Z_1 \succ_1 Z$ and $Z \succ_1 Z_1$. That is, the update improves or worsens the beliefs about electricity revenues. If bidders are risk-averse or risk-neutral, according to Proposition 1, the auctioneer expects that $y^*_N(p_N) > y^*_C(p_C)$. If $Z_1 \succ_1 Z$, then it follows that $\hat{y}^*_N > y^*_N(p_N)$. Consequently, the realization probability is expected to be higher in N than in C, and the difference becomes even larger than in the basic model with Z in Section 4. Thus, the advantage of N is reinforced. This result already holds under the weaker condition of second-order stochastic dominance, $Z_1 \succ_2 Z$ (Rothschild and Stiglitz, 1970). This includes the case that Z_1 is a mean preserving contraction of Z, i.e., $\mathbb{E}[Z] = \mathbb{E}[Z_1]$, but Z_1 exhibits less dispersion around the mean. Such a case reflects the situation in which bidders receive updated information about the future electricity market, which reduces uncertainty regarding future revenue. The decrease in uncertainty raises the expected utility of the risk-averse bidder and thereby increases the realization probability in scenario N. In contrast, if $Z \succ_1 Z_1$, then $\hat{y}^*_N < y^*_N(p_N)$. However, no general statement can be made with respect to the realization probability between C and N, because it is expected to be higher for N under Z in the basic model. Thus, the advantage of N over C weakens and may reverse. That is, if expectations regarding the future electricity market worsen substantially during the implementation decision period, the realization probability in N decreases, possibly falling below that in C.

Shifting the distribution Z by a constant Δz in either direction, without changing its shape, i.e., $h_1(z + \Delta z) = h(z), \forall z \in [\underline{z}, \bar{z}]$, is a special case of first-order stochastic dominance: $\Delta z > 0 \Leftrightarrow Z_1 \succ_1 Z$ and $\Delta z < 0 \Leftrightarrow Z \succ_1 Z_1$. The indifference equation becomes

$$\int_{\underline{z}}^{\bar{z}} u(w + p_N - \theta - \tau - y^*_N(p_N) + z)h(z)dz$$

$$= \int_{\underline{z}+\Delta z}^{\bar{z}+\Delta z} u(w + p_N - \theta - \tau - \hat{y}^*_N + x)h_1(x)dx$$

$$= \int_{\underline{z}}^{\bar{z}} u(w + p_N - \theta - \tau - \hat{y}^*_N + z + \Delta z)h(z)dz.$$

Consequently, $\hat{y}^*_N = y^*_N(p_N) + \Delta z$. According to Lemma 3, define $\Delta y^* := y^*_N(p_N) - y^*_C(p_C) = y^*_N(b^*_N) - y^*_C(b^*_C) + \Delta\theta^N - \Delta\theta$. It follows that $\hat{y}^*_N \geq y^*_C(p_C) \Leftrightarrow \Delta z \geq -\Delta y^*$.

If bidders are risk-neutral or risk-averse, Proposition 1 implies $\Delta y^* > 0$. Therefore, if $\Delta z \geq 0$, i.e., the bidder's beliefs about future revenue improves during the implementation decision period, then the realization probability is expected to be higher in N than in C. This also applies if the bidder's beliefs worsen only to the extent that the shift does not exceed Δy^*, i.e., $\Delta z \geq -\Delta y^*$. Only if $\Delta z < -\Delta y^*$, the realization probability in N falls below that in C. In other words, bidders in N effectively "insure" against unfavorable belief updates by bidding more "conservatively" and thus expecting higher revenue upfront. This conservatism creates a buffer Δy^*, which protects the implementation decision against moderate negative belief updates.

If bidders are risk-seeking, since no general relationship can be established between $y^*_N(p_N)$ and $y^*_C(p_C)$, no general statement can be made between $\hat{y}^*_N$ and $y^*_C(p_C)$. In principle, regardless of risk preference of the bidders, $Z_1 \succ_1 Z$ – including the special case $\Delta z \geq 0$ – improves the realization probability in N relative to that in C compared to the basic model, while the reverse holds for $Z \succ_1 Z_1$ or $\Delta z < 0$.

The information update concerns bidders' expectations regarding future electricity market revenues. In contrast, severe deteriorations in investment conditions after the auction, such as supply-chain constraints or rising material costs, are captured in our model as a post-auction shock through a high realization of y. Such shocks affect both scenarios equally.

5.3. Payment auction with payment before the implementation decision

The following considerations apply only to the usual case in practice, where only negative bids can be submitted in the N auction, meaning that the winning bidders must make a payment to the auctioneer (see also Section 6). Therefore, only bidders with a negative indifference bid participate, i.e., those with $b_N^* \leq 0$.[12] This is only feasible if the project is expected to be profitable without support.

Now consider the case in which a part of the payment is due before the implementation decision. This reflects, for instance, the payment requirement in current U.S. offshore wind auctions (BOEM, 2018, 2022) and the 10% payment due within the first year after the auction in the current German offshore wind auction (WindSeeG, 2023, §23). Denote by $\delta, \delta \in (0,1]$, the proportion of the payment that is due before the implementation decision. This payment is not reimbursed if the auction winner decides not to realize the project. Eq. (5) then extends to

$$U_N(b_N^*) = \int_{\underline{y}}^{y_N^*(b_N^*)} \int_{\underline{z}}^{\bar{z}} u(w + b_N^* - \theta - \tau - y + z)h(z)dz\,g(y)dy + \int_{y_N^*(b_N^*)}^{\bar{y}} u(w - s + \delta b_N^*)g(y)dy = u(w).$$

Compared to Eq. (5), the second term now contains the additional negative component δb_N^*. To satisfy $U_N(b_N^*) = u(w)$, both the indifference bid b_N^* and the corresponding threshold $y_N^*(b_N^*)$ must increase relative to the basic model. That is, $|b_N^*|$ becomes smaller, reflecting more conservative bidding behavior. Consequently, in the equilibrium, the award price, denoted by p_N^b, is higher, i.e., $p_N < p_N^b \leq 0$.[13]

At the time of the implementation decision, this early payment is sunk for the winning bidder since it is incurred regardless of the implementation decision. Eq. (4) becomes

$$\int_{\underline{z}}^{\bar{z}} u(w + p_N^b - \theta - \tau - y_N^*(p_N) + z)h(z)dz = u(w - s + \delta b_N^*).$$

Since δb_N^* on the right-hand side of the equation is negative, the threshold $y_N^*(p_N)$ increases compared to that in the basic model. Since the project is profitable in itself, bidders are willing to sacrifice part of their expected market revenue to win the auction. This sacrificed portion makes the project less profitable. If this sacrificed portion is paid before the implementation decision and becomes sunk, the project implementation is more attractive, thus raising the realization probability. The larger the portion of the early payment, the more attractive the project at the time of the implementation decision, and thus the higher the realization probability, while this must be weighed against potential higher financial costs of early payment.

In summary, requiring payments before the implementation decision can increase the realization probability in N, thus contributing to efficiency and welfare. This result holds regardless of the bidders' risk preference. However, this effect is only beneficial as long as the associated additional financial costs do not outweigh the gains in implementation incentives. Additionally, the early payment approach can create financial issues for developers if the project proves to be significantly more expensive than expected after payment has been made. Nevertheless, the project will be carried out due to sunk costs, which would not have been the case with a later payment. Furthermore, a higher proportion of early payment increases the risk of non-participation if only negative payment bids are permitted. Under the mechanism proposed in Section 7, however, this adverse effect no longer arises.

6. Implementation in practice

In the model in Section 4, all bidders can participate in the auctions in scenarios C and N. In C, this is achieved by allowing unrestricted CfD bids. This is not usually the case in practice. Instead, a maximum bid price is set that excludes less profitable projects. In N, participation is achieved by allowing negative and positive bids, through which bidders determine whether they will make a payment to the auctioneer or receive a payment from the auctioneer. The latter corresponds to an investment subsidy. In practice, however, this option is usually not available; only the option of a payment to the auctioneer is available.

In this framework, the auctioneer has two options: to allocate a CfD in an auction with a maximum price (scenario C); or to receive a payment from the winning bidder in an auction, which only allows negative bids, i.e., payments from the bidders to the auctioneer (scenario N). So far, with one exception (see Section 6.2), the auctioneer has decided in advance on one of the two options C or N. Section 6.1 contains examples of auctions that have led to undesirable results in this regard.

6.1. Examples

At the 2021 Danish offshore wind CfD auction, several bidders submitted the same bid with the largest possible capacity and at a minimum price of only 0.01 øre/kWh, so the auction winner was determined by lottery (Danish Energy Agency, 2021). In interpreting this outcome, note that the auction design included a 20-year CfD with a payment cap of 2.8 billion Danish kroner (DKK) from the operator to the state (European Commission, 2021). With the expected electricity prices, it was anticipated that the winning bidder would reach this cap after approximately 3.5 years. After that, the CfD does not apply anymore and a free market regime applies. This result indicates the attractiveness of the location and the conditions, as the operators were willing to forgo effective support or hedging from the state and to pay for the right to build and operate this offshore wind farm. Had the auction been designed as a payment auction, bids of at least DKK 2.8 billion could have been expected. The auction was deemed unsuccessful. First, drawing the winner through a lottery carries the risk of inefficiency.[14] Second, the concept of a CfD as a support and hedging instrument has been reduced to absurdity by the auction. This example also shows that when conditions are favorable, intense competition for a CfD is to be expected, leading to low prices.

This event was apparently at least partly responsible for Denmark's switch to payment auctions. Since these only permit negative bids, i.e., bidders can only make payments to the auctioneer and not vice versa, they no longer have the option of receiving support. The Danish December 2024 auction for 3 GW of capacity did not attract any bidders, so the planned early 2025 auction for an additional 3 GW was suspended (Memija, 2024, 2025). The main reason was that procurement conditions had worsened for developers. Factors inhibiting

[12] We assume that the bidders' wealth level w is sufficient to cover the payment when due. Otherwise, w imposes an upper bound on the negative bid, resulting in a higher expected utility and thus a higher realization probability than at b_N^*.

[13] This presupposes that the new, higher indifference bid is also negative. Otherwise, the bidder would not participate in the auction. Therefore, early payment increases the risk of general non-participation and failure of the auction.

[14] In the 2021 German offshore wind auctions, several bidders submitted zero-cent-bids for oFIP. Since the bidders could not further differentiate themselves—negative bids, for example, were not permitted—the auction winners were also determined by lottery (BNetzA, 2021; WindSeeG, 2021, §14 et seqq.). In this context, it seems almost bizarre that previous permission holders with a last call could take over the zero-cent award WindSeeG (2021, §60 et seqq.)—which is exactly what happened (e.g., BNetzA, 2022).

them include higher inflation, rising interest rates, supply chain bottlenecks, expected low electricity prices, a lack of market opportunities, and uncertainties in the electricity market (e.g., Turner et al., 2024). Another factor was that the auction winners had to pay for the grid connection. Apparently, the projects required electricity sales revenue that exceeds market expectations. However, this could not be achieved through a payment auction. Denmark reversed course and reintroduced CfDs in late 2025 (Danish Energy Agency, 2025). The ongoing Danish offshore wind auction is based on a cCfD that eliminates all price risk (see Section 2.2).

The same outcome as the 2024 Danish offshore wind auction was observed in Germany in 2025 at the auction for two centrally pre-investigated offshore wind sites. In this multi-attribute auction with a payment component, no bids were submitted (BNetzA, 2025b).

In 2025, the UK put three offshore wind sites, each for a capacity of 1.5 GW, out to tender in a payment auction. However, only two sites were awarded because no bids were submitted for one of the sites (Crown Estate, 2025). This case is also interesting because the auction winners have the opportunity to obtain a CfD in a later auction. The payment auction and the CfD auction should be evaluated together. The rule that sites must first be auctioned and paid before a developer can apply for support creates additional uncertainty and risks for developers, which could discourage them from participating.[15]

6.2. Combining oFIP and payment

The aforementioned problems could be avoided by using an auction design that includes both elements, support and payment. Such an approach is currently used in Germany to allocate non-centrally pre-investigated offshore wind sites (WindSeeG, 2023, §16 et seqq.).[16] This two-stage design combines a oFIP auction and a payment auction. In the first stage, each bidder submits a bid for a oFIP in a simultaneous first-price auction. If no more than one bidder submits a zero-cent per kWh bid in the first stage, the bidder with the lowest bid wins the auction and receives a oFIP equal to the bid. If at least two bidders offer zero cents per kWh, indicating their expectation to manage the project without a oFIP, a payment auction will take place. All zero-cent bidders from the first stage can participate in this payment auction. In the payment auction, bidders offer a payment with their bid for the site. The bidder offering the largest absolute payment wins and has to pay that amount.[17] This means that if conditions are such that no bidder expects to be able to manage without support, then there will be support via oFIP. On the other hand, if at least one bidder believes the project can be managed without support, the market solution applies instead. To date, seven sites in Germany have been put out to tender under this procedure in 2023–2025, each of which was competitively allocated in the second stage through the payment auction (BNetzA, 2025a).

7. Design proposal

The examples in Section 6.1 show that the auctioneer's decision to use either CfD or payment may not be suitable. In this regard, one of the main arguments in favor of auctions emerges, namely asymmetric information (e.g., Klemperer, 1999). This means that the bidders have a better knowledge of the factors determining the project value than the auctioneer does. One solution to this problem is to allow the bidders to decide competitively whether or not they need support, as is the case in the design in Section 6.2.

This section proposes a design for combining CfD and payment, as described in the first paragraph of Section 6: a CfD auction with a maximum bid price, and a payment auction in which only negative bids are permitted. If the oFIP is to be replaced by a CfD, the design in Section 6.2 must be adjusted to ensure proper functionality with CfD and negative payments. Unlike a oFIP, a CfD caps revenues. A negative payment is not a negative CfD price; rather, it is an alternative below a certain CfD price threshold, i.e., the strike-price level that corresponds to a zero payment. That is, for each CfD price below the strike-price level, there exists a corresponding negative payment that makes the bidder indifferent between the CfD and the negative payment. Therefore, a different procedure is required, in which bidders choose between the CfD and the payment.[18]

The following presents such a mechanism in which the market solution is prioritized. The CfD solution should only be implemented if all bidders prefer it. The proposed priority rule is motivated by focusing on realization probability and the induced welfare effects rather than auction revenue considerations, as stated in Section 4. This is supported by the arguments of market integration and risk distribution in Section 2.1. Additionally, payment-only auctions entail lower regulatory complexity and implementation costs.

Definition 1. Mechanism $\mathcal{M}$ consists of two alternative bidding processes: one for a CfD and one for a non-positive payment.

The bidders simultaneously submit their bids. A CfD bid, b_C, may not be negative and may not exceed the maximum price $\bar{b}_C$: $0 \le b_C \le \bar{b}_C$. A payment bid, b_N, may not be positive: $b_N \le 0 = \bar{b}_N$. Each bidder has four options:

1. Submit only a CfD bid, b_C.
2. Submit both a CfD bid, b_C, and a payment bid, b_N.
3. Submit only a payment bid, b_N.
4. Submit no bid.

If at least one bidder chooses the third option, the payment auction will take place. In this case, all bidders who submit a payment bid (second and third option) participate in this auction with their payment bids. If all bidders choose the fourth option, no auction will take place. In other cases, the CfD auction will take place, in which the bidders' CfD bids will then apply (first and second option).

In either auction, the bidder with the lowest bid wins. This bidder either receives a CfD at the second-lowest CfD bid or makes a payment equal to the second-lowest payment bid.[19]

The mechanism $\mathcal{M}$ implies that through the bid of the first option, the bidder indicates that they will only accept a CfD; through the bid of the second option, the bidder indicates that they prefer a CfD, but will accept the market solution; through the bid of the third option, the bidder indicates that they prefer the market solution. The mechanism $\mathcal{M}$ consistently considers all possible bidder preferences. Since only one bidder who prefers the market solution is sufficient to initiate it, the

[15] In the UK, CfD auctions are held annually for various technologies, including offshore wind energy. Technologically specific maximum bid prices apply in these auctions. After no bids were submitted for offshore wind energy in 2023 (e.g., New Energy World, 2023), the maximum price was raised for subsequent auctions in 2024 and 2025 (GOV.UK, 2023).

[16] To our knowledge, this is still the only application worldwide of the combination of a support and a payment auction in the context of RE.

[17] Note that in the formal model, payment bids are treated as negative numbers, so the "lowest" bid wins; here we follow the real-world convention of absolute euro amounts.

[18] We do not pursue concepts that would result in a combination of a CfD and a negative payment, but only those that result in either a CfD or a payment. Reasons are that combined solutions are difficult to implement and monitor, and their benefits are questionable.

[19] If multiple bidders submit the winning bid, tie-breaking rules must be established. The options are to randomly select the winner or use the first-come, first-served time rule. If only one bidder participates, appropriate rules must be established. For example, the bidder could choose whether to receive a CfD at the maximum price $\bar{b}_C$ or accept the market solution without payment.

question of acceptance of the CfD in the case of a preference for the market solution does not need to be addressed. This design choice is intentional: a single bidder preferring the market solution is sufficient to trigger it, reflecting the mechanism's objective of maximizing project realization while avoiding unnecessary subsidies.

The following applies to bidders with private cost signals (as described in Section 4), regardless of their risk preference.

Proposition 4. *The mechanism $\mathcal{M}$ is incentive compatible:*

1. *If $b_C^* \le \bar{b}_C$ and $b_N^* > \bar{b}_N$, then $b_C = b_C^*$ and $b_N = \emptyset$.*
2. *If $b_C^* \le \bar{b}_C$ and $b_N^* \le \bar{b}_N$ and $EU_C(b_C^*) > EU_N(b_N^*)$, then $b_C = b_C^*$ and $b_N = b_N^*$.*
3. *If $b_C^* \le \bar{b}_C$ and $b_N^* \le \bar{b}_N$ and $EU_C(b_C^*) \le EU_N(b_N^*)$, or if $b_C^* > \bar{b}_C$ and $b_N^* \le \bar{b}_N$, then $b_N = b_N^*$ and $b_C = \emptyset$.*
4. *If $b_C^* > \bar{b}_C$ and $b_N^* > \bar{b}_N$, then $b_C = \emptyset$ and $b_N = \emptyset$.*

Proposition 4 states that it is optimal for each bidder to submit bid(s) truthfully based on two considerations: (i) whether the bidder accepts a CfD below the maximum price and/or the market solution, as determined by the relationship between the own indifference bids and the respective maximum prices, and (ii) the preference between the CfD and the payment auctions. For either auction, if a bidder decides to participate, submitting the corresponding indifference bid is a weakly dominant strategy, as in the basic model.

For the further analysis of $\mathcal{M}$, we use the basic model with different τ introduced in Section 4. We consider two cases of risk preferences: all bidders are risk-neutral or all bidders are risk-averse. According to Proposition 2, regardless of risk preference, a bidder with τ_ℓ prefers scenario N, while a bidder with τ_h prefers scenario C, provided the bidder is willing to participate in both auctions. Moreover, from the perspective of a bidder with τ_ℓ, the realization probability in N is greater than in C. These results are expected to hold as well if $\bar{b}_N$ excludes more bidders than $\bar{b}_C$, provided that $\Delta\tau$ or n are sufficiently large (see the proof of Lemma 5 in the appendix). The proof introduces this as an additional assumption and provides a plausibility argument. Under this assumption, the following results hold independently of the bidders' risk preferences.

Let $\hat{\theta}_{C,\ell}$, $\hat{\theta}_{C,h}$, $\hat{\theta}_{N,\ell}$ and $\hat{\theta}_{N,h}$ denote the cutoff costs for bidders in C and N with τ_ℓ and τ_h. The cutoff costs represent the values of θ at which the corresponding indifference bid equals the maximum bid, i.e., either $\bar{b}_C$ or $\bar{b}_N$. That is, if a bidder's private cost signal lies below (above) the corresponding cutoff cost, the bidder's indifference bid will be below (above) the maximum price, and the bidder will (not) participate in the corresponding auction. For instance, a bidder with τ_h and $\theta < \hat{\theta}_{N,h}$ satisfies $b_N^* < \bar{b}_N$ and thus participates in N. Therefore, the cutoff costs mark the upper limit of θ up to which bidders participate in the C auction or the N auction. This means that the higher the cutoff costs, the higher the expected number of bidders. Thus, higher cutoff costs indicate greater attractiveness of the auction. The cutoff costs depend on the utility function and τ and are monotone in the respective maximum bid. It holds that $\hat{\theta}_{C,\ell} = \hat{\theta}_{C,h} := \hat{\theta}_C$ and $\hat{\theta}_{N,h} = \hat{\theta}_{N,\ell} - \Delta\tau$, where $\Delta\tau = \tau_h - \tau_\ell > 0$. The cutoff costs do not need to be specified in more detail for the following analysis. In practice, while the market solution with $\bar{b}_N = 0$ may be challenging to implement depending on specific site and market conditions, the maximum CfD price is usually set generously to encourage participation.[20] Therefore, we assume that $\hat{\theta}_C > \hat{\theta}_{N,\ell} > \hat{\theta}_{N,h}$, i.e., a bidder who can cope with the market solution will also be able to do so with the maximum CfD price.[21]

[20] The case described in Footnote 6.1 could be considered a counterexample.

[21] Lemma 5 can be adapted to other possible relationships between the cutoff costs, where a bidder with $b_C^* > \bar{b}_C$ and $b_N^* \le \bar{b}_N$ can also initiate the payment auction, leading to different probabilities. The proof and generalization of Lemma 5 are provided in the appendix.

Table 1
Probabilities of cases (i)–(iii) at different values of n and $\hat{\theta}_{N,\ell}$.

$\hat{\theta}_{N,\ell}$	Case	$n = 2$	$n = 3$	$n = 5$	$n = 10$
0.25	(i)	23.44%	33.01%	48.71%	73.69%
	(ii)	1.00%	0.10%	< 0.01%	≪ 0.01%
	(iii)	75.56%	66.89%	51.29%	26.31%
0.75	(i)	60.94%	75.59%	90.46%	99.09%
	(ii)	1.00%	0.10%	< 0.01%	≪ 0.01%
	(iii)	38.06%	24.31%	9.54%	0.91%

Lemma 5. *Consider the model with different τ, where each of the n bidders is independently and randomly assigned to τ_h with probability λ and to τ_ℓ with probability $1-\lambda$, for $\lambda \in [0,1]$. There are three possible outcomes of $\mathcal{M}$:*

(i) If there is at least one bidder with τ_ℓ such that $b_N^* \le \bar{b}_N$, the payment auction takes place. The probability of this case is $1-[\lambda+(1-\lambda)(1-F(\hat{\theta}_{N,\ell}))]^n$.

(ii) If $b_C^* > \bar{b}_C$ and $b_N^* > \bar{b}_N$ for all bidders, then no bidder participates in either auction. The probability of this case is $(1-F(\hat{\theta}_C))^n$.

(iii) In all other cases, the CfD auction will take place. The probability is $[\lambda+(1-\lambda)(1-F(\hat{\theta}_{N,\ell}))]^n-(1-F(\hat{\theta}_C))^n$.

The probability of Case (i) increases in n and converges to 1 as $n \to \infty$, decreases in λ, and increases in $\hat{\theta}_{N,\ell}$. That is, stronger competition, a higher expected share of bidders with τ_ℓ, and greater attractiveness of the payment auction for bidders with τ_ℓ favor the payment auction. The probability of Case (ii) decreases in n and $\hat{\theta}_C$. Hence, the probability of no participation is high when competition is weak and the CfD maximum price offers insufficient attractiveness. The probability of Case (iii) benefits from less attractiveness of the payment auction for bidders with τ_ℓ and greater attractiveness of the CfD auction. If n is sufficiently large, then the probability of Case (iii) decreases in n and converges to 0 as $n \to \infty$. Note that $\hat{\theta}_{N,h}$ and thus $\Delta\tau$ does not influence the probabilities of any of the three cases. The following numerical examples help to illustrate the underlying probability patterns: $\lambda = 50\%$, bidders' private cost signals are uniformly distributed on $[0,1]$, $n \in \{2,3,5,10\}$, $\hat{\theta}_C = 0.9 > \hat{\theta}_{N,\ell}$, and $\hat{\theta}_{N,\ell} \in \{0.25, 0.75\}$ (see Table 1).

We now compare the performance of $\mathcal{M}$ in terms of realization probability to that of the two individual auction formats, C and N.

Proposition 5. *Mechanism $\mathcal{M}$ selects the auction with the weakly higher realization probability between C and N in most cases, except when no bidder with τ_ℓ satisfies $b_N^* \le \bar{b}_N$ but at least one bidder with τ_h does.*

The exceptional case requires the bidders with τ_h to have significantly lower private cost signals θ_i – at least $\Delta\tau$ less – than bidders with τ_ℓ. The probability of this scenario is $[\lambda+(1-\lambda)(1-F(\hat{\theta}_{N,\ell}))]^n - [\lambda(1-F(\hat{\theta}_{N,\ell}-\Delta\tau))+(1-\lambda)(1-F(\hat{\theta}_{N,\ell}))]^n$, which decreases in $\Delta\tau$, increases in λ, and converges to 0 if $n \to \infty$. For instance, $\lambda = 50\%$, bidders' private cost signals are uniformly distributed on $[0,1]$, $n = 5$, $\hat{\theta}_C = 0.9$, $\hat{\theta}_{N,\ell} = 0.75$, and $\hat{\theta}_{N,h} = 0.5$, the probability is 8.8%.

In conclusion, mechanism $\mathcal{M}$ positively contributes to welfare by combining bidders' knowledge of their support needs with the selection of solutions that increase the probability of project realization. The welfare gains from the proposed mechanism depend on the magnitude of the cost differential $\Delta\tau = \tau_h - \tau_\ell$. When $\Delta\tau$ is small, bidders' preferences for one auction format over the other become ambiguous, so the welfare gain from $\mathcal{M}$ is limited. In contrast, larger $\Delta\tau$ strengthens bidders' preferences, allowing $\mathcal{M}$ to more effectively select the auction that yields the weakly higher realization probability, thereby improving welfare.

8. Policy implications and conclusion

The increasingly demanded CfDs are particularly advantageous for promoting the further expansion of RE if projects cannot be realized without support. In this context, CfDs can effectively promote participation and thus the expansion of renewables. However, CfDs are not a panacea. Provided that developers can realize projects without support, we show that, despite various parties' claims to the contrary, CfDs allocated through auctions are disadvantageous in terms of project realization compared to a market solution without support. This finding applies to both second-price and first-price (pay-as-bid) auctions and to both risk-neutral and risk-averse bidders. The latter is particularly relevant because risk-averse bidders are often cited as the main reason for using CfDs. The advantage of the market solution over CfDs exists despite the additional financing costs associated with the market solution. Assuming higher costs for bidders in the market solution, CfDs yield lower expected costs (higher expected revenues) for the auctioneer than the market solution with risk-neutral bidders. The same applies to risk-averse bidders, even when their costs are equal in both scenarios. Therefore, the auctioneer faces a trade-off between realization probability and auction revenue. If the auctioneer's primary objective is to achieve a high realization probability, and given the advantages in terms of market integration and regulatory effort, the auctioneer should prefer the market solution.

Therefore, with a focus on high project realization rates, which is an essential aspect of the expansion of RE, we recommend using CfDs only if developers cannot implement their projects without support, and to implement a market solution with payments by the auction winner, if possible. Due to information asymmetry – the developers have the best knowledge of the expected profitability of their planned project – the developers should decide competitively which of the two options to implement. This promises efficient solutions with low subsidy costs or high auction revenues. The argument of information asymmetry also implies that developers know best whether they need support to implement their project. A misjudgment by the auctioneer, as recently observed in several countries, can lead to undesirable outcomes such as a lack of participation and project delays. Therefore, our findings suggest the goal of a high project implementation rate should be pursued by leaving the decision between CfD and market solutions to the developers. We present an auction design that meets this requirement. It invites developers to participate and almost always selects the solution with the higher realization probability.

We also considered several model extensions. Beyond the robustness of our main result under pay-as-bid pricing, we show that risk-averse bidders add a buffer to their bids that protects the implementation decision against moderate negative belief updates. However, if expectations about the future electricity market deteriorate substantially, the realization probability with the market solution decreases, potentially falling below that of the CfD solution. The policy implications should therefore be interpreted conditional on the baseline setting and moderate information updates regarding future electricity market conditions during the implementation period. Additionally, we recommend that the winning bidder in a payment auction make a partial payment to the auctioneer before the implementation decision is made. This is because an early payment increases the probability of realization, regardless of the bidders' risk preferences. The proportion or amount of early payments should be determined while taking into account potential adverse effects, such as higher financing costs and an increased risk of general non-participation. As discussed in Section 7, the proposed mechanism mitigates the risk of non-participation, as bidders whose negative payment bids become infeasible can still submit CfD bids. This feature ensures that the proposed mechanism strengthens realization incentives without discouraging participation.

Of course, our theoretical model and its conclusions are subject to limitations, as it does not account for all real-world factors. First, to compare with the market solution under full revenue uncertainty, we assume perfect hedging under CfDs, i.e., no residual revenue uncertainty. In practice, operators in the market solution may mitigate revenue uncertainty through bilateral PPAs, while CfD-backed operators may still face residual uncertainty such as volume or basis risk, which are not explicitly modeled. However, our main results remain unaffected as long as revenue uncertainty under CfDs is sufficiently lower than under the market solution. Comparisons across different CfD designs are ambiguous and outside the scope of this paper. Second, our model does not consider bidders with mixed risk preferences. According to Wang (2025), a more risk-tolerant bidder has a competitive advantage over the less risk-tolerant bidder with the same private cost signal, reflected in a higher winning probability and, under certain conditions, higher expected profits and realization probabilities. This advantage is greater under the market solution than under CfDs. Consequently, more risk-tolerant bidders are more likely to prefer the market solution, while less risk-tolerant bidders may prefer CfDs. Moreover, our work does not focus on comparing first-price and second-price auctions and highlighting their differences, as our key findings regarding the comparison of market solution and CfD apply to both auction formats. In our context, extending the model to compare different auction formats would constitute a valuable new research direction. Such an extension supports the use of dynamic multi-round second-price auctions, in which bidders can learn from each other about uncertain investment costs and electricity market prices, thereby reducing winner's curse risk. However, such analyses are only feasible for risk-neutral bidders, not for risk-averse ones, who play a significant role in our analysis.

Last but not least, if market conditions for investment deteriorate drastically after the auction, as was the case in 2023–2025 (e.g., Boston Consulting Group, 2025) – a scenario captured in our model by a significant post-auction shock – neither auction format fully protects bidders from such developments. One possible approach to protecting bidders against severe post-auction shocks is to index essential cost components (e.g., European Commission, 2023). CfD indexation during the implementation decision period can reduce cost uncertainty and increase realization probability. Since indexing a lump-sum payment is not meaningful, introducing CfD indexation within our proposed either-or design may shift bidders' preferences toward CfDs. The objective of reducing cost uncertainty prior to the implementation decision should therefore be carefully weighed against the priority given to the market solution.

CRediT authorship contribution statement

Runxi Wang: Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Conceptualization. **Karl-Martin Ehrhart:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Conceptualization.

Declaration of generative AI and AI-assisted technologies in the manuscript preparation process

During the preparation of this work the authors used ChatGPT and Refine in order to obtain critical feedback and improve the language. After using these tools, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

Declaration of competing interest

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Appendix. Proofs

Proof of Lemma 1. Under risk neutrality, bidders evaluate uncertain revenues solely according to their expected value. Therefore, Eqs. (6) and (7) become $w+b_C^*-\theta=w-s+y_C^*(b_C^*)$ and $w+b_N^*-\theta-\tau+\mathbb{E}[Z]=w-s+y_N^*(b_N^*)$. Substituting these expressions into Eq. (5) yields

$$\int_{\underline{y}}^{y_C^*(b_C^*)}(w-s+y_C^*(b_C^*)-y)g(y)dy+\int_{y_C^*(b_C^*)}^{\bar{y}}(w-s)g(y)dy=w$$

$$=\int_{\underline{y}}^{y_N^*(b_N^*)}(w-s+y_N^*(b_N^*)-y)g(y)dy+\int_{y_N^*(b_N^*)}^{\bar{y}}(w-s)g(y)dy$$

$$\Leftrightarrow\quad \int_{\underline{y}}^{y_C^*(b_C^*)}(y_C^*(b_C^*)-y)g(y)dy=s=\int_{\underline{y}}^{y_N^*(b_N^*)}(y_N^*(b_N^*)-y)g(y)dy.$$

Since the left-hand and right-hand expressions are strictly increasing in $y_C^*(b_C^*)$ and $y_N^*(b_N^*)$, respectively, it follows that $y_C^*(b_C^*)=y_N^*(b_N^*)$. Using Eqs. (6) and (7), we obtain $b_C^*=b_N^*+\mathbb{E}[Z]-\tau$. Given these two conditions, it is easy to proof that $U_C(b_C^*)=U_N(b_N^*)$ and $u(w+b_C^*-\theta-y_C^*(b_C^*))=\int_{\underline{z}}^{\bar{z}}u(w+b_N^*-\theta-\tau-y_N^*(b_N^*)+z)h(z)dz$.

For a risk-averse bidder, first assume that $b_C^*=b_N^*+\mathbb{E}[Z]-\tau$ and $y_C^*(b_C^*)=y_N^*(b_N^*)$ as in the risk-neutral case. According to (5), by setting $y_C^*(b_C^*)=y_N^*(b_N^*)$, we have

$$\int_{\underline{y}}^{y_C^*(b_C^*)}u(w+b_C^*-\theta-y)g(y)dy$$
$$=\int_{\underline{y}}^{y_N^*(b_N^*)}\int_{\underline{z}}^{\bar{z}}u(w+b_N^*-\theta-\tau-y+z)h(z)dzg(y)dy \tag{A.1}$$

Due to risk aversion and by setting $b_C^*=b_N^*+\mathbb{E}[Z]-\tau$, it holds that

$$\int_{\underline{y}}^{y_N^*(b_N^*)}\int_{\underline{z}}^{\bar{z}}u(w+b_N^*-\theta-\tau-y+z)h(z)dzg(y)dy \tag{A.2}$$
$$<\int_{\underline{y}}^{y_N^*(b_N^*)}u(w+b_N^*-\theta-\tau-y+\mathbb{E}[Z])g(y)dy \tag{A.3}$$
$$=\int_{\underline{y}}^{y_C^*(b_C^*)}u(w+b_C^*-\theta-y)g(y)dy$$

This contradicts Eq. (A.1), and therefore, the assumption $b_C^*=b_N^*+\mathbb{E}[Z]-\tau$ and $y_C^*(b_C^*)=y_N^*(b_N^*)$ cannot hold. To increase the expression (A.2) so that $U_C(b_C^*)=U_N(b_N^*)$ holds, b_N^* or $y_N^*(b_N^*)$ must increase. According to (7), b_N^* and $y_N^*(b_N^*)$ are positively related – an increase in one requires an increase in the other. Consequently, both must increase. It follows that $b_C^*<b_N^*+\mathbb{E}[Z]-\tau$ and $y_C^*(b_C^*)<y_N^*(b_N^*)$.

Similarly, assume $b_C^*=b_N^*+\mathbb{E}[Z]-\tau$ and $y_C^*(b_C^*)=y_N^*(b_N^*)$ for a risk-seeking bidder, the corresponding expression (A.2) should be larger than the expression (A.3), leading to a contradiction with Eq. (A.1). Therefore, to satisfy the condition $U_C(b_C^*)=U_N(b_N^*)$, it must hold that $b_C^*>b_N^*+\mathbb{E}[Z]-\tau$ and $y_C^*(b_C^*)>y_N^*(b_N^*)$. □

Proof of Lemma 2. Under scenario C, according to Eq. (6), it holds that

$$u(w+b_{C,j}^*-\theta_j-y_{C,j}^*(b_{C,j}^*))=u(w-s)=u(w+b_{C,i}^*-\theta_i-y_{C,i}^*(b_{C,i}^*))$$
$$\Leftrightarrow w+b_{C,j}^*-\theta_j-y_{C,j}^*(b_{C,j}^*)=w-s=w+b_{C,i}^*-\theta_i-y_{C,i}^*(b_{C,i}^*)$$
$$\Rightarrow b_{C,j}^*-\theta_j=y_{C,j}^*(b_{C,j}^*)-s,\ \ b_{C,i}^*-\theta_i=y_{C,i}^*(b_{C,i}^*)-s \tag{A.4}$$

According to Eq. (5), we have

$$U_C(y_{C,j}^*(b_{C,j}^*),b_{C,j}^*)=U_C(y_{C,i}^*(b_{C,i}^*),b_{C,i}^*)=u(w) \tag{A.5}$$

If $b_{C,j}^*-\theta_j<b_{C,i}^*-\theta_i$, then according to (A.4), $y_{C,j}^*(b_{C,j}^*)<y_{C,i}^*(b_{C,i}^*)$. We have

$$\begin{aligned}
&U_C(y_{C,i}^*(b_{C,i}^*),b_{C,i}^*)\\
&=\int_{\underline{y}}^{y_{C,i}^*(b_{C,i}^*)}u(w+b_{C,i}^*-\theta_i-y)g(y)dy+\int_{y_{C,i}^*(b_{C,i}^*)}^{\bar{y}}u(w-s)g(y)dy\\
&=\int_{\underline{y}}^{y_{C,j}^*(b_{C,j}^*)}u(w+b_{C,i}^*-\theta_i-y)g(y)dy\\
&\quad+\int_{y_{C,j}^*(b_{C,j}^*)}^{y_{C,i}^*(b_{C,i}^*)}u(w+b_{C,i}^*-\theta_i-y)g(y)dy\\
&\quad+\int_{y_{C,j}^*(b_{C,j}^*)}^{\bar{y}}u(w-s)g(y)dy-\int_{y_{C,j}^*(b_{C,j}^*)}^{y_{C,i}^*(b_{C,i}^*)}u(w-s)g(y)dy\\
&>\int_{\underline{y}}^{y_{C,j}^*(b_{C,j}^*)}u(w+b_{C,j}^*-\theta_j-y)g(y)dy\\
&\quad+\int_{y_{C,j}^*(b_{C,j}^*)}^{y_{C,i}^*(b_{C,i}^*)}u(w+b_{C,i}^*-\theta_i-y_{C,i}^*(b_{C,i}^*))g(y)dy\\
&\quad+\int_{y_{C,j}^*(b_{C,j}^*)}^{\bar{y}}u(w-s)g(y)dy-\int_{y_{C,j}^*(b_{C,j}^*)}^{y_{C,i}^*(b_{C,i}^*)}u(w-s)g(y)dy\\
&=U_C(y_{C,j}^*(b_{C,j}^*),b_{C,j}^*)+\int_{y_{C,j}^*(b_{C,j}^*)}^{y_{C,i}^*(b_{C,i}^*)}(u(w+b_{C,i}^*\\
&\quad-\theta_i-y_{C,i}^*(b_{C,i}^*))-u(w-s))g(y)dy\\
&=U_C(y_{C,j}^*(b_{C,j}^*),b_{C,j}^*)
\end{aligned}$$

This contradicts Eq. (A.5), thus, $b_{C,j}^*-\theta_j<b_{C,i}^*-\theta_i$ does not hold.

If $b_{C,j}^*-\theta_j>b_{C,i}^*-\theta_i$, then according to (A.4), $y_{C,j}^*(b_{C,j}^*)>y_{C,i}^*(b_{C,i}^*)$. We have

$$\begin{aligned}
&U_C(y_{C,j}^*(b_{C,j}^*),b_{C,j}^*)\\
&=\int_{\underline{y}}^{y_{C,j}^*(b_{C,j}^*)}u(w+b_{C,j}^*-\theta_j-y)g(y)dy+\int_{y_{C,j}^*(b_{C,j}^*)}^{\bar{y}}u(w-s)g(y)dy\\
&=\int_{\underline{y}}^{y_{C,i}^*(b_{C,i}^*)}u(w+b_{C,j}^*-\theta_j-y)g(y)dy\\
&\quad+\int_{y_{C,i}^*(b_{C,i}^*)}^{y_{C,j}^*(b_{C,j}^*)}u(w+b_{C,j}^*-\theta_j-y)g(y)dy\\
&\quad+\int_{y_{C,i}^*(b_{C,i}^*)}^{\bar{y}}u(w-s)g(y)dy-\int_{y_{C,i}^*(b_{C,i}^*)}^{y_{C,j}^*(b_{C,j}^*)}u(w-s)g(y)dy\\
&>\int_{\underline{y}}^{y_{C,i}^*(b_{C,i}^*)}u(w+b_{C,i}^*-\theta_i-y)g(y)dy\\
&\quad+\int_{y_{C,i}^*(b_{C,i}^*)}^{y_{C,j}^*(b_{C,j}^*)}u(w+b_{C,j}^*-\theta_j-y_{C,j}^*(b_{C,j}^*))g(y)dy\\
&\quad+\int_{y_{C,i}^*(b_{C,i}^*)}^{\bar{y}}u(w-s)g(y)dy-\int_{y_{C,i}^*(b_{C,i}^*)}^{y_{C,j}^*(b_{C,j}^*)}u(w-s)g(y)dy\\
&=U_C(y_{C,i}^*(b_{C,i}^*),b_{C,i}^*)+\int_{y_{C,i}^*(b_{C,i}^*)}^{y_{C,j}^*(b_{C,j}^*)}(u(w+b_{C,j}^*-\theta_j-y_{C,j}^*(b_{C,j}^*))\\
&\quad-u(w-s))g(y)dy\\
&=U_C(y_{C,i}^*(b_{C,i}^*),b_{C,i}^*)
\end{aligned}$$

This contradicts Eq. (A.5), thus, $b_{C,j}^*-\theta_j>b_{C,i}^*-\theta_i$ does not hold.

If $b_{C,j}^*-\theta_j=b_{C,i}^*-\theta_i$, then according to (A.4), $y_{C,j}^*(b_{C,j}^*)=y_{C,i}^*(b_{C,i}^*)$. We have

$$U_C(y_{C,j}^*(b_{C,j}^*),b_{C,j}^*)$$

$$= \int_{\underline{y}}^{y^*_{C,j}(b^*_{C,j})} u(w + b^*_{C,j} - \theta_j - y)g(y)dy + \int_{y^*_{C,j}(b^*_{C,j})}^{\bar{y}} u(w-s)g(y)dy$$
$$= \int_{\underline{y}}^{y^*_{C,i}(b^*_{C,i})} u(w + b^*_{C,i} - \theta_i - y)g(y)dy + \int_{y^*_{C,i}(b^*_{C,i})}^{\bar{y}} u(w-s)g(y)dy$$
$$= U_C(y^*_{C,i}(b^*_{C,i}), b^*_{C,i})$$

This coincides with Eq. (A.5), thus, $b^*_{C,j} - \theta_j = b^*_{C,i} - \theta_i$ and $y^*_{C,j}(b^*_{C,j}) = y^*_{C,i}(b^*_{C,i})$.

Under scenario N, according to Eq. (7), it holds that

$$\int_{\underline{z}}^{\bar{z}} u(w + b^*_{N,j} - \theta_j - \tau_j - y^*_{N,j}(b^*_{N,j}) + z)h(z)dz = u(w-s)$$
$$= \int_{\underline{z}}^{\bar{z}} u(w + b^*_{N,i} - \theta_i - \tau_i - y^*_{N,i}(b^*_{N,i}) + z)h(z)dz$$
$$\Rightarrow b^*_{N,j} - \theta_j - \tau_j - y^*_{N,j}(b^*_{N,j}) = b^*_{N,i} - \theta_i - \tau_i - y^*_{N,i}(b^*_{N,i}) \tag{A.6}$$

According to Eq. (5), we have

$$U_N(y^*_{N,j}(b^*_{N,j}), b^*_{N,j}) = U_N(y^*_{N,i}(b^*_{N,i}), b^*_{N,i}) = u(w) \tag{A.7}$$

If $b^*_{N,j} - \theta_j - \tau_j < b^*_{N,i} - \theta_i - \tau_i$, then according to (A.6), $y^*_{N,j}(b^*_{N,j}) < y^*_{N,i}(b^*_{N,i})$. We have

$$U_N(y^*_{N,i}(b^*_{N,i}), b^*_{N,i})$$
$$= \int_{\underline{y}}^{y^*_{N,i}(b^*_{N,i})} \int_{\underline{z}}^{\bar{z}} u(w + b^*_{N,i} - \theta_i - \tau_i - y + z)h(z)dzg(y)dy$$
$$+ \int_{y^*_{N,i}(b^*_{N,i})}^{\bar{y}} u(w-s)g(y)dy$$
$$= \int_{\underline{y}}^{y^*_{N,j}(b^*_{N,j})} \int_{\underline{z}}^{\bar{z}} u(w + b^*_{N,i} - \theta_i - \tau_i - y + z)h(z)dzg(y)dy$$
$$+ \int_{y^*_{N,j}(b^*_{N,j})}^{\bar{y}} u(w-s)g(y)dy - \int_{y^*_{N,j}(b^*_{N,j})}^{y^*_{N,i}(b^*_{N,i})} u(w-s)g(y)dy$$
$$+ \int_{y^*_{N,j}(b^*_{N,j})}^{y^*_{N,i}(b^*_{N,i})} \int_{\underline{z}}^{\bar{z}} u(w + b^*_{N,i} - \theta_i - \tau_i - y + z)h(z)dzg(y)dy$$
$$> \int_{y^*_{N,j}(b^*_{N,j})}^{y^*_{N,i}(b^*_{N,i})} \left[\int_{\underline{z}}^{\bar{z}} (u(w + b^*_{N,i} - \theta_i - \tau_i - y^*_{N,i}(b^*_{N,i}) + z)h(z)dz - u(w-s))g(y)dy\right]$$
$$+ U_N(y^*_{N,j}(b^*_{N,j}), b^*_{N,j})$$
$$= U_N(y^*_{N,j}(b^*_{N,j}), b^*_{N,j})$$

This contradicts Eq. (A.7), thus, $b^*_{N,j} - \theta_j - \tau_j < b^*_{N,i} - \theta_i - \tau_i$ does not hold.

Analogously, if $b^*_{N,j} - \theta_j - \tau_j > b^*_{N,i} - \theta_i - \tau_i$, then according to (A.6), $y^*_{N,j}(b^*_{N,j}) > y^*_{N,i}(b^*_{N,i})$. We have $U_N(y^*_{N,j}(b^*_{N,j}), b^*_{N,j}) > U_N(y^*_{N,i}(b^*_{N,i}), b^*_{N,i})$, which contradicts Eq. (A.7). Thus, $b^*_{N,j} - \theta_j - \tau_j > b^*_{N,i} - \theta_i - \tau_i$ does not hold.

If $b^*_{N,j} - \theta_j - \tau_j = b^*_{N,i} - \theta_i - \tau_i$, then according to (A.6), $y^*_{N,j}(b^*_{N,j}) = y^*_{N,i}(b^*_{N,i})$. And we have $U_N(y^*_{N,j}(b^*_{N,j}), b^*_{N,j}) = U_N(y^*_{N,i}(b^*_{N,i}), b^*_{N,i})$, which coincides with Eq. (A.7). Thus, $b^*_{N,j} - \theta_j - \tau_j = b^*_{N,i} - \theta_i - \tau_i$ and $y^*_{N,j}(b^*_{N,j}) = y^*_{N,i}(b^*_{N,i})$. □

Proof of Lemma 3.

Under scenario C, according to Eqs. (3) and (6), we have

$$u(w + b^*_{C,j} - \theta_i - y^*_{C,i}(b^*_{C,j})) = u(w-s) = u(w + b^*_{C,i} - \theta_i - y^*_{C,i}(b^*_{C,i}))$$
$$\Rightarrow y^*_{C,i}(b^*_{C,j}) = y^*_{C,i}(b^*_{C,i}) + b^*_{C,j} - b^*_{C,i} = y^*_{C,i}(b^*_{C,i}) + b^*_{C,j} - b^*_{C,i}.$$

Since $b^*_{C,j} - \theta_j = b^*_{C,i} - \theta_i$ as proved in Lemma 2, it follows that $y^*_{C,i}(b^*_{C,j}) = y^*_{C,i}(b^*_{C,i}) + \theta_j - \theta_i$.

Under scenario N, according to the Eqs. (4) and (7), we have

$$\int_{\underline{z}}^{\bar{z}} u(w + b^*_{N,j} - \theta_i - \tau_i - y^*_{N,i}(b^*_{N,j}) + z)h(z)dz$$
$$= \int_{\underline{z}}^{\bar{z}} u(w + b^*_{N,i} - \theta_i - \tau_i - y^*_{N,i}(b^*_{N,i}) + z)h(z)dz$$
$$\Rightarrow y^*_{N,i}(b^*_{N,j}) = y^*_{N,i}(b^*_{N,i}) + b^*_{N,j} - b^*_{N,i}$$
$$= y^*_{N,i}(b^*_{N,i}) + \theta^N_j - \theta^N_i \qquad \text{(Lemma 2)} \quad \square$$

Proof of Lemma 4. Since T is independent of Θ and Θ has a log-concave density, it holds that $\Theta \leq_{disp} \Theta^N = \Theta + T$, i.e., Θ is less dispersive than Θ^N (Shaked and Shanthikumar, 2007, Theorem 3.B.7).[22] According to Alzaid and Proschan (1992, Theorem 2.6), $\mathbb{E}[\Theta_{(i)}] - \mathbb{E}[\Theta^N_{(i)}]$ is decreasing in i. Thus, $\mathbb{E}[\Theta^N_{(i)}] - \mathbb{E}[\Theta_{(i)}]$ is increasing in i, implying $\mathbb{E}[\Theta^N_{(2)}] - \mathbb{E}[\Theta^N_{(1)}] \geq \mathbb{E}[\Theta_{(2)}] - \mathbb{E}[\Theta_{(1)}]$. In other words, the additional dispersion induced by T increases the expected spacing between adjacent order statistics of Θ^N relative to Θ. Consequently, the expected cost difference between the winner and the price-setting bidder is weakly larger in scenario N than in scenario C. □

Proof of Proposition 1. Let p_C and p_N denote the respective prices again, and let the winning bidders in auctions C and N be indexed as $(C1)$ and $(N1)$ respectively. Lemma 4 implies that $\mathbb{E}[\Delta(\Theta^N)] \geq \mathbb{E}[\Delta\Theta]$ for any two order statistics. Then we have $\Delta(\theta^N) > \Delta\theta$ in expectation and thus

$$\begin{aligned}
y^*_{N,(N1)}(p_N) &= y^*_{N,(N1)}(b^*_{N,(N1)}) + \Delta(\theta^N) && \text{(Lemma 3)}\\
&\underset{(=)}{>} y^*_{C,(N1)}(b^*_{C,(N1)}) + \Delta(\theta^N) && \text{(Lemma 1)}\\
&= y^*_{C,(C1)}(b^*_{C,(C1)}) + \Delta(\theta^N) && \text{(Lemma 2)}\\
&\geq y^*_{C,(C1)}(b^*_{C,(C1)}) + \Delta(\theta) && \text{(Lemma 4)}\\
&= y^*_{C,(C1)}(p_C)
\end{aligned}$$

In the second line, $>$ holds for risk-averse bidders and $=$ holds for risk-neutral bidders. For risk-seeking bidders, $<$ holds in the second line, so the comparison is ambiguous.

Since the realization probability is given by $G(y^*)$, and G is strictly increasing in y^*, a higher expected implementation threshold directly implies a higher expected realization probability. Therefore, the larger expected threshold buffer in scenario N translates into a higher expected realization probability. □

Proof of Proposition 3. Under risk-neutrality, the ex-ante expected utility conditional on winning of a representative bidder bidding b_C in scenario C is

$$U^{PaB}_C(b_C) = \int_{\underline{y}}^{y^{PaB}_C(b_C)} u(w + b_C - \theta - y)g(y)dy + \int_{y^{PaB}_C(b_C)}^{\bar{y}} u(w-s)g(y)dy,$$

where $y^{PaB}_C(b_C) = b_C - \theta + s$ according to condition (3). Analogously to our basic model, the expected utility is

$$EU^{PaB}_C(b_C)$$
$$= (1 - F^{PaB}_C(b_C))U^{PaB}_C(b_C) + F^{PaB}_C(b_C)w$$
$$= (1 - F^{PaB}_C(b_C))\left[\int_{\underline{y}}^{y^{PaB}_C(b_C)} u(w + b_C - \theta - y)g(y)dy + \int_{y^{PaB}_C(b_C)}^{\bar{y}} u(w-s)g(y)dy\right]$$
$$+ F^{PaB}_C(b_C)u(w)$$

The first-order condition is

$$\frac{dEU^{PaB}_C(b_C)}{db_C}$$
$$= -f^{PaB}_C\left[\int_{\underline{y}}^{y^{PaB}_C(b_C)} u(w + b_C - \theta - y)g(y)dy + \int_{y^{PaB}_C(b_C)}^{\bar{y}} u(w-s)g(y)dy - u(w)\right]$$

[22] Random variable X is less dispersive than random variable X', denoted by $X \leq_{disp} X'$, if and only if

$$F^{-1}_X(\beta) - F^{-1}_X(\alpha) \leq F^{-1}_{X'}(\beta) - F^{-1}_{X'}(\alpha)$$

for $0 < \alpha < \beta < 1$, where F_X and $F_{X'}$ denote the distribution functions of X and X' (e.g., Alzaid and Proschan, 1992, Def. 1.2).

$$+ (1 - F_C^{PaB}(b_C)) \int_{\underline{y}}^{y_C^{PaB}(b_C)} u'(w + b_C - \theta - y)g(y)dy = 0.$$

Given that the symmetric equilibrium exists, as discussed above, it must satisfy that $\frac{d^2 EU_C^{PaB}(b_C)}{d^2 b_C} < 0$ and $F_C^{PaB}(b_C) = F_{(1,n-1)}(\theta)$. The optimal bid b_C^{PaB} satisfies

$$u(w) - \int_{\underline{y}}^{y_C^{PaB}(b_C^{PaB})} u(w + b_C^{PaB} - \theta - y)g(y)dy - \int_{y_C^{PaB}(b_C^{PaB})}^{\bar{y}} u(w-s)g(y)dy + \frac{1 - F_{(1,n-1)}(\theta)}{f_{(1,n-1)}(\theta)} \int_{\underline{y}}^{y_C^{PaB}(b_C^{PaB})} u'(w + b_C^{PaB} - \theta - y)g(y)dy = 0 \tag{A.8}$$

and the left side of (A.8) decreases in b_C and thus also in $y_C^{PaB}(b_C)$. Similarly, in scenario N it holds that

$$U_N^{PaB}(b_N) = \int_{\underline{y}}^{y_N^{PaB}(b_N)} \int_{\underline{z}}^{\bar{z}} u(w + b_N - \theta - \tau - y + z)h(z)dzg(y)dy + \int_{y_N^{PaB}(b_N)}^{\bar{y}} u(w-s)g(y)dy,$$

where $\int_{\underline{z}}^{\bar{z}} u(w + b_N - \theta - \tau - y_N^{PaB}(b_N) + z)h(z)dz = u(w-s)$ according to condition (4), and

$$EU_N^{PaB}(b_N) = (1 - F_N^{PaB}(b_N))U_N^{PaB}(b_N) + F_N^{PaB}(b_N)u(w)$$

The first-order condition is

$$\frac{dEU_N^{PaB}(b_N)}{db_N} = -f_N^{PaB}(b_N)\left[\int_{\underline{y}}^{y_N^{PaB}(b_N)} \int_{\underline{z}}^{\bar{z}} u(w + b_N - \theta - \tau - y + z)h(z)dzg(y)dy + \int_{y_N^{PaB}(b_N)}^{\bar{y}} u(w-s)g(y)dy - u(w)\right] + (1 - F_N^{PaB}(b_N)) \int_{\underline{y}}^{y_N^{PaB}(b_N)} \int_{\underline{z}}^{\bar{z}} u'(w + b_N - \theta - \tau - y + z)h(z)dzg(y)dy = 0.$$

Given that the symmetric equilibrium exists, it must satisfy that $\frac{d^2 EU_N^{PaB}(b_N)}{d^2 b_N} < 0$ and $F_N^{PaB}(b_N) = F^N_{(1,n-1)}(\theta^N)$. The optimal bid b_N^{PaB} satisfies

$$u(w) - \int_{\underline{y}}^{y_N^{PaB}(b_N^{PaB})} \int_{\underline{z}}^{\bar{z}} u(w + b_N^{PaB} - \theta - \tau - y + z)h(z)dzg(y)dy - \int_{y_N^{PaB}(b_N^{PaB})}^{\bar{y}} u(w-s)g(y)dy + \frac{1 - F^N_{(1,n-1)}(\theta^N)}{f^N_{(1,n-1)}(\theta^N)} \int_{\underline{y}}^{y_N^{PaB}(b_N^{PaB})} \int_{\underline{z}}^{\bar{z}} u'(w + b_N^{PaB} - \theta - \tau - y + z) h(z)dzg(y)dy = 0 \tag{A.9}$$

and the left side of (A.9) decreases in b_N^{PaB} and thus also in $y_N^{PaB}(b_N^{PaB})$.

Now we compare conditions (A.8) and (A.9).

If all bidders are risk-neutral, (A.8) and (A.9) can be simplified as

$$s - \int_{\underline{y}}^{y_C^{PaB}(b_C^{PaB})} (y_C^{PaB}(b_C^{PaB}) - y)g(y)dy + \frac{1 - F_{(1,n-1)}(\theta)}{f_{(1,n-1)}(\theta)} G(y_C^{PaB}(b_C^{PaB})) = 0$$

$$s - \int_{\underline{y}}^{y_N^{PaB}(b_N^{PaB})} (y_N^{PaB}(b_N^{PaB}) - y)g(y)dy + \frac{1 - F^N_{(1,n-1)}(\theta^N)}{f^N_{(1,n-1)}(\theta^N)} G(y_N^{PaB}(b_N^{PaB})) = 0$$

If τ is constant, then $F^N_{(1,n-1)}(\theta^N) = F_{(1,n-1)}(\theta)$. Consequently, $y_C^{PaB}(b_C^{PaB}) = y_N^{PaB}(b_N^{PaB})$ and therefore $b_C^{PaB} = b_N^{PaB} - \tau + \mathbb{E}[Z]$. If τ is non-constant, assume that $\mathbb{E}[T] = 0$ without loss of generality. If $\mathbb{E}[T] \neq 0$, the constant term $\mathbb{E}[T]$ can be absorbed (priced) into b_N^{PaB}, which does not affect the comparison. This is because only the difference $b_N^{PaB} - \tau$, rather than the individual values b_N^{PaB} and τ, is relevant for the comparison of optimal bids and realization probabilities. In this case, Θ^N is a nontrivial mean-preserving spread of Θ. Thus, $\mathbb{E}[\Theta^N_{(1)}] < \mathbb{E}[\Theta_{(1)}]$. Moreover, as shown in the proof of Lemma 4, $\Theta \le_{disp} \Theta^N$. Given that both F and F^N satisfy the strictly increasing failure rate property, Bagai and Kochar (1986) show that $\Theta \le_{hr} \Theta^N$, i.e., Θ is smaller than Θ^N in the sense of hazard rate ordering. Consequently, it holds that

$$\frac{f(\mathbb{E}[\Theta_{(1)}])}{1 - F(\mathbb{E}[\Theta_{(1)}])} \ge \frac{f^N(\mathbb{E}[\Theta_{(1)}])}{1 - F^N(\mathbb{E}[\Theta_{(1)}])} > \frac{f^N(\mathbb{E}[\Theta^N_{(1)}])}{1 - F^N(\mathbb{E}[\Theta^N_{(1)}])} \tag{A.10}$$

Consider now the realization probabilities in the two scenarios from the auctioneer's point of view, represented by $y_C^{PaB}(b_C^{PaB})$ for the bidder with $\mathbb{E}[\Theta_{(1)}]$ in C and $y_N^{PaB}(b_N^{PaB})$ for the bidder with $\mathbb{E}[\Theta^N_{(1)}]$ in N. Since $\frac{1-F_{(1,n-1)}(\theta)}{f_{(1,n-1)}(\theta)} = \frac{1-F(\theta)}{(n-1)f(\theta)}$ and $\frac{1-F^N_{(1,n-1)}(\theta^N)}{f^N_{(1,n-1)}(\theta^N)} = \frac{1-F^N(\theta^N)}{(n-1)f^N(\theta^N)}$, (A.10) implies that $\frac{1-F_{(1,n-1)}(\mathbb{E}[\Theta_{(1)}])}{f_{(1,n-1)}(\mathbb{E}[\Theta_{(1)}])} \le \frac{1-F^N_{(1,n-1)}(\mathbb{E}[\Theta^N_{(1)}])}{f^N_{(1,n-1)}(\mathbb{E}[\Theta^N_{(1)}])}$. Suppose that $y_C^{PaB}(b_C^{PaB}) = y_N^{PaB}(b_N^{PaB})$, then the left-hand side of (A.9) would exceed the left-hand side of (A.8), contradicting the fact that both conditions hold with equality. Since the left-hand side of each condition is decreasing in the corresponding realization probability, $y_C^{PaB}(b_C^{PaB})$ as well as $y_N^{PaB}(b_N^{PaB})$, it follows that $y_C^{PaB}(b_C^{PaB}) < y_N^{PaB}(b_N^{PaB})$ and thus $b_C^{PaB} < b_N^{PaB} - \tau + \mathbb{E}[Z]$.

If all bidders are risk-averse, the assumption of non-increasing Arrow–Pratt measures of absolute risk aversion, i.e., $-\frac{u''}{u'}$ is non-increasing, implies

$$-\frac{u'''u' - (u'')^2}{(u')^2} \le 0 \Rightarrow u''' > 0.$$

Hence, u' is convex. If τ is constant, $\frac{1-F^N_{(1,n-1)}(\theta^N)}{f^N_{(1,n-1)}} = \frac{1-F_{(1,n-1)}(\theta)}{f_{(1,n-1)}}$. Let b_C^{PaB} and $y_C^{PaB}(b_C^{PaB})$ satisfy condition (A.8). Suppose that $y_N^{PaB}(b_N^{PaB}) = y_C^{PaB}(b_C^{PaB})$ and $b_N^{PaB} + \mathbb{E}[Z] - \tau = b_C^{PaB}$, it follows that

$$\begin{aligned}
&u(w) - \int_{\underline{y}}^{y_N^{PaB}(b_N^{PaB})} \int_{\underline{z}}^{\bar{z}} u(w + b_N^{PaB} - \theta - \tau - y + z)h(z)dzg(y)dy \\
&- \int_{y_N^{PaB}(b_N^{PaB})}^{\bar{y}} u(w-s)g(y)dy \\
&+ \frac{1 - F^N_{(1,n-1)}(\theta^N)}{f^N_{(1,n-1)}(\theta^N)} \int_{\underline{y}}^{y_N^{PaB}(b_N^{PaB})} \int_{\underline{z}}^{\bar{z}} u'(w + b_N^{PaB} - \theta - \tau - y + z)h(z)dzg(y)dy \\
&= u(w) - \int_{\underline{y}}^{y_C^{PaB}(b_C^{PaB})} \int_{\underline{z}}^{\bar{z}} u(w + b_N^{PaB} - \theta - \tau - y + z)h(z)dzg(y)dy \\
&- \int_{y_C^{PaB}(b_C^{PaB})}^{\bar{y}} u(w-s)g(y)dy \\
&+ \frac{1 - F^N_{(1,n-1)}(\theta^N)}{f^N_{(1,n-1)}(\theta^N)} \int_{\underline{y}}^{y_C^{PaB}(b_C^{PaB})} \int_{\underline{z}}^{\bar{z}} u'(w + b_N^{PaB} - \theta - \tau - y + z)h(z)dzg(y)dy \\
&> u(w) - \int_{\underline{y}}^{y_C^{PaB}(b_C^{PaB})} u(w + b_N^{PaB} - \theta - \tau - y + \mathbb{E}[Z])g(y)dy \\
&- \int_{y_C^{PaB}(b_C^{PaB})}^{\bar{y}} u(w-s)g(y)dy \\
&+ \frac{1 - F_{(1,n-1)}(\theta)}{f_{(1,n-1)}(\theta)} \int_{\underline{y}}^{y_C^{PaB}(b_C^{PaB})} u'(w + b_N^{PaB} - \theta - \tau - y + \mathbb{E}[Z])g(y)dy \\
&= u(w) - \int_{\underline{y}}^{y_C^{PaB}(b_C^{PaB})} u(w + b_C^{PaB} - \theta - y)g(y)dy \\
&- \int_{y_C^{PaB}(b_C^{PaB})}^{\bar{y}} u(w-s)g(y)dy \\
&+ \frac{1 - F_{(1,n-1)}(\theta)}{f_{(1,n-1)}(\theta)} \int_{\underline{y}}^{y_C^{PaB}(b_C^{PaB})} u'(w + b_C^{PaB} - \theta - y)g(y)dy \\
&= 0.
\end{aligned} \tag{A.11}$$

This contradicts condition (A.9), and therefore, the assumption $y_N^{PaB}(b_N^{PaB}) = y_C^{PaB}(b_C^{PaB})$ and $b_N^{PaB} + \mathbb{E}[Z] - \tau = b_C^{PaB}$ cannot hold. To decrease the left-hand side of (A.9) so that the condition is satisfied,

b_N^{PaB} or $y_N^{PaB}(b_N^{PaB})$ must increase. According to (4), b_N^{PaB} and $y_N^{PaB}(b_N^{PaB})$ are positively correlated – an increase in one requires an increase in the other. Consequently, both must increase. It follows that $y_N^{PaB}(b_N^{PaB}) > y_C^{PaB}(b_C^{PaB})$ and $b_N^{PaB} + \mathbb{E}[Z] - \tau > b_C^{PaB}$.

If τ is non-constant, consider again the realization probabilities in the two scenarios from the auctioneer's point of view, represented by $y_C^{PaB}(b_C^{PaB})$ for the bidder with $\mathbb{E}[\Theta_{(1)}]$ in C and $y_N^{PaB}(b_N^{PaB})$ for the bidder with $\mathbb{E}[\Theta_{(1)}^N]$ in N. As shown above, $\frac{1-F_{(1,n-1)}(\mathbb{E}[\Theta_{(1)}])}{f_{(1,n-1)}(\mathbb{E}[\Theta_{(1)}])} \leq \frac{1-F^N_{(1,n-1)}(\mathbb{E}[\Theta^N_{(1)}])}{f^N_{(1,n-1)}(\mathbb{E}[\Theta^N_{(1)}])}$. This inequality further strengthens the difference between conditions (A.8) and (A.9) relative to the case of a constant τ as shown in (A.11). Analogously, supposing $y_N^{PaB}(b_N^{PaB}) = y_C^{PaB}(b_C^{PaB})$ and $b_N^{PaB} + \mathbb{E}[Z] - \theta^N_{(1)} = b_C^{PaB} - \theta^C_{(1)}$ yields a contradiction. Therefore, it holds that $y_N^{PaB}(b_N^{PaB}) > y_C^{PaB}(b_C^{PaB})$ and $b_N^{PaB} + \mathbb{E}[Z] - \theta^N_{(1)} > b_C^{PaB} - \theta^C_{(1)}$.

If all bidders are risk-seeking and τ is constant, the inequality in (A.11) is reversed. Therefore, $y_N^{PaB}(b_N^{PaB}) < y_C^{PaB}(b_C^{PaB})$. If τ is non-constant, since $\frac{1-F_{(1,n-1)}(\mathbb{E}[\Theta_{(1)}])}{f_{(1,n-1)}(\mathbb{E}[\Theta_{(1)}])} \leq \frac{1-F^N_{(1,n-1)}(\mathbb{E}[\Theta^N_{(1)}])}{f^N_{(1,n-1)}(\mathbb{E}[\Theta^N_{(1)}])}$, the comparison of realization probabilities becomes ambiguous. □

Proof of Proposition 4. In the basic model without maximum prices, i.e., $\bar{b}_C = \bar{b}_N = \infty$, it holds for all bidders that $b_C^* < \bar{b}_C$ and $b_N^* < \bar{b}_N$, implying $EU_C(b_C^*) > u(w)$ and $EU_N(b_N^*) > u(w)$. As a result, regardless of risk preference or private cost, all bidders have an incentive to participate in both the CfD and the payment auction.

In contrast, under Mechanism $\mathcal{M}$ with $\bar{b}_C < \infty$ and $\bar{b}_N = 0$, it is possible that $b_C^* \geq \bar{b}_C$ and/or $b_N^* \geq \bar{b}_N$. In either auction, if a bidder's indifference bid equals the maximum bid, the winning probability becomes zero and the expected utility equals the utility of the initial wealth: $EU_C(b_C^*) = u(w)$ if $b_C^* = \bar{b}_C$, and $EU_N(b_N^*) = u(w)$ if $b_N^* = \bar{b}_N$. In such cases, the bidder is indifferent between participating and not participating. If the indifference bid exceeds the upper bound, e.g., $b_C^* > \bar{b}_C$ in the CfD auction, then submitting any allowed bid ($b_C \leq \bar{b}_C < b_C^*$) would result in a price below the bidder's indifference bid in the case of winning, leading to an expected utility strictly below $u(w)$. Hence, the bidder has no incentive to participate in the CfD auction. The same reasoning applies for $b_N^* > \bar{b}_N$.

We now consider the following four cases based on the relationship between the bidder's indifference bids and the maximum bids:

Case $b_C^* \leq \bar{b}_C$ and $b_N^* > \bar{b}_N$: The bidder has an incentive to participate only in the CfD auction C. Therefore, the bidder only submits $b_C = b_C^*$, which ensures participation if and only if the CfD auction takes place and abstains from participating in the payment auction. This corresponds to option 1, expressing the acceptance of only the CfD auction.

Case $b_C^* \leq \bar{b}_C$ and $b_N^* \leq \bar{b}_N$: The bidder has an incentive to participate in both auctions and the preference depends on the comparison between the expected utilities. If $EU_C(b_C^*) > EU_N(b_N^*)$, the bidder prefers the CfD auction and thus submits $b_C = b_C^*$ and $b_N = b_N^*$. The submission of both CfD and payment bids ensures participation in either auction but favors the CfD auction, which will be implemented unless another bidder submits only b_N^*. This corresponds to option 2, expressing the acceptance of both auctions but a preference for the CfD auction. If $EU_C(b_C^*) \leq EU_N(b_N^*)$, the bidder prefers the payment auction and submits only $b_N = b_N^*$, ensuring that the preferred payment auction takes place. This corresponds to option 3, which initiates the payment auction.

Case $b_C^* > \bar{b}_C$ and $b_N^* \leq \bar{b}_N$: The bidder has an incentive to participate only in the payment auction. Therefore, the bidder only submits $b_N = b_N^*$, which initiates the payment auction. This corresponds to option 3.

Case $b_C^* > \bar{b}_C$ and $b_N^* > \bar{b}_N$: The bidder has no incentive to participate in either auction and thus submits no bid. This corresponds to option 4.

In sum, if a bidder accepts only one of both auctions (a CfD under the maximum price or the market solution), it submits the indifferent bid only for that auction; if the bidder accepts both auctions and prefers the CfD auction, it submits both the CfD and the payment indifference bids to ensure participation in either auction while signaling a preference for the CfD auction; if the bidder accepts both auctions and prefers the payment auction, it submits only the payment indifference bid to initiate the payment auction; if the bidder accepts neither auction, it submits no bid. No bidder has an incentive to deviate from this strategy. Therefore, mechanism $\mathcal{M}$ is incentive-compatible. □

Proof (*Proof and generalization of Lemma 5*)**.** According to Proposition 2, regardless of risk preference, a bidder with τ_ℓ prefers the payment auction, while a bidder with τ_h prefers the CfD auction, provided the bidder is willing to participate in both auctions. With finite maximum prices $\bar{b}_C$ and $\bar{b}_N$, however, both auctions may exclude bidders – though possibly a different number in each. If only one bidder participates in an auction, the awarded price will be the respective maximum price; in the other auction, the awarded price may either be the respective maximum price or be set by another bidder. As a result, the expected utilities of the bidders across the two auction formats are not clearly comparable in general.

Nevertheless, we assume that the impact of the maximum prices on bidders' expected utilities does not systematically differ between the CfD auction and the payment auction in expectation and therefore does not alter the preferences stated in Proposition 2. This assumption is particularly plausible when either $\Delta\tau$ or n is large. If $\Delta\tau$ is sufficiently large, the advantage of bidders with τ_ℓ over bidders with τ_h in the payment auction becomes so substantial that, regardless of maximum prices, bidders with τ_ℓ will always prefer the payment auction, while bidders with τ_h will always prefer the CfD auction. If n is sufficiently large, the probability that only one bidder participates in either auction converges to zero. In this case, the probability that the awarded price in either auction is set by the respective maximum price also converges to zero, so that the impact of the maximum prices is negligible.

Therefore, we proceed under the assumption that the preferences stated in Proposition 2 hold regardless of the presence of maximum prices. Consequently, a bidder with τ_ℓ will never prefer the CfD auction if $b_N^* \leq \bar{b}_N$ and a bidder with τ_h will never prefer the payment auction if $b_C^* \leq \bar{b}_C$.

Building on Proposition 4, we now restrict attention to the parameter range $\hat{\theta}_C > \hat{\theta}_{N,\ell}$. Under this condition, the "second part" of Case 3 – namely $b_C^* > \bar{b}_C$ and $b_N^* \leq \bar{b}_N$ – is algebraically ruled out. Consequently, bidders with τ_h, who prefer the CfD auction as long as $b_C^* \leq \bar{b}_C$, will never submit only a payment bid, and the payment auction can only be initiated by a bidder with τ_ℓ and $b_N^* \leq \bar{b}_N$.

Without assuming $\hat{\theta}_C > \hat{\theta}_{N,\ell}$, the case $b_C^* > \bar{b}_C$ and $b_N^* \leq \bar{b}_N$ can occur, for example, if the bidder can accept the market solution but not the CfD because the CfD maximum price is set too low. Thus, a bidder with τ_h can also initiate the payment auction if and only if $b_C^* > \bar{b}_C$ and $b_N^* \leq \bar{b}_N$. The three possible outcomes of $\mathcal{M}$ and their probabilities are adapted as follows:

(i) If (a) there is at least one bidder with τ_ℓ and $b_N^* \leq \bar{b}_N$, or (b) there is at least one bidder with τ_h and $b_C^* > \bar{b}_C$ and $b_N^* \leq \bar{b}_N$, the payment auction will take place.
The probability of (a) is $\sum_{m=0}^{n-1}\binom{n}{m}\lambda^m(1-\lambda)^{n-m}(1-(1-F(\hat{\theta}_{N,\ell}))^{n-m}) = 1-[\lambda+(1-\lambda)(1-F(\hat{\theta}_{N,\ell}))]^n$.
The probability of (b) is $\sum_{m=1}^{n}\binom{n}{m}\lambda^m(1-\lambda)^{n-m}\left[1-\min\{(1-F(\hat{\theta}_{N,h})+F(\hat{\theta}_C))^m,1\}\right] = 1-\left[\lambda\cdot\min\{1-F(\hat{\theta}_{N,h})+F(\hat{\theta}_C),1\}+(1-\lambda)\right]^n$.
The probability of (a) $\wedge$ (b) is $\sum_{m=1}^{n-1}\binom{n}{m}\lambda^m(1-\lambda)^{n-m}\left[1-\min\{(1-F(\hat{\theta}_{N,h})+F(\hat{\theta}_C))^m,1\}\right]\cdot\left[1-(1-F(\hat{\theta}_{N,\ell}))^{n-m}\right] = 1-\left[\lambda\cdot\min\{1-F(\hat{\theta}_{N,h})+F(\hat{\theta}_C),1\}+(1-\lambda)\right]^n-[\lambda+(1-\lambda)(1-F(\hat{\theta}_{N,\ell}))]^n+\left[\lambda\cdot\min\{1-F(\hat{\theta}_{N,h})+F(\hat{\theta}_C),1\}+(1-\lambda)(1-F(\hat{\theta}_{N,\ell}))\right]^n$
The probability of (a) $\vee$ (b), i.e., the probability that the payment auction takes place, is $1-\left[\lambda\cdot\min\{1-F(\hat{\theta}_{N,h})+F(\hat{\theta}_C),1\}+(1-\lambda)(1-F(\hat{\theta}_{N,\ell}))\right]^n$.

(ii) If all bidders have $b_C^* > \bar{b}_C$ and $b_N^* > \bar{b}_N$, there will be no participant. The probability of this case is $\left[\lambda(1 - F(\max\{\hat{\theta}_C, \hat{\theta}_{N,h}\})) + (1-\lambda)(1 - F(\max\{\hat{\theta}_C, \hat{\theta}_{N,\ell}\}))\right]^n$.

(iii) In all other cases, the CfD auction will take place. The probability is $\left[\lambda \cdot \min\{1 - F(\hat{\theta}_{N,h}) + F(\hat{\theta}_C), 1\} + (1-\lambda)(1 - F(\hat{\theta}_{N,\ell}))\right]^n - \left[\lambda(1 - F(\max\{\hat{\theta}_C, \hat{\theta}_{N,h}\})) + (1-\lambda)(1 - F(\max\{\hat{\theta}_C, \hat{\theta}_{N,\ell}\}))\right]^n$. □

Proof of Proposition 5. We consider the three cases from Lemma 5:

(i) If $\mathcal{M}$ results in the payment auction (N auction), we distinguish three subcases:

(a) If at least one bidder with τ_h satisfies $b_N^* \leq \bar{b}_N$, the auction in N includes a mix of bidders with τ_ℓ and τ_h, while the CfD auction (C auction) may include additional bidders with $b_N^* > \bar{b}_N$ and $b_C^* \leq \bar{b}_C$. These bidders are weaker than those who participate in both the N auction and the C auction and can thus neither win nor set the price in the C auction. Therefore, their existence has no effect on the auction outcome. Consider only the bidders who participate in both auctions, according to Proposition 1, the dispersion in τ improves the realization probability in N compared to C. Hence, mechanism $\mathcal{M}$ selects the auction with the higher realization probability.

(b) If no bidder with τ_h satisfies $b_N^* \leq \bar{b}_N$, then only bidders with τ_ℓ (i.e., whose private cost signals satisfy $\theta \leq \hat{\theta}_{N,\ell} < \hat{\theta}_C$) participate in the N auction, while the C auction may also include additional bidders with τ_h with $b_C^* \leq \bar{b}_C$ (i.e., whose private cost signals satisfy $\hat{\theta}_{N,h} < \theta \leq \hat{\theta}_C$). Thus, the competition is more intense in C, but the additional bidders are expected to be weaker than those bidders in N. First, consider the case in which at least two bidders with τ_ℓ participate in the N auction. If bidders are risk-neutral, the realization probability is identical in C and N; if bidders are risk-averse, the realization probability is higher in N. In addition, the increased competition in C due to additional bidders with τ_h reduces the expected difference in indifference bids between the winner and the price setter, thereby lowering the realization probability in C. Therefore, $\mathcal{M}$ selects the auction with the higher realization probability. Second, if only one bidder participates in the N auction, the awarded price is $\bar{b}_N$. In contrast, the C auction may include additional bidders with τ_h, so that the awarded price is determined by a bid. However, as stated in Section 7, for a bidder with τ_ℓ who wins in both C and N, the maximum prices do not affect the realization probability in N being larger than in C if $\Delta\tau$ or n are sufficiently large. Together with the arguments in the first case, it follows that, from the auctioneer's perspective, the realization probability in N is larger than in C. Therefore, $\mathcal{M}$ selects the auction with the higher realization probability.

(ii) In this case, no bidder participates in either auction. As a result, the choice of $\mathcal{M}$ is irrelevant.

(iii) If the conditions in cases (i) or (ii) from Lemma 5 are not met, $\mathcal{M}$ results in the CfD auction, we distinguish two subcases:

(a) If at least one bidder with τ_h satisfies $b_N^* \leq \bar{b}_N$, all participants in the payment auction would have τ_h (i.e., whose private cost signals satisfy $\theta \leq \hat{\theta}_{N,h} < \hat{\theta}_{N,\ell}$). The CfD auction may include additional bidders with τ_ℓ (i.e., whose private cost signals satisfy $\hat{\theta}_{N,\ell} < \theta \leq \hat{\theta}_C$), who are weaker than those with τ_h and thus cannot win. However, one of these bidders with τ_ℓ may become price setter in the CfD auction if exactly one bidder with τ_h satisfies $b_N^* \leq \bar{b}_N$. Consider first only bidders with τ_h and assume that there are at least two such bidders. If bidders are risk-neutral, then the realization probability is identical in C and N; if bidders are risk-averse, the realization probability is higher in N. In addition, bidders with τ_ℓ may lower the awarded price in C and thus reduce the realization probability. Therefore, $\mathcal{M}$ selects the auction with the lower realization probability. The probability of subcase (iii)(a) is $\sum_{k=0}^{n}\binom{n}{k}\lambda^k(1-\lambda)^{n-k}[1-(1-F(\hat{\theta}_{N,h}))^k](1-F(\hat{\theta}_{N,\ell}))^{n-k} = [\lambda+(1-\lambda)(1-F(\hat{\theta}_{N,\ell}))]^n - [\lambda(1-F(\hat{\theta}_{N,h}))+(1-\lambda)(1-F(\hat{\theta}_{N,\ell}))]^n$. Similar to the subcase (i)(b), if only one bidder with τ_ℓ participates in the payment auction, we assume that the impact of the maximum prices on realization probabilities does not systematically differ between C and N in expectation and therefore does not alter the results above.

(b) If no bidder with τ_h satisfies $b_N^* \leq \bar{b}_N$, then no bidder participates in the payment auction. Therefore, by selecting C, $\mathcal{M}$ ensures participation and thus also a higher realization probability.

In summary, except for subcase (iii)(a), mechanism $\mathcal{M}$ selects the auction with the higher realization probability. Subcase (iii)(a) arises when no bidder with τ_ℓ satisfies $b_N^* \leq \bar{b}_N$ but at least one bidder with τ_h does. □

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