Reverse Auctions to Procure Negative Emissions at Industrial Scale

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Abstract

Many climate solutions including carbon dioxide removal (CDR) technologies require investments in capital intensive technologies that require large capacity investments and exhibit modest unit costs. Governments seeking to achieve net zero goals may invest directly in CDR to procure negative emissions credits to offset emissions in hard-to-abate sectors such as agriculture. In a procurement auction for a declining cost industry, the optimal allocation will generally require all winning bidders operating at full capacity, but this may not fit within the government's budget, leaving one or more winning bidders at the margin, operating at less than full capacity, and with higher average costs. Protection can be provided to the marginal bidder by letting bids specify a range of acceptable quantities up to full capacity. The auction can be executed with sealed bids (with minimum quantities) or by having the proposed bid price be lowered sequentially in a "clock auction" with quantity intervals specified by bidders at the current clock price. We consider the performance of sealed bid and clock auctions, in the presence of 1) a fixed government procurement budget, 2) "common value" uncertainty about the true per-unit production cost, and 3) the presence of a large fixed cost. Laboratory experiment simulations with financially motivated human subjects are valuable for testing and developing auction designs that have never been used before, without relying on theoretical properties that depend on implausible assumptions of perfect cost information and "truthful bidding." Preliminary experiment results indicate that winner's curse effects (bidder losses) are infrequent in both auction formats (clock and sealed bid), but the clock tends to restrict bidder profits in a manner that reduces the average cost for the buyer of the "units" representing CDR. Our experiments are informed by the projected use of auctions by the government of Sweden to procure carbon capture and sequestration from its domestic wood products industry.

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Introduction

Pledges to achieve climate goals by jurisdictions and corporations describe a net zero outcome where greenhouse gas emissions fall substantially but typically remain at 10-15 percent of 2005 levels by 2050. Many of the residual emissions will be associated with the industrial sector, where process changes and other technologies that can reduce emissions are unable to practically achieve absolute zero emissions (Lamb et al., 2021; Rissman et al., 2020). To halt greenhouse gas accumulation, these remaining emissions must be balanced by carbon dioxide removal (CDR) achieved through managed natural processes (e.g., forests, enhanced rock weathering, ocean uptake), or mechanical means (e.g., carbon capture coupled with utilization or geologic sequestration).[1] Global modeling exercises suggest substantial gains from implementing a variety of approaches (Fuhrman et al., 2020, 2023). Nations and other actors wishing to meet climate pledges are looking to industrial scale projects using direct air capture (DAC) and carbon capture and storage at bioenergy facilities (bioenergy with carbon capture and storage, or BECCS) to achieve negative emissions. For bioenergy, if the life cycle emissions of biofuels are small, then the capture and storage of carbon that is released during their combustion results in net-negative emissions while providing useful energy at an industrial scale.

This paper will use laboratory simulations to generate insights about effective auction procedures for procurement of carbon reduction credits. In the early stages of the development of the new CDR industry, government efforts to procure CDR will have a dual goal of inducing early investments in a risky new technology but also purchasing actual CO2 sequestration at the lowest feasible subsidy price, which helps the government meet its international obligations for emission reductions. But the procurement agency is not able to observe *ex ante* the cost function of the competing firms and, in particular, the risk of non-performance should a firm's costs be higher than anticipated. Given the risky nature of investment in novel production technologies, low per unit subsidies may be associated with higher risk that winning bidders in an auction will

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[1] Carbon dioxide removal is often referred to as "negative emissions." We will use these terms interchangeably.

face losses and decide ex post to accept penalties for non-performance. For this reason, a procurement strategy needs to balance the short-run, per-unit cost of sequestration against the likelihood of default should costs be too high to support production at the winning procurement price.

The ability to achieve internationally agreed climate targets will depend critically on early investments in this new industrial infrastructure so that CDR can contribute meaningfully to mid-century decarbonization goals (Nemet et al., 2023). While the individual elements of the industrial-scale production of net-negative emissions are proven technologies, their coordination and application at a commercial scale remains a monumental task with substantial investment risk regarding cost and performance (Lackner & Azarabadi, 2021). Achieving sufficiently rapid scaling of these new, risky technologies will require government incentive payments including investment and production subsidies and risk sharing in some form.

At least in the near term, the technologies for capturing and sequestering carbon are likely to be highly capital intensive and hence to exhibit increasing returns (concave costs) in concentrated, capital-intensive industries. In industries with concave costs, aggregate production costs are minimized with a few large firms operating at high capacity levels and with product prices above marginal cost to remain profitable (Arthur, 1994). The large, risky investments required give first-movers a leg up in capturing supply chains and realizing network economies in system operations, contracting, and access to markets. Technological learning, which is essential for the success of the CDR industry, may, at least in the short run, offer an additional advantage that amplifies with scale, creating barriers to entry that enable oligopolistic behavior and operational inefficiency. The prospect of extra-normal profits in the product market creates incentives for anti-competitive behavior that may propagate back and motivate collusion in an auction for BECCS subsidies. Over time, as the technology matures, entry costs can be expected to fall.

A useful example is the initiative by the Swedish Energy Agency to provide approximately 3.2 billion euro to support the development of BECCS in the domestic energy and wood products industries for the years 2026-2046. This support will be allocated through a reverse auction that seeks to maximize the emissions sequestered given the fixed procurement budget. Because the carbon capture technology in this case will be retrofitted onto the existing industrial facilities, it will have a fixed maximum capacity. Due to the large fixed costs (Beiron et al., 2022; Kearns & Consoli, 2021), for any price per ton of sequestered carbon, the bidding firms will need to sell enough to cover average costs. The minimum profitable quantity will rise at low auction prices, but the maximum capacity will likely not change. The procuring agency will wish to cover average costs to avoid default but by the lowest margin that would induce firms to participate.

As in the case of Sweden's energy and wood products industries, it will often be the case that, in the early-stage procurement of sequestration services, a small number of large firms will be well-positioned to bid for payments to capture emissions. This means that any procurement procedure will need to be resistant to collusive behavior by participating firms.

This research has broad relevance to industrial decarbonization. It is likely that many opportunities for carbon capture in industrial processes such as cement or petrochemicals will share the key characteristics of increasing returns and small numbers of participating producers. Developing reliable mechanisms for inducing emission reductions will become increasingly important in these otherwise recalcitrant sectors.

The importance of the institutional context

Important to the overall policy design is the government's motivation for support of CDR. In Sweden the state is motivated to procure CDR to comply with its national climate goals and international commitments by offsetting emissions in hard-to-abate sectors like agriculture.[2] Sweden is also motivated to develop a skill base and technological capability that could support investments by domestic enterprise and "promote the uptake of the technology, making Sweden a leading nation in the field of bio-CCS" (SEA, 2021). In general, countries have an interest in promoting economic development within their borders where BECCS activities may be concentrated. Within an EU context, doing so requires compliance with the European Commissions' guidelines on state aid which are generally restrictive in order to promote competitive markets, but which allows for aid to promote the long-term objectives of a low-emission economy.[3] These motivations align with a primary goal of achieving as many in-country emissions reductions as possible for a given level of state support. However, whether

[2] Offsetting refers to the use of credits resulting from emissions reductions or removals outside an actors' value chain to count against the carbon footprint of the actor's activity or use of its product.
[3] Guidelines on State aid for environmental protection and energy for 2014 - [2020] (2014/C 200/01), OJ C 200, 28.6.2014, Section 3.6, as cited in SEA (2021, p. 52).

these motivations are best addressed solely through the direct procurement of CDR credits by the government or by using state support to leverage private investments in CDR depends critically on the accounting and ownership of CDR credits.

The accounting for CDR credits is the subject of negotiations around Article 6 of the Paris Agreement, which allows for voluntary cooperation between nations to achieve national mitigation targets. The rules of Article 6 are relevant, for example, to a situation in which Country A provides financing towards BECCS in Sweden and Country A wants to claim the associated CDR toward its national target (Möllersten and Zetterberg 2023). To avoid double counting, Article 6 requires that "corresponding adjustments" be made between national accounts so that credit accruing to Country A would be deducted from Sweden's emission balance.

Voluntary transactions in CDR credits are expanding to record levels not due to demand from nations, but due to demand from non-state actors (primarily international corporations) seeking to satisfy climate commitments. If a non-state CDR owner that developed or purchased CDR has operations in the host country of the CDR activity, it might use its CDR credits to offset emissions and meet its national compliance obligations in that country; but to avoid double counting, those credits could not be used to offset other emissions from agriculture or other sources. Similarly, if the CDR owner used the credits to offset emissions in other countries to meet its global commitments, then a corresponding adjustment would be made, and those credits could not be used in the host country.[4]

Hence, an important influence on bidder behavior in a CDR auction will be the determination of ownership rights for the carbon sequestration credits that are produced. If the host nation were motivated only by achieving emissions outcomes consistent with its Paris commitments and not by other economic development goals, then the existence of a private market for CDR credits should place a ceiling on the subsidy that the procuring agency needs to pay for credits because, subject to ongoing international negotiations, the procuring agency could simply purchase credits rather than invest in CDR. Generally, if the investing firm retains ownership and can sell the credits it produces at the market price, then the subsidy necessary to

[4] Remaining at issue in negotiations under the Paris agreement and within the EU, and subject to varying rules in programs internationally, is whether and how the CDR owner could use the credits to comply with obligations including emissions caps or taxes in other countries.

initiate an investment is the difference between the current expected market price and cost of CDR. If the private market price were sufficiently high to compensate for investment risks, a private firm would be motivated to invest in CDR without subsidy and retain ownership of the CDR credits; although, with a corresponding adjustment protocol in place, the host nation could not then claim CDR credits towards its national accounts.

In a declining cost industry, the state might best achieve its goals by agreeing to guarantee a minimum level of purchases implemented through an auction, guaranteeing the purchase of a quantity sufficient to reduce investment risk but leaving producers the option to sell additional units of CDR in the private market. The procurement price required in this case might be less than the conditional average cost at the procurement level of production. In Figure 1, with declining average costs and economies of scale, assuming a competitive procurement process, a minimum purchase agreement might only require a subsidy equal to long-run average costs for a quantity less than long-run capacity. Other reasons the state might offer a minimum procurement agreement (rather than procurement of all capacity at a facility) could be to spread its subsidies across multiple facilities to drive innovation, develop technological capability, and to reduce the potential market power that can be expected in the emerging capital-intensive, declining cost industry.

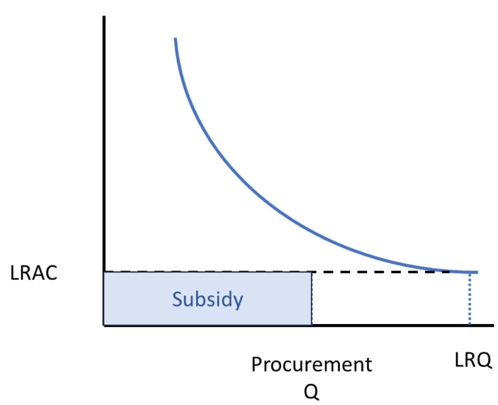

Figure 1: Minimum procurement commitment for a quantity less than long run quantity that yields minimum average cost.

Designing a practical procurement auction for CDR

The objective of this research is to use laboratory experiments to develop effective auction procedures for use in procuring carbon capture services from private companies. To focus on auction design, we exclude consideration of private investment and shared ownership of CDR credits with private investors through a minimum procurement agreement, and assume the government seeks to acquire all CDR credits at the subsidized facility.

Laboratory experiments have been used extensively to design and adjust auctions for environmental goods, especially for procedures that have not been used previously (Cummings et al., 2004; Holt & Shobe, 2016; Holt et al., 2007).

In the present context, a government agency with a fixed budget for the purchase of CDR credits seeks to procure credits from a small group of incumbent domestic firms, each with a capacity constraint on the CDR production based on prior investment decisions in the production of bio fuels (wood pellets). Sellers would have to make major investments after winning contracts.[5]

Concave costs present a key difficulty in procuring CDR. Because of declining average costs, the procuring agency would minimize costs by having any producing firms operating at full capacity. But with a limited budget and only a few relatively large suppliers, having one firm drop out of a procurement auction may leave a significant portion of the procurement agency's budget unspent. In this case of a small number of incumbent firms, there may not be an opportunity for holding subsequent auctions for the residual budget. The agency, then, will have as a secondary goal, using most of its procurement budget in the single auction, since not spending its budget may leave the agency far short of its procurement goal. To accomplish this, the agency may wish to pay a marginal firm to operate at something less than full capacity, even though this firm's average costs will be higher than those of the firms operating at full capacity. A similar case was analyzed in (Baranov et al., 2017).

Default by a winning bidder is costly to the agency. The agency does not know the probability of default by bidders but needs to choose an auction design that does not encourage overly aggressive bidding, which would increase the probability of default by a winning bidder. Overly aggressive bidding is a common feature in auctions where there is uncertainty over factors that are common to the profitability of all bidders. The common value uncertainty is known to lead to the "winner's curse" where the participants with the lowest bids are likely to

[5] It is not essential that the buyer be a government agency. Private firms may have incentive to procure CDR services and may choose to use an auction to purchase them.

lose money, which, in this case, also increases the potential of a costly default in contract performance.

Auction outcomes can be highly sensitive to contextual details (Fabra et al., 2006; Kremer & Nyborg, 2004). Several attributes of this procurement context make a theoretical prediction of effective auction designs particularly difficult:

- Concave costs
- Small numbers of potential bidders
- Correlated common-value risks
- Fixed (capped) budget but variable quantity to purchase
- High cost to agency of performance default

Commonly used procurement auction designs are not likely to work well in this context. We use simulated laboratory auctions with financially motivated human subjects to develop and stress test auction designs that can be used by government agencies to procure sequestration of CO2 or for other environmental services. The auction design, while informed by the needs of the Swedish government CDR procurement program, has much wider application in the procurement of risky investment in industries with concave costs. We examine various bid structures in static and dynamic auction formats, comparing discriminatory and uniform settlement designs along with information treatments that may affect the possibility for collusion. We also test a set of modifications suggested by the Baranov et al. (2017) design along with elements that reduce the likelihood of collusion among the small number of participating bidders.

Some relevant auction design literature

In this paper, we concern ourselves with the problem of procuring multiple, divisible goods in an auction process from a relatively small number of bidders with concave costs and individual capacity constraints. Bidder benefits of winning have a positively correlated uncertainty. The buyer has a fixed budget for the auction procurement, so the quantity procured will depend on the auction outcome. For our purposes, the fixed budget has a use it or lose it character; that is, there is only one auction. No further auctions can be held to spend any balances. We do not directly address the question of default by successful bidders in our current experiments, but we tally outcomes with zero and negative profits as a proxy for possible default and consider this a fruitful area of future research.

Auction formats for procurement

The choice among auction formats for buying and selling multiple, identical units of a good is idiosyncratic, depending on many specific features of the buyers, sellers and markets in which they are embedded (Burtraw et al., 2009). The format most frequently observed in both public and private procurement contracts is the sealed-bid, discriminatory (first) price auction. Sealed-bid, second price auctions or dynamic auctions (descending price) auctions are rarely used in public procurement. In the small number of bidders case, there is reason to expect that, for risk averse bidders, discriminatory price auctions can produce lower prices in the procurement auction (Holt, 1980). The lower prices might be due to the effects of increased uncertainty over rival bids or increased entry in the auction by smaller competitors (i.e., bidders with less production capacity). But this conclusion is not robust. The seller's choice between discriminatory and uniform price auctions depends on many specific characteristics of the goods being procured and the participants in the market.

Multiple lines of evidence suggest that first-price sealed bid auctions may, under many circumstances, lower procurement costs relative to second bid auctions and that this may explain why sealed bid tenders are so common in public and private procurement. While second price sealed bid auctions have the attractive property of encouraging truthful bidding in ideal circumstances, experimental studies suggest that first-price auctions encourage more aggressive bidding, with the effect of lowering procurement costs for buyers (Aloysius et al., 2016; Katok, 2013). Decarolis (2014, 2018) empirically evaluated first price versus average price auction formats, showing that first price procurement auctions result in lower prices but may induce a "perverse" tradeoff between low prices at auction and poor ex post performance because overly aggressive bidding my cause an increase in costly performance default. First price auctions can result in better outcomes but only if accompanied by effective methods to reduce default risk by winning bidders. This explains why many private procurement processes use an auction as a price-setting first stage followed by a "bid quality" evaluation stage after the low-price bidders are determined (Katok, 2013). For procurement auctions where contract performance can be well-specified *ex ante*, first price auctions, often with pre-specified payment to the procurer for default can be optimal. This format is widely observed in public procurement contracting (Birulin, 2020).

Sealed bid versus open (dynamic) auction formats

Dynamic auctions are not used with any frequency in the procurement setting, where sealed bid auctions dominate (Birulin, 2020). In the multiple unit procurement of identical goods, theory suggests that there may be strong incentives for bidders in uniform price auctions to shade their marginal bids in order to lower the price paid for all units (Wilson, 1979). Numerous authors have made a strong case for the empirical relevance of the demand reduction incentive (L M Ausubel et al., 2014). As in the case of other auction design elements, the importance of this theoretical observation in practice depends on many details of the procurement auction context.

Athey and Levin (2001) compare bidding patterns in sealed bid and open auctions with heterogeneous bidders for the case of U.S. Forest Service timber sales. They find that sealed-bid auctions attract more small bidders, award more sales to smaller bidders, and can also generate higher revenues. In open auctions, strong bidders may shade their bids to effectively shut-out weaker bidders. Haruvy and Katok (2013) find experimental evidence that the sealed bid format generates higher buyer surplus than does the open-bid dynamic format even without endogenous participation. In electricity procurement, the effects on both prices and efficiency are sensitive to specifics of the market including the elasticity of demand and the symmetry of bidders (Fabra et al., 2006). The tendency for bid shading (raising procurement prices) is attenuated by the level of competition, by introducing uncertainty in the quantity sold (LiCalzi & Pavan, 2005; McAdams, 2007), and by changing details of the lot size or bid price intervals (Kremer & Nyborg, 2004).

Ausubel and Cramton (2006) suggest that one persuasive argument for open auction formats is when bidder costs are uncertain and positively correlated. In this circumstance, bidders will tend to observe other bidders' withdrawals and bid less aggressively to avoid the winner's curse. A sequential auction structure allows bidders to have better information about the item's actual cost and can induce more aggressive bidding.[6]

Procurement when suppliers have concave costs and capacity constraints

The case we analyze in this paper is one where there are likely only a few qualified bidders, and each potential bidder has to make a large (uncertain) investment in order to produce, at

[6] Holt and Sprott (2022) investigate the effects of the winner's curse in the context of U.S. offshore wind auctions.

relatively low marginal cost, the good desired by the procurement agency. Each bidder has a known capacity limit, since the investment involves retrofits on existing capital stock. A similar situation has been analyzed in some detail in Baranov et al. (2017) where a procurement agency needs to buy a fixed quantity of vaccines from a small set of existing, qualified pharmaceutical firms. The production of the vaccines by each firm is subject to concave costs due to the large investment and relatively low marginal cost of vaccine production, and each firm has a limited capacity.

To minimize costs, the agency will generally want the firms operating at capacity, but this may leave a marginal firm operating at less than capacity. To be competitive, each firm would bid the price assuming that it is operating at full capacity. But to choose a marginal firm that will operate at less than full capacity, the auctioneer needs to know what firms would need to be paid to operate at less than capacity, which would be higher than the full capacity price. This information would not normally be available to the auctioneer who takes a single price bid from each bidder. To reveal information about firm willingness to supply goods at less than full capacity, the authors propose a descending clock auction where bidders are asked to specify a range of production that they would be willing to provide at each price. To recover fixed costs, the minimum profitable quantity will rise as the announced clock price falls.

Since our case is also one of declining average costs with capacity constraints, we use the insights of Baranov et al. and apply them to the case of procurement of CDR where it is the budget that is fixed rather than the quantity purchased. They advocate using a declining price (reverse) "clock" auction in which bidders can stipulate a minimum acceptable sale quantity associated with each full-capacity bid at the going clock price. They derive attractive theoretical properties of the proposed procedure, under which bidders will "truthfully" reveal the range of sale quantities that would provide positive profits at the current clock price. But our case differs from theirs due to incomplete information about both production costs and the number of units that will be sold. In contrast, we focus on a "common-value" auctions in which each bidder receives a noisy signal about the underlying cost. The presence of cost uncertainty raises the specter of a winner's curse, in which the low bidder is likely to have underestimated the cost and may lose money if their low bid is accepted.

Our case differs from that paper in another key respect. There will be a very limited number of potential suppliers and only one auction is likely to be held to spend the available budget. This implies that the agency has two criteria for success, maximizing the tons of sequestration purchased while not leaving a large share of the budget unspent.

Procedures

In our experimental test, we retained a version of the minimum quantity bid provision suggested by Baranov et al. and adapted it for both the declining clock and a sealed bid auction format. In the clock auction, the seller's minimum sale quantity can be raised by the bidder as the clock price falls, to ensure coverage of fixed costs at a lower sale price. Because, in prior work, we have found clock auctions to be susceptible to collusion (Burtraw et al., 2009), we also considered "discriminatory" price (pay as bid) auctions with a single round of sealed bids with the added option for the bidder to specify a minimum price for operating at a level less than full capacity.

We focus on a "common-value" cost structure under which realized costs are common across producers, but ex ante each bidder receives a noisy signal about the underlying cost drawn from a commonly observed distribution of potential costs. We directly compare the performance of the clock auction with a single round "discriminatory" price (pay as bid) sealed bid auction across several metrics. The presence of cost uncertainty raises the specter of a winner's curse, in which the low bidder is likely to have underestimated the cost and may lose money if their low bid is accepted. Where winners don't observe actual costs until after the auction, the winner's curse can lead to non-performance (default) by a winning bidder wherein a license to proceed with the investment is not exercised, and no production occurs. Negative earnings by experiment participants serve as a signal for potential performance failure.

For each auction design (multi-round clock and single-round sealed bid), we develop a mechanism for a minimum quantity bid provision as suggested by Baranov, et al. In doing so, we identified implementation issues in pilot experiments that required procedural adjustments to improve performance. In the clock auction, a minimum sale quantity is a component of the auction bid and can be raised by the bidder as the clock price falls to ensure coverage of fixed costs at a lower sale price. Recall that the clock auction price is lowered from round to round until the total sales offers from bidders fall below the government purchase budget, caused by bidders withdrawing from the auction when the price was considered to be too low. One tendency that showed up in tests of the declining clock auction was that the simultaneous withdrawal of multiple bidders in the same round would leave a large fraction of the purchase budget unused, resulting in a low sales quantity for the auction (analogous to low purchases of liquified carbon CDR credits).

Such low sales would be undesirable from the perspective of a government agency, which is seeking to purchase and dispose of captured carbon, so we implemented a "lookback" feature that seeks to retrieve the prior period's bid of bidders who dropped out of the bidding in the final round. After the purchase budget is used to purchase units from the bidders who did not drop out, the prior round bids of those who did drop out are considered to see if one or more of those prior bids could be accepted (at the previous round's higher clock price, subject to the minimum quantity specified by the bidder in that prior round). This lookback procedure resulted in high sales quantities overall, and a high proportion of the auction budget being used.

By analogy, in the discriminatory sealed bid auction, the bidder submits a price bid for a quantity associated with its full potential capacity and a second bid associated with half capacity, effectively submitting a two-part, quantity-price bid schedule in the auction. The secondary bid price is to be used in the event that the bidder was not able to sell their full capacity. The two-part bid in the discriminatory price sealed-bid procedure represents a parallel modification to the clock auction with a look back by protecting the bidder who, at the margin, does not sell their full capacity. Such secondary bids could be higher than the primary bid in order to help cover the fixed cost in the event of less than full capacity sales.

Informal discussions with Swedish officials have revealed a concern with possible collusion in auctions, especially if the numbers of active bidders turn out to be low. Since our prior work on emissions permit auctions indicated that, with small numbers of bidders, laboratory clock auctions had relatively high levels of collusion, we are working on another modification of the clock auction that would let bidders submit price bids in a specified "price band" at or below the current clock price. As the clock price declines, the band would shift down from round to round. An initial test session with graduate students using pencil and paper bid sheets suggested that this type of "band bidding" would make collusion more difficult. The idea is to make it harder to guess what it takes to "undercut" the others and by reducing the salience of all-or-nothing withdrawals.

In summary, we evaluate auction results according to the following performance metrics.

- Average cost per ton
- Bidder earnings
- The frequency of negative earnings foreshadowing performance failures
- The full use of the government budget
- Potentially collusive outcomes

The experimental setup

The experiment involved performance comparisons between two auction procedures: the sealed bid discriminatory auction and the declining price clock auction. Each "session" involved 6 subjects as bidders, with the same auction procedure, sealed bid discriminatory or clock in all auctions for that session. The unknown common production cost per "unit" was determined randomly by providing each bidder with a private "signal" of $3, $4, or $5, each with equal probability. The common production cost for the auction was then determined to be the average of the 6 bidders' signals, so this common cost was between $3 and $5. Hence, before the auction each bidder could observe a part of the unknown distribution of per-unit production cost, which was revealed after the auction. In addition to the per-unit production costs there was a $6 fixed cost incurred if any units were sold by the bidder. Subjects received an initial $20 endowment, and all earnings were divided by 2 to determine cash earnings, which were added to earnings from a single practice auction and the initial $10 payment made on arrival. These earnings amounts were structured to yield average earnings of about $30 per person for a session lasting at most 90 minutes.

In addition to the practice auction, there were 6 auctions in each session, using the same sequence of random realizations in each. Bidders were told that they have a capacity limit of 6 "units," and that the purchaser had a budget of $168 to spend in each auction. In each auction round, subjects earned the difference between auction payments and the realized production costs.

The sealed bid auctions were executed with two bids, a primary bid per unit for a full capacity award (6 units), and a secondary bid per unit if the firm operates at least half capacity but less than full capacity., that is, 3, 4, or 5 units. The clock auctions also allowed bidders to specify minimum sale quantities in this range in each round, with the clock price starting at $8 and declining in $0.50 cent increments in each subsequent round. Analogously, the permissible bid amounts in the sealed bid auctions were constrained to be in $0.50 cent increments on a range from $4 to $8.

Results

To date, we have conducted 12 sessions, each with 6 bidders and 6 auctions per session. The summary results by session and treatment are provided in Table 1. The results for the two treatments are similar, but suggest a somewhat better outcome for the procurement agency with the clock auction. The average cost of a unit procured was 5% lower for the clock auction (p=0.07). The clock also resulted in a higher average number of units procured per auction, although this result was not statistically significant.[7] The amount procured was higher for the clock than for the sealed bid in all but one session.

On the opposite side of the ledger, the average bidder earnings were about 33% lower for the clock than for the sealed bid, as shown in Figure 2 and in the *Average Bidder Earnings* column of Table 1, with average earnings per bidder per auction being about $3 in the sealed bid treatment (top part of the table), as compared to earnings of about $2 in the clock auctions (p=0.08). There appears to be a general tendency for bidders to bid more aggressively in the clock auction but not so aggressively that they succumbed to the winner's curse resulting in losses. For each treatment, there were 216 earnings amounts (6 sessions with 6 auctions and 6 bidders), and losses (negative earnings) occurred in less than ten percent of the cases (17 cases with sealed bids; 7.9% , 14 cases with the clock; 6.5%). The difference here is not statistically significant (p=0.4). But the clock auction resulted in a much higher frequency of bidders making "zero profits", that is, just breaking even in an auction where the bidder "wins" a share of the production. This occurred 11 times in the sealed bid auction and 33 times in the clock (p=0.013).

In both specifications, the ability to use more than one signal about the bidders cost function allowed the agency to procure additional units in the auctions, while still having most bidders operate at full capacity. For example, the option to sell to a marginal bidder at their secondary capacity bid resulted in an average of 11 additional units being sold in each session.

These initial results offer some support for the approach suggested in Baranov et al (2017). When selling to bidders with concave costs, obtaining a modest additional amount of information about the bidders' costs can allow the procurement agency to purchase units from marginal bidders operating at less-than full capacity with only a modest complication in the auction procedures. Our results also provide tentative support for the use of a dynamic auction such as a descending clock in a common value setting. The clock appears to encourage more aggressive bidding, lowering procurement costs, but without bidders falling prey to the winner's curse. The avoidance of substantial losses due to overly aggressive bidding helps reduce the likelihood of expensive default by winning bidders.

[7] The lack of significance is due to sealed bid session #4, which is something of an outlier in our sessions, with extremely low bidder earnings and, by far, the lowest average unit cost. The participants in this session had the lowest score on the three-question cognitive test held at the end of each session.

Table 1: Results By Session (6 Subjects, 6 Auctions per Session)

	Average Bidder Earnings	Total Units Procured	Average Auction Expenditure	Average Cost per Unit
Discriminatory 2-Bid				
Session 1 (rffa20)	3.43	29.50	166.75	5.65
Session 2 (rffa21)	3.59	29.17	166.50	5.71
Session 3 (rffa24)	3.81	28.50	165.42	5.80
Session 4 (rffa25)	1.01	31.50	161.75	5.14
Session 5 (rffa28)	4.4	27.17	163.58	6.02
Session 6 (rffa29)	2.72	29.83	164.00	5.50
Discriminatory Average	**3.16**	**29.28**	**164.67**	**5.64**
Clock with Lookback				
Session 7 (rffb7)	1.19	30.00	155.50	5.18
Session 8 (rffb8)	2.03	30.00	160.50	5.35
Session 9 (rffb11)	0.86	30.00	153.50	5.12
Session 10 (rffb13)	2.03	30.00	160.50	5.35
Session 11 (rffb15)	2.94	30.00	166.00	5.53
Session 12 (rffb17)	2.86	30.00	165.50	5.52
Clock Average	**1.99**	**30.00**	**160.25**	**5.34**

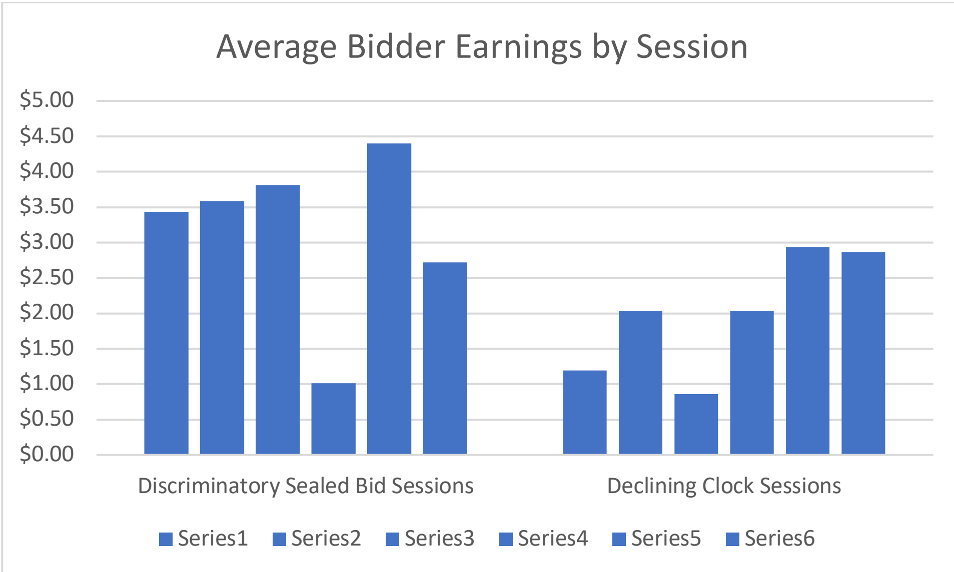

Figure 2, Average Earnings per Bidder in Each Session

References

Aloysius, J., Deck, C., Hao, L., & French, R. (2016). An Experimental Investigation of Procurement Auctions with Asymmetric Sellers. *Production and Operations Management*, *25*(10), 1763–1777. https://doi.org/10.1111/poms.12576

Arthur, W. (1994). *Increasing returns and path dependence in the economy*. University of Michigan Press. https://doi.org/10.3998/mpub.10029

Athey, S., & Levin, J. (2001). Information and competition in U.S. forest service timber auctions. *Journal of Political Economy*, *109*(2), 375–417. https://doi.org/10.1086/319558

Ausubel, Lawrence M., & Cramton, P. (2006). Dynamic auctions in procurement. In N. Dimitri, G. Piga, & G. Spagnolo (Eds.), *Handbook of Procurement* (pp. 220–246). Cambridge University Press. https://doi.org/10.1017/CBO9780511492556.010

Ausubel, L M, Cramton, P., Pycia, M., Rostek, M., & Weretka, M. (2014). Demand Reduction and Inefficiency in Multi-Unit Auctions. *The Review of Economic Studies*, *81*(4), 1366–1400. https://doi.org/10.1093/restud/rdu023

Baranov, O., Aperjis, C., Ausubel, L. M., & Morrill, T. (2017). Efficient Procurement Auctions with Increasing Returns. *American Economic Journal: Microeconomics*, *9*(3), 1–27. https://doi.org/10.1257/mic.20160087

Beiron, J., Normann, F., & Johnsson, F. (2022). A techno-economic assessment of CO2 capture in biomass and waste-fired combined heat and power plants – A Swedish case study. *International Journal of Greenhouse Gas Control*, *118*, 103684. https://doi.org/10.1016/j.ijggc.2022.103684

Birulin, O. (2020). Optimality of simple procurement auctions. *International Journal of Industrial Organization*, *70*, 102610. https://doi.org/10.1016/j.ijindorg.2020.102610

Burtraw, D., Goeree, J., Holt, C. A., Myers, E., Palmer, K., & Shobe, W. (2009). Collusion in auctions for emission permits: An experimental analysis. *Journal of Policy Analysis and Management*, *28*(4), 672–691. https://doi.org/10.1002/pam.20460

Cummings, R. G., Holt, C. A., & Laury, S. K. (2004). Using laboratory experiments for policymaking: An example from the Georgia irrigation reduction auction. *Journal of Policy Analysis and Management : [The Journal of the Association for Public Policy Analysis and Management]*, *23*(2), 341–363. https://doi.org/10.1002/pam.20007

Decarolis, F. (2014). Awarding Price, Contract Performance, and Bids Screening: Evidence from Procurement Auctions. *American Economic Journal: Applied Economics*, *6*(1), 108–132. https://doi.org/10.1257/app.6.1.108

Decarolis, F. (2018). COMPARING PUBLIC PROCUREMENT AUCTIONS. *International Economic Review*, *59*(2), 391–419. https://doi.org/10.1111/iere.12274

Fabra, N., von der Fehr, N. H., & Harbord, D. (2006). DUPLICATE_Designing Electricity Auctions. *The Rand Journal of Economics*, *37*(1), 23–46.

Fuhrman, J., Bergero, C., Weber, M., Monteith, S., Wang, F. M., Clarens, A. F., Doney, S. C., Shobe, W., & McJeon, H. (2023). Diverse carbon dioxide removal approaches could reduce impacts on the energy–water–land system. *Nature Climate Change*. https://doi.org/10.1038/s41558-023-01604-9

Fuhrman, J., McJeon, H., Patel, P., Doney, S. C., Shobe, W. M., & Clarens, A. F. (2020). Food–energy–water implications of negative emissions technologies in a +1.5 °C future. *Nature Climate Change*, *10*(10), 920–927. https://doi.org/10.1038/s41558-020-0876-z

Haruvy, E., & Katok, E. (2013). Increasing revenue by decreasing information in procurement auctions. *Production and Operations Management*, *22*(1), 19–35. https://doi.org/10.1111/j.1937-5956.2012.01356.x

Holt, C. A. (1980). Competitive Bidding for Contracts under Alternative Auction Procedures. *Journal of Political Economy*, *88*(3), 433–445. https://doi.org/10.1086/260878

Holt, C. A., Shobe, W., Burtraw, D., Palmer, K. L., & Goeree, J. K. (2007). Auction design for selling co_2 emission allowances under the regional greenhouse gas initiative. *SSRN Electronic Journal*. https://doi.org/10.2139/ssrn.2459462

Holt, C. A., & Shobe, W. M. (2016). Reprint of: Price and quantity collars for stabilizing emission allowance prices: Laboratory experiments on the EU ETS market stability reserve. *Journal of Environmental Economics and Management*, *80*(0), 69–86. https://doi.org/10.1016/j.jeem.2016.01.003

Katok, E. (2013). Experiments with Buyer-Determined Procurement Auctions. In N. Vulkan, A. E. Roth, & Z. Neeman (Eds.), *The handbook of market design* (pp. 573–586). Oxford University Press. https://doi.org/10.1093/acprof:oso/9780199570515.003.0023

Kearns, D., & Consoli, C. (2021). *Technology Readiness and Costs of CCS*. Global CCS Institute.

Kremer, I., & Nyborg, K. G. (2004). Underpricing and market power in uniform price auctions. *Review of Financial Studies*, *17*(3), 849–877. https://doi.org/10.1093/rfs/hhg051

Lackner, K. S., & Azarabadi, H. (2021). Buying down the Cost of Direct Air Capture. *Industrial & Engineering Chemistry Research*, *60*(22), 8196–8208. https://doi.org/10.1021/acs.iecr.0c04839

Lamb, W. F., Wiedmann, T., Pongratz, J., Andrew, R., Crippa, M., Olivier, J. G. J., Wiedenhofer, D., Mattioli, G., Al Khourdajie, A., House, J., Pachauri, S., Figueroa, M., Saheb, Y., Slade, R., Hubacek, K., Sun, L., Ribeiro, S. K., Khennas, S., de la Rue du Can, S., … Minx, J. C. (2021). A review of trends and drivers of greenhouse gas emissions by sector from 1990 to 2018. *Environmental Research Letters*. https://doi.org/10.1088/1748-9326/abee4e

LiCalzi, M., & Pavan, A. (2005). Tilting the supply schedule to enhance competition in uniform-price auctions. *European Economic Review*, *49*(1), 227–250. https://doi.org/10.1016/S0014-2921(02)00324-0

McAdams, D. (2007). Adjustable supply in uniform price auctions: Non-commitment as a strategic tool. *Economics Letters*, *95*(1), 48–53. https://doi.org/10.1016/j.econlet.2006.08.035

Nemet, G. F., Gidden, M. J., Greene, J., Roberts, C., Lamb, W. F., Minx, J. C., Smith, S. M., Geden, O., & Riahi, K. (2023). Near-term deployment of novel carbon removal to facilitate longer-term deployment. *Joule*. https://doi.org/10.1016/j.joule.2023.11.001

Rissman, J., Bataille, C., Masanet, E., Aden, N., Morrow, W. R., Zhou, N., Elliott, N., Dell, R., Heeren, N., Huckestein, B., Cresko, J., Miller, S. A., Roy, J., Fennell, P., Cremmins, B., Koch Blank, T., Hone, D., Williams, E. D., de la Rue du Can, S., … Helseth, J. (2020). Technologies and policies to decarbonize global industry: Review and assessment of mitigation drivers through 2070. *Applied Energy*, *266*, 114848. https://doi.org/10.1016/j.apenergy.2020.114848

SEA. (2021). *First, second, third... Proposals for the design of a support scheme for bio-CCS* (2021:31; Energy Reports, p. 1). Swedish Energy Agency.

Wilson, R. (1979). Auctions of Shares. *The Quarterly Journal of Economics*, *93*(4), 675. https://doi.org/10.2307/1884475