Carbon Allowance Auction Design: An Assessment of Options for the U.S.

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Abstract

Carbon allowance auctions are a component of existing and proposed regional cap-and-trade programs in the U.S. and are also included in recent bills in the U.S. Congress that would establish a national cap-and-trade program to regulate greenhouse gases ("carbon"). We discuss and evaluate the two leading candidates for auction format: a uniform-price sealed-bid auction and an ascending-bid dynamic auction, either of which could be augmented with a "price collar" to ensure that the price of allowances is neither too high nor too low. We identify the primary trade-offs between these two formats as applied to carbon allowance auctions and suggest additional auction design features that address potential concerns about efficiency losses from collusion and other factors. We conclude that, based on currently available evidence, a uniform-price sealed-bid auction is more appropriate for the sale of carbon allowances than the other leading auction formats, in part because it offers increased robustness to collusion without significant sacrifice of price discovery.

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INTRODUCTION

Any future legislation aimed at reducing carbon dioxide (CO_2) emissions in the United States appears likely to include an auction component to assign CO_2 emission permits (also called allowances). The basic appeal of auctions is that they can be a relatively effective and efficient way to allocate permits to those with the greatest cost of abatement, thereby minimizing the overall economic burden associated with reducing CO_2 emissions. Auctions can also generate significant government revenue, reducing the need for distortionary taxes. Even if some permits are assigned to firms free of charge, an auction for a fraction of the available permits can be a valuable tool for "price discovery," providing information that can be useful to firms as they plan investment and regulators as they develop policy and seek to establish a "market price" to facilitate more efficient trading of permits after the auction. Finally, in contrast to the primary alternative of assigning permits based on historical output or emissions (grandfathering), auctions avoid generating windfall profits for incumbent firms, which could create a backlash against cap-and-trade policies.[5]

Less clear is what auction format is best suited for emissions permits. The Regional Greenhouse Gas Initiative (RGGI), the cap-and-trade program regulating Northeast U.S. electric utilities, auctions CO_2 emission permits using a "uniform-price sealed-bid" format, in which each bidder announces the most that it is willing to pay for any given quantity of permits – a bid can be interpreted as a demand curve – and all winners pay the same market-clearing price. On the other hand, under the Environmental Protection Agency (EPA) SO_2 emissions trading program, permits are auctioned using a "discriminatory sealed-bid" format, in which bidders submit

[5] See, e.g., "Money and Lobbyists Hurt European Efforts to Curb Gases," *New York Times*, December 10, 2008, discussing the early experiences of the European Union's Emissions Trading Scheme (ETS). See also the experimental results of Goeree et al. (2010) and the discussion of Cramton and Kerr (2002).

demand curves but each bidder pays its own prices for any permits it wins. In its June 2004 auction of nitrogen oxide (NO_x) emission permits, the Commonwealth of Virginia used another format, the "uniform-price ascending-bid" auction. Here, the auctioneer calls out a sequence of prices, starting low and raising the price incrementally until demand at the announced price no longer exceeds supply. When the bidding stops, all remaining active bids win and all winning bidders pay the same market-clearing price.

The choice of auction format is significant, with potentially important ramifications for the efficiency of the final assignment of permits, revenue raised, and other issues such as price discovery, price volatility, vulnerability to collusion and/or market manipulation, transaction costs, fairness (distributional effects), and transparency. Thus it is important to carefully evaluate the strengths and weaknesses of each format for selling emissions permits. This article critically reviews the evidence and economic arguments for and against the leading auction formats for assigning CO_2 emissions permits. We conclude that a uniform-price sealed-bid format is best-suited for the sale of CO_2 emission permits and argue strongly *against* the sealed-bid discriminatory auction that is used in the EPA's SO_2 emissions trading program. We also discuss some additional market design issues that could affect the performance of these auctions.

The remainder of this article proceeds as follows. First, we review relevant auction formats that are currently in use. Then we discuss the objectives and desirable properties of carbon allowance auctions. We next consider the strengths and weaknesses of pay-as-bid versus uniform-price auctions, and ascending-bid versus sealed-bid auctions. Then we examine issues concerning bounding the auction price and other design details. The final section provides concluding comments.

AUCTION FORMATS IN PRACTICE

Auctions are used to buy, sell, or trade everything from unique objects such as art and cars to multiple dissimilar objects such as telecommunications spectrum rights and bus network service, to multiple identical objects such as flowers, fish, stocks, bonds, and electricity. Auctions of emission permits fit within this last category, so-called "multi-unit auctions" of multiple identical objects. Four multi-unit auction formats are most common in practice. Roughly speaking, these auction formats are characterized by whether (i) the bidding is "dynamic" or "sealed" and (ii) winners pay their own bids (pay-as-bid) or the market-clearing price (uniform price) when they win. "Dynamic" auctions involve real-time interaction between an auctioneer and multiple bidders, and may include "ascending" and "descending" auctions in which prices are raised or lowered over time.

		Bidding	
Pricing		Dynamic	Sealed
	Pay-as-bid	Dutch Tulips Sydney Fish Market	U.S. Sulfur dioxide U.S. Treasury bonds (pre-1992) Mexico Treasury (pre-1990)
	Uniform-price	Virginia Nitrogen Oxide	RGGI Carbon dioxide (CO_2) EU Emissions Trading System (CO_2) U.S. Treasury bonds (post-1992) Mexico Treasury (post-1990) Electricity procurement (selected)

Table 1: Some Examples of Multi-Unit Auctions

Table 1 lists some prominent examples of multi-unit auctions for each format. Below we discuss the three formats currently used to auction emission permits in the United States (pay-as-bid auction with sealed bids, uniform-price auction with sealed bids, and uniform-price auction with ascending bids).[6] Other auctions have significant theoretical interest, such as the Vickrey auction proposed by Nobel Laureate William Vickrey (1961), but we focus here on the simplest and most common auction formats seen in practice.

[6] We are unaware of any dynamic pay-as-bid auction for emissions permits. Such auctions are most useful in settings where many identical items need to be sold quickly, as with fish or flowers.

Pay-as-Bid Auction

In a pay-as-bid auction with sealed bids (also commonly known as the "discriminatory auction"), each bidder simultaneously submits a collection of bids, with each bid specifying a price and a quantity. The bids are then ranked to determine the market-clearing price (i.e., the price at which total demand equals available supply). Bids at or above the market-clearing price are winners, and winning bidders receive the quantity bid *at the prices they bid*. Thus, bidders will typically pay different prices, with every bidder paying at least the market-clearing price.

U.S. Sulfur dioxide. SO_2 emission permits have been required for certain electric utilities and freely traded in the U.S. since 1995.[7] The main targets of the program are SO_2 emissions produced by coal-fired electric generating plants. In Phase I (1995-1999), the 263 dirtiest large generating units were required to reduce SO_2 emissions by about 3.5 million tons per year. In Phase II, which began in 2000 and continues today, virtually all fossil-fueled electric generating plants are subject to a national cap on aggregate annual SO_2 emissions.

The emission cap is enforced through the requirement that any regulated plant must surrender tradable emission permits (allowances) for each ton of SO_2 it emits that year. Allowances can be banked for future use, but firms cannot borrow allowances from the future. The EPA sets aside 2.8% of allowances for an annual auction, with the proceeds returned pro rata to all firms receiving the remaining 97.2% of allowances that are allocated for free. This auction uses the pay-as-bid sealed-bid format,[8] although there is debate about whether a uniform-price sealed-bid auction might be preferable (see e.g., Cason and Plott (1996) and Søberg (1998)).

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[7] The underlying legislation is Title IV of the 1990 Clean Air Act Amendments, which describes the U.S. Acid Rain Program. See Ellerman et al. (2000) for an excellent overview.

[8] Joskow, Schmalensee and Bailey (1998) provide a descriptive analysis of bidding behavior in this market.

Treasury bonds and bills. Governments sell trillions of dollars worth of securities every year. Unlike auctions of emissions permits, the primary objective of Treasury auctions is revenue generation. Among economists, there is little consensus as to the best auction mechanism for these treasury sales (see Chari and Weber (1992), Bikhchandani and Huang (1993), Malvey and Archibald (1998), and Klemperer (2000)). Yet in 39 out of the 42 countries surveyed by Bartolini and Cottarelli (1997), the government uses a pay-as-bid sealed-bid auction. However, in the 1990s the U.S. switched to a uniform-price sealed-bid auction. Commenting on this change, Bartolini and Cottarelli (1997, p.274) say: "Scholars of treasury bill auctions have been particularly interested in the contribution of different auction formats to collusive behavior and cornering, an issue brought to the forefront of the debate by recurrent episodes of allegedly non-competitive behavior in auctions of government securities in the United States and elsewhere. The controversy initially arose in the 1960s, and revolved around the suggestion to replace the multiple-price format of U.S. Treasury auctions with the uniform-price format." The Mexican government switched from discriminatory to uniform-price sealed-bid auctions in 1990 for similar reasons. Bidders' profits dropped sharply following this switch (Umlauf 1993).

Uniform-Price Auction with Sealed Bids

In a uniform-price sealed-bid auction, each bidder also submits a collection of bids, with each bid specifying a price and a quantity, and all bids at prices above the market-clearing price win. However, each winning bidder pays the market-clearing price on every unit won, regardless of his actual bid.

RGGI and EU ETS Carbon dioxide permits. The RGGI, which encompasses Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New Jersey, New York, Rhode Island, and Vermont, held its first auction on September 25, 2008 (www.rggi.org). CO_2 allowances are sold through quarterly auctions using a uniform-price sealed-bid format.[9]

In the June 2009 auction, the market-clearing price was $3.23 per ton of CO_2, and 30.8 million allowances were sold for revenue of approximately $100 million. Eighty-five percent of allowances were purchased by compliance entities (electric power generators), with the rest purchased by brokers, environmental groups, private citizens, and others. Six Midwestern states and seven Western states are currently developing regional carbon cap-and-trade programs similar to RGGI.

In Europe, the European Union Emission Trading System (EU ETS) covers over 10,000 facilities, which generate approximately half of the EU's CO_2 emissions. Permits are currently trading at around $20 per ton of CO_2.

The initial phases of the EU ETS relied almost exclusively on free allocation of allowances to regulated entities, rather than auctions. However, some member states, including the UK and Germany, auctioned a small share of their permits. There will be a significant shift in the next phase of the EU ETS, which starts in 2013, with half or more of the allowances expected to be auctioned. In July 2010, the EU issued draft regulations regarding how auctions are to be handled in the next phase (http://ec.europa.eu/environment/climat/emission/auctioning_en.htm). The auction format will be a single-round, sealed-bid, uniform-price auction with bidders able to submit as many bids as they wish during the auction window period. Each bid specifies the number of allowances the bidder will buy at a specific price. All bidders will pay the market-clearing price, the lowest price at which the number of allowances bid equals the number

[9] This choice of auction format was supported by experimental results in Holt et al. (2007).

available at auction. Regulated entities as well as registered financial intermediaries will be allowed to bid.

Electricity procurement. Electricity auctions are conducted in deregulated power exchanges around the world, for the most part by uniform-price auction (see Cramton and Stoft (2006), Wolfram (1998), and Borenstein, Bushell, and Wolak (2002). Some governments (e.g., California (U.S.), Australia, England, and New Zealand (Contreras et al., 2001)) have created two-sided auction markets for wholesale power, where generating companies bid to sell their power and wholesale customers bid to buy power. Trades are executed at the market-clearing price, which equates supply and demand. Roughly speaking, each generator submits a schedule detailing the prices at which it would be willing to supply power during various blocks of time, and wholesale customers submit demand forecasts. Although there has been considerable debate concerning the most appropriate format for electricity auctions, most economists have argued strongly against the pay-as-bid auction format for electricity because it would introduce new inefficiencies, weaken competition in new generation, and impede expansion of capacity (see Kahn et al 2001a, Kahn et al. 2001b, and Cramton and Stoft 2007).

Uniform-Price Ascending-Bid Auction

In a uniform-price ascending-bid auction, the auctioneer announces a sequence of increasing prices. At each price, bidders indicate the quantity they would be willing to purchase. The auction typically begins at a low price, at which bidders are likely to demand more than the entire supply, and continues at higher and higher prices until the total quantity demanded equals the quantity supplied.   Every bidder then pays the final, market-clearing price for each unit won.

VA Nitrogen oxide. In response to a budget shortfall in 2004, the Commonwealth of Virginia sold tradable emission permits for NOx using a uniform-price ascending-bid auction. The choice of this format was supported by experimental results (Porter et al. 2009) showing that an ascending ("clock") uniform-price auction performed better in terms of efficiency and revenue than a sealed-bid alternative when demand was relatively elastic.[10]

DESIRABLE PROPERTIES OF CARBON ALLOWANCE AUCTIONS

An effective auction for CO_2 emission permits should achieve several objectives. First, the auction should assign the scarce permits to those who are willing to pay the most to continue to emit, thereby achieving an efficient assignment of permits and minimizing the total economic cost of any given emissions reduction. Since revenue generated by the auction may be less distortionary than other sources of government revenue, thus providing a corrective efficiency benefit, revenue enhancement may be a complementary objective of the auction format. However, in some cases, governments explicitly state a preference for efficiency over revenue when designing auctions.[11] To help achieve the efficiency objective, it is important for the auction to be designed to minimize collusion and other forms of market manipulation. The auction should also provide useful price discovery to help guide firms' long-term planning and investment, as well as government policy. In addition, to promote confidence among market participants, the auction process should be fair and transparent. Finally, the auction should be designed to minimize transaction costs. These objectives are discussed in more detail below.

[10] "Experimental" economics involves the analysis of data generated through laboratory or field experiments involving cash-motivated subjects.
[11] For example, Congress explicitly required that revenues *not* be a primary consideration in designing the Federal Communications Commission (FCC) spectrum license auctions (Kwerel and Rosston 2000).

Efficiency

Achieving an efficient assignment of goods is an important challenge of auction design. [12] First, the cost of bidding must be low enough to induce full participation, so that the bidders who need permits most have an opportunity to bid for them. Even if all bidders participate, however, there is no guarantee that those willing to pay the most to avoid further abatement will acquire the right number of permits to ensure efficiency. For example, coordinated bidding ("collusion"), market manipulation, and/or the exercise of unilateral market power all have the potential to distort auction outcomes. Collusion in particular can distort market outcomes, undermining the efficiency and price discovery benefits of an auction. Hence, minimizing collusion and other forms of market manipulation is another important element of effective auction design.

Minimization of Collusion and Market Manipulation

How best to combat collusion can be surprisingly subtle, since firms with an interest in colluding can respond to market rules in creative and sometimes unexpected ways. As a prominent example, consider the early design of the Federal Communications Commission (FCC) spectrum license auctions, which stressed the importance of high transparency and flexibility for bidders.[13] Unfortunately, the information revealed during the auctions facilitated retaliatory bidding, signaling, market division, and gaming of the auction's activity rules, which

[12] Such efficiency includes allowing non-emitting parties who value reductions in emissions to buy permits (and not use them). See Israel (2007) on environmentalist participation in U.S. SO_2 emission permit markets.

[13] The FCC has held auctions for spectrum licenses since 1994 using primarily a simultaneous multiple round auction. See McMillan (1994), McAfee and McMillan (1996), Cramton (1997), Kwerel and Rosston (2000), and Marx (2006).

were detrimental both to revenue and allocative efficiency (see, e.g., McAfee and McMillan (1996), Cramton and Schwartz (2000, 2002), Kwasnica and Sherstyuk (2001), Brusco and Lopomo (2002), Reitsma, et al. (2002), and Marx (2006)). Recent FCC auctions have moved to an anonymous format that masks bidder identities and thereby reduces bidders' opportunities and incentives for anti-competitive behavior (see Marx (2006); Brusco, Lopomo, and Marx (2009); and Marshall and Marx (2009)). Novel features of carbon allowance auctions, such as a "price collar" to bound the price of permits, could also create an environment more conducive to collusion. We will explore this issue below, including how to modify the auction design to limit opportunities for successful collusion.

Price Discovery

Prices are more likely to reflect true market values and thus provide better information if they emerge as the final outcome of transparent (see below), competitive auction mechanisms. Moreover, advance auctions for future vintages can help to elicit information about expectations regarding the future evolution of industry fundamentals, such as expected "low carbon" technological developments or policy changes affecting the future stringency of the cap. Burtraw et al. (2010, p.4) find that the Virginia NOx auction prices "seemed to provide important information about evolving market conditions." They also argue that empirical evidence on RGGI auction prices indicates "the early auction prices outperformed futures prices in terms of predicting allowance prices in subsequent auctions" and that "the RGGI auction provided informative signals about the anticipated scarcity of the RGGI allowances." (p.6)

Fairness and Transparency

Fairness of auction outcomes and transparency of the auction process are also desirable properties of any auction. Transparency in bidding is a common objective of federal auctions and procurements. However, pre-auction transparency in the form of transparent registration, and real-time transparency in the form of revealing the identities of bidders, can also have significant pro-collusive effects (Marshall and Marx 2009). Presumably, a primary motivation for transparency in bidding is the need to allay fears about corruption. In this case, however, the remedy is simple -- post-auction transparency. Enough information regarding auction outcomes should be made available after the auction (at least to a monitoring authority) to detect any illicit activity.

Minimization of Transaction Costs

Finally, the auction should be designed to minimize transaction costs associated with participating in the auction (e.g., time spent submitting bids). The auction should impose minimal burdens on bidders, of course, but also deter exploitative behaviors, such as costly ex-post defaults by liquidity-constrained bidders (see Brusco and Lopomo (2008, 2009), that disrupt the auction process.

The next four sections discuss the theoretical and empirical evidence for and against 1. pay-as-bid versus uniform-price auctions; 2. ascending-bid versus sealed-bid auctions; 3. supply rules, especially bounding the auction price; and 4. other auction design details.

PAY-AS-BID VERSUS UNIFORM-PRICE AUCTIONS

There is broad consensus among economists specializing in auction design that a pay-as-bid auction is *not* best-suited for CO_2 emissions. Several disadvantages of this auction format have been noted in the literature (see e.g., Cramton and Stoft 2007), but perhaps the most damning disadvantage has received relatively little attention. That is, even in an idealized "perfect competition" setting in which all bidders lack market power, the pay-as-bid auction need not lead to an efficient – or even an approximately efficient – distribution of emission permits (see Jackson and Kremer 2007).

To see why pay-as-bid auctions are not "asymptotically efficient," consider a scenario in which each emitter knows its own cost of reducing emissions, but the economy-wide distribution of such costs depends on some underlying factor about which each party receives an unclear signal. In the carbon emissions context, such a factor could be the rate of economic growth, the adoption rate of a new technology that decreases the marginal cost of carbon emissions, the availability of carbon offsets from uncapped sectors, etc. Emitters who believe that the economy-wide distribution of costs is high have an incentive to bid high in the auction because they will expect stiffer competition to win permits and greater payoff from reselling their unused permits to higher cost entities. Consequently, bidders who have overestimated the distribution of others' costs will tend to outbid others with higher abatement costs who have underestimated this distribution, leading to an inefficient assignment of permits. By contrast, in the uniform-price auction (whether with sealed or ascending bids), each bidder knows that it will pay the market-clearing price whenever it wins. Thus, each bidder's dominant strategy is to bid up to its true willingness to pay, which means the bidders with the highest marginal value for permits win them and the efficient outcome is realized.[14]

In our view, the asymptotic inefficiency of the pay-as-bid auction is highly relevant in the context of CO_2 allowances, and sufficient to disqualify it from serious consideration as the best

[14] When bidders have some market power, uniform-price auctions will lead to some inefficiency. However, the convergence to efficiency is rapid as the number of bidders grows. For theoretical results, see Gresik (1991), Satterthwaite and Williams (1989a, 1989b), and Wilson (1985, 1993), and for empirical evidence, see Gjerstad and Dickhaut (1998).

auction format for CO_2 allowances. However, the pay-as-bid auction suffers from other significant weaknesses relative to the uniform-price auction.

Since in a pay-as-bid auction each winning bidder pays its own bid, each bidder has an incentive to bid as close as possible to the realized market-clearing price, so as to win at the lowest possible price. As noted by Cramton and Stoft (2007): "Indeed, the pay-as-bid auction may be renamed 'Guess the clearing price.' The pay-as-bid auction rewards those that can best guess the clearing price. ... Typically, this favors larger companies that can spend more on forecasting" (p.33). By contrast, since in a uniform-price auction each winning bidder pays the same market-clearing price, bidding one's true value is a dominant strategy for any bidder with no influence over the market-clearing price. Thus, the uniform-price auction imposes a smaller informational burden on small bidders, because to determine its optimal bid, a small bidder need know nothing about the distribution of others' abatement costs. Consequently, such small bidders may be more willing to participate in a uniform-price auction than a pay-as-bid auction.

Furthermore, since bidders in a pay-as-bid auction optimally bid less than their true willingness to pay for permits, the market-clearing price in the auction does not provide clear information about the true marginal cost of abatement.

From the perspective of revenue generation, there is no clear ranking of pay-as-bid vs. uniform-price auctions. Indeed, Ausubel and Cramton (1998) provide examples of both types of auctions generating greater expected revenue. In a more recent study, Rostek, Weretka, and Pycia (2010) have shown that the pay-as-bid auction generates greater expected revenue in a particular set of circumstances with symmetric bidders and complete information (with *ex ante* uncertainty resolved before the bidding). However, even in these circumstances, the uniform-price auction outperforms the pay-as-bid auction as the number of bidders grows large, because although both auctions generate the same expected revenue, the pay-as-bid auction generates riskier returns.

ASCENDING-BID VERSUS SEALED-BID AUCTIONS

Although the economics literature generally suggests that a uniform-price auction would be more suitable than a pay-as-bid format to sell CO_2 emission permits, there is much less consensus regarding whether a sealed-bid or an ascending-bid uniform-price auction would be preferable. For instance, whereas the experimental results of Holt et al. (2007) and Burtraw et al. (2009) support sealed bids, the evaluations by Evans & Peck (2007), Betz et al. (2009) (for Australia) and Cramton and Kerr (2002) (for the U.S.) support using ascending bids.

The Evans & Peck (2007) argument in favor of an ascending-bid format is a helpful starting point for our own evaluation. They focus on four desirable properties of an ascending-bid uniform-price auction, particularly one where multiple vintages are offered in one auction (p.xiv):

1) "An ascending-bid uniform-price auction is a simple procedure that is easy to understand. Implementation is web-based and transaction costs are low."
2) "Uniform pricing provides a strong signal regarding the participants' aggregated estimates of the future value of a permit and thus the economy's marginal abatement costs."
3) "Revealing demand at the end of each round improves transparency and increases the information available to participants."
4) "By allowing bidders to shift their demand from one vintage to another, a simultaneous auction offers the necessary flexibility to deal with highly substitutable items and picks up

the advantages of the simultaneous multiple-round ascending bid auction."

At least two of these properties, easy implementation (#1) and uniform pricing to provide information about the economy's marginal abatement cost (#2), are shared by both ascending-bid and sealed-bid versions of the uniform-price auction. Moreover, participants may find sealed-bid auctions even simpler to understand and time spent bidding reduced relative to ascending-bid auctions. Ascending-bid auctions require activity rules to function well,[15] as well as certain add-on features such as intra-round bidding, second-stage sealed-bid rounds, or roll-back procedures to deal with unsold units. By contrast, in a sealed-bid auction, a bidder need only determine how to bid once. Thus, any case in favor of an ascending-bid over a sealed-bid format rests primarily on relative advantages in terms of transparency (#3) and/or the ability to accommodate multiple vintages (#4).

Transparency

Transparency is a double-edged sword. The main benefit of transparency is that information about others' bids may help bidders assess the true value of the permits being sold.[16] This enhances efficiency and can induce more aggressive bidding as bidders have less fear of "the winner's curse." With CO_2 emissions permits, this benefit of transparency is likely to be mitigated by the fact that most bidders have "private values" – their willingness to pay for a permit depends primarily on their own cost of reducing emissions – in which case revealing others' bids has no impact on bidders' individual estimates of a permit's value.

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[15] Activity rules are required to prevent bidders from "sniping," whereby they wait until late in the auction before bidding seriously. See Cramton (2007) on the implementation of activity rules in an ascending-bid auction.

[16] However, transparency alone does not necessarily result in complete price discovery. For example, Burtraw et al. (2010) provide evidence that the information provided in open auction formats may not be sufficient for auction prices to incorporate the effects of shifts in the demand for permits.

On the other hand, concerns about "common values" could be significant in auctions of permits for *future* emissions, as bidders will be uncertain about underlying common factors such as economic growth and technological change.[17] If the common component of bidder values is sufficiently important, an ascending-bid format could create substantial benefits relative to a sealed-bid format because, in that setting, bidders at a sealed-bid auction may respond to the threat of a winner's curse by significantly reducing their bids, an effect that is less pronounced in an ascending-bid format. However, "common values" only arise when bidders have private information relevant to the common factors driving bidders' willingness to pay for permits. If, instead, information about common factors such as economic growth, seasonal weather forecasts, and energy market conditions is public, each bidder's *private information* about its willingness to pay will simply be those private factors that impact its estimate of its own use value of the allowance (such as the profitability of its output, its own installed emissions-reduction technology, etc). In this case, bidding transparency would not have any meaningful information-sharing benefits.

A liquid after-market could also lead bidders to have a common value, as every bidder tries to estimate whether the price of permits will increase or decrease after the auction. However, in the presence of even small after-market imperfections, non-speculative bidders will typically prefer to acquire their permits in the auction, thereby potentially reducing transaction volumes in the after-market, which could in turn reduce after-market liquidity. For this reason, we find it prudent to design the initial auction with the idea that after-market trading may be imperfect. Thus, bidders can again best be viewed as having private values, which means bidding transparency will have little information-sharing benefit.

[17] Common value components may also be relevant in contemporaneous markets. For example, Burtraw et al. (2010) raise the possibility that uncertainty over federal climate change legislation and its interaction with RGGI affected pricing of RGGI allowances.

The main cost of bidding transparency is that revealing bids may change bidding behavior and lead to less desirable auction outcomes. In particular, the literature suggests that revealing bids at each stage of a multi-round bidding process can facilitate collusive bidding (see Holt et al. (2007); Klemperer (2000); Lopomo, Marshall, and Marx (2005); and Kovacic et al. (2006)). Burtraw et al. (2009) assessed the impact of tacit and explicit collusion in an ascending-bid ("clock") uniform-price auction, and found that collusion is more effective in these auctions than in sealed-bid auctions.

Multiple Vintages

In most emission permit markets, permits are available that allow emissions at different times. For example, should permits be bankable for future use, a 2012-vintage permit could be used in 2012 or any later time. Naturally, bidders may value the ability to build a portfolio of permits of different vintages. A properly synchronized *simultaneous ascending-bid* auction for multiple vintages could allow bidders to do this in a single auction, although at the cost of increased complexity of the auction design and bidding strategies.

Cramton (2007, p.2) argues that sealed-bid auctions may not be well-suited for such simultaneous multi-vintage auctions, warning that a sealed-bid uniform-price auction may result in a price inversion – a higher price for future vintages than for the current vintage. Since earlier vintages can be banked and used later, every bidder is willing to pay at least as much for an earlier vintage. For this reason, price inversions never arise in an auction that correctly elicits bidders' true marginal willingness to pay. To address this concern, Holt et al. (2008) propose a multi-vintage auction using a uniform-price sealed-bid auction, with the twist that a bid for a particular vintage is treated as a request to purchase that vintage or an earlier vintage, whichever is less expensive. With this format, price inversions are impossible. However, this auction design may not fully capture bidders' preferences for substitution across vintages, something a simultaneous ascending-bid auction can do in principle. Burtraw et al. (2009) examine this potential weakness and find that a single-round sealed-bid uniform-price auction achieves as much price discovery as a simultaneous ascending-bid format.

Conclusions: Sealed Bids vs. Ascending

Within the context of uniform-price auctions, there are valid arguments in favor of both sealed-bid and ascending-bid formats. Ultimately, the question of which auction format is better-suited for CO_2 allowances boils down to the relative importance of two factors: *robustness to collusion* and *within-auction price discovery*.

Because an ascending-bid format allows bidders to change their bids based on others' bidding behavior, such an auction may be better able to assign permits to those who value them the most. When multiple vintages are sold simultaneously, an ascending-bid format may have the additional advantage of generating more accurate price signals about bidders' willingness to pay for permits of different vintages. Yet this very transparency and flexibility of ascending-bid auctions means that bidders may coordinate their bidding behavior and, through this collusion, distort both the assignment of permits and the quality of the price signals sent to the market.

The experimental evidence to date suggests that the risk of collusion is real and significant while the risk of inadequate price discovery is relatively slight. Thus, if this finding is correct, a sealed-bid uniform-price auction is best-suited for CO_2 permits.

Supply Rules: Bounding the auction price

Thus far, we have focused on the strengths and weaknesses of various pricing rules that determine how much bidders pay for a fixed supply of permits. However, the supply of permits need not be fixed before the auction. Indeed, taxation of carbon emissions can be interpreted as a system in which the supply of permits is perfectly elastic at the price specified by the tax. Between these two extremes of perfectly inelastic and perfectly elastic supply are many possible supply rules. Such supply rules can potentially improve auction outcomes, by allowing the social cost of incremental emissions to influence the total quantity of permitted emissions.

We will focus here on one supply rule that has received much attention in the debate over climate change legislation, the so-called price collar. The simplest price collar is characterized by a price ceiling, a price floor, and a target supply. Bidders submit bids for the target supply and, if the resulting market-clearing price falls within the "collar" bounded by the price ceiling and price floor, the auction proceeds as if there were no collar. However, if the market-clearing price that would result exceeds the price ceiling, the quantity supplied is increased enough to meet all demand at the ceiling. Similarly, if the market-clearing price that would result falls below the minimal price, the quantity supplied is decreased so that only those bidding above the floor win any permits.

Benefits of a Price Collar

Price collars can reduce emitters' uncertainty about future prices as they plan long-term investments. For instance, if the price ceiling will remain in effect throughout the planning horizon, sufficiently profitable businesses can be confident that they will be able to avoid shutting down, and hence will not delay making necessary investments to sustain their operations. Similarly, if allowances will not cost less than the price floor, such businesses will not delay investing in carbon-reducing technologies which can reduce emissions at a per-unit cost that is less than the price floor. Also, as a supply rule, a price collar allows demand information that is revealed through the bids to influence how many allowances are issued. Namely, should the cost of emission reductions be revealed to be high, the price ceiling will bind and more allowances will be issued, and vice versa. If policy-makers are confident that the social cost of emissions lies within the collar, then this flexibility could allow for a more efficient carbon-reduction regime.

Risk of "Collusive-seeming Bidding"

A potential downside of price collars is that they can facilitate harmful "collusive-seeming behavior" among bidders,[18] as illustrated in the following simple example.

Suppose that 100 allowances are for sale in a uniform-price auction, with a price floor of $10, a price ceiling of $20, and a minimal price increment of $1. Two "large" bidders A and B have sufficiently profitable carbon-emitting operations that each is willing to pay up to the price ceiling of $20 for all 100 allowances. In addition, twenty "small" bidders each require just one allowance, with maximal willingness to pay (value) ranging from $0 to $19.

The small bidders have an incentive (technically, a "weakly dominant strategy") to bid competitively; those with values below the $10 price floor do not bid for allowances, while the others bid from $10 to $19 for one allowance each. If the large bidders were also to bid competitively, the auction would generate an efficient outcome in which only the large bidders receive allowances at a market-clearing price equal to $20, the true marginal cost of abatement. However, in this case, the auction would have squeezed all bidders of their profits: the small

[18] This could be of particular concern in regional carbon allowance markets in which a handful of energy companies and/or financial intermediaries may be positioned to buy a sizable fraction of the allowances.

bidders do not receive any allowances while the large bidders pay their full values to secure allowances.

Suppose now that, instead of competitively bidding $20 for all 100 units, bidders A and B bid $20 for 45 units each and then bid $10 for all further allowances. Since there are exactly ten small bidders willing to pay $10, the market-clearing price given these strategies will be $10. Furthermore, neither A nor B has any incentive to bid more aggressively to increase its allotment. For example, to win a 46-th allowance, each would have to raise the market-clearing price from $10 to $11, at an overwhelming cost of $45 on the allowances that it has already won. Thus, these "collusive-seeming" strategies constitute an equilibrium in which (i) the market-clearing price is not reflective of the true marginal cost of abatement, (ii) some small bidders inefficiently remain in operation, and (iii) all bidders who receive allowances are strictly better off than in the truthful-bidding equilibrium.[19] (Bidders in such an equilibrium are not colluding in the traditional sense, since they are each playing a best response to the other's strategy, hence the term "collusive-seeming bidding.")

A simple and intuitive way to think about collusive-seeming bidding in the uniform-price auction is as a means to divide the quantity for sale into "shares" and to avoid competing for others shares. To deter competition, each bidder bids a high price on all allowances in its share; to induce a low market-clearing price, each bidder then bids a low price on all allowances not in its share. Once bidders have carved out shares in this way, they have little if any incentive to try to steal away another bidder's share, since doing so would only raise the price paid on all other units. This type of arrangement can make collusive-seeming behavior persistent once established.

[19] For more on such collusive-seeming equilibria, see Back and Zender (1993), Wang and Zender (2002), and McAdams (2002, 2007).

Addressing Potential Concerns about Collusive-Seeming Bidding

Economic theory suggests that even a little supply uncertainty can significantly reduce concerns related to collusive-seeming bidding (Wang and Zender, 2002; McAdams, 2007). To see why, suppose that two bidders would like to split an offering of allowances in half and always pay a low price, but are not sure whether 100 or 120 allowances will be offered. To avoid paying a high price when the supply is only 100 allowances, they cannot bid aggressively for more than 50 allowances. But, in that case, each bidder has the tempting opportunity to bid a little more aggressively and win 70 allowances when supply turns out to be 120. In this way, uncertainty about supply tends to undermine players' ability to enjoy equilibrium prices below the true marginal cost of abatement.

In some applications, supply uncertainty arises naturally. For instance, in many Treasury auctions, bidders often do not know how much is being sold and/or who is bidding (Hortaçsu and McAdams 2009). Similarly, in spot electricity auctions, the quantity of electricity demanded depends on usage patterns that generators cannot perfectly predict when bidding. In these settings, collusive-seeming bidding is not likely to be a serious concern (Cramton and Stoft, 2007).

Of course, predictability of supply is an important aspect of carbon allowance markets. Without such predictability, market transactions would fail to provide as much meaningful information about future costs of emission reductions, and emitters would face an unnecessary additional source of risk. However, while there is a compelling efficiency rationale for all market participants to know the total quantity of emission allowances to be issued, there is no such rationale for large bidders in a particular auction to know how many allowances are available to them in that particular auction.

In the context of carbon emissions, one way to create some supply uncertainty among emitters is to allow non-emitters to bid, including speculators who plan to re-sell any allowances that they win in the auction and environmentally-sensitive individuals or organizations who would like to reduce the number of allowances available to emitters.

Participation by such non-emitters could be encouraged through a variety of measures.

First, allowances of a specific vintage could be released over several auctions, with two-sided trading permitted. This would allow bidders who had won allowances in an earlier auction to sell them in a later auction. Such a sequence of auctions could make speculative bidding more convenient, as a ready and liquid market would be periodically available for re-sale. Second, participation by environmentally-sensitive non-emitters ("environmentalists") could be encouraged by creating a special category of bid ("buy-down bid") that only wins when doing so will reduce total emissions.

To encourage environmentalists to participate, even in small numbers, the bidding process needs to be as simple and transparent as possible. Unfortunately, non-competitive bids (that win regardless of the price, as in Treasury bond auctions) are impractical when there is a price ceiling. To see why , consider a simple example: 100 allowances are for sale, environmentalists submit non-competitive bids for 50 allowances, while emitters demand 150 allowances at the price ceiling. Because of the price ceiling, the auctioneer will increase the quantity supplied to 200, at a price equal to the ceiling, rendering futile the environmentalists' attempts to reduce the quantity supplied to the emitters.

One simple way to address this issue is to allow bidders who do not plan to use or re-sell their allowances to submit a special type of non-competitive bid, called a "buy-down bid." When the price ceiling is binding, a bidder who submits a buy-down wins nothing and pays nothing. Otherwise, such a bidder pays the market-clearing price and causes a reduction of the supply of allowances relative to what supply would have been without such a bid. When the price floor is binding, supply is first reduced so that the price floor is binding, after which the buy-down bid is used to further reduce supply.

Another way to combat collusive-seeming bidding is to give the auctioneer flexibility to reduce the quantity sold after receiving the bids, if collusive-seeming bidding is suspected (Back and Zender, 2001; McAdams, 2007). Such "reducible supply" could be implemented by deferring the sale of some allowances in one auction to a later date, at the discretion of the auction monitor.

OTHER DESIGN DETAILS

Clearly, there are details other than price and supply rules that must be considered in designing carbon emissions permit auctions. This section presents a list of some, although certainly not all, of the more prominent design details that will ultimately need to be addressed.

- *Ties*: In Treasury security auctions, if there are multiple bids at the market-clearing price, those orders are filled on a *pro rata* basis. We agree with the recommendation of Holt et al. (2007), concerning the RGGI, that ties should be resolved by a random process to help guard against collusive bidding.

- *Public disclosure*: It is important to limit public disclosure, with exceptions for a monitoring body and potentially for academic research, but with appropriate guarantees for the privacy of the individual bidders. As mentioned earlier, such limited monitoring can reduce the potential for collusion; however, it also prevents public interest groups from monitoring corporate behavior that they deem to be in the public interest

- *Buyer qualifications*: Steps should be taken to ensure that winning bidders do not default on their bids. Such default has been a real problem in a number of auction markets. It can be deterred by requiring bidders to post a bond to qualify to bid.[20]

- *Anti-collusion rules*: All auction participants should be required to certify that they are not engaged in any type of coordination or collusion with other bidders.[21]

- *Experimental testing*: It can be valuable to conduct experimental testing of auction designs. This approach has been useful to government agencies such as the FCC as they have considered adjustments to their auction designs. With the exception of the EPA SO_2 auction, the auctions that have been used for selling emission allowances have been designed with the help of considerable experimental testing.

- *Market power*: There is an ongoing debate over the desirability of using spectrum caps in telecommunications to limit the market power of wireless telecommunications providers. It may be valuable to consider allowance caps if there are concerns that firms could use control of large numbers of allowances to limit competition. These concerns may be more salient in

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[20] See, e.g., the testimony of Robert D. Reischauer, Director, Congressional Budget Office, on Auctioning FCC Spectrum Licenses before the Committee on the Budget, U.S. House of Representatives, September 29, 1994 (available at http://www.cbo.gov/doc.cfm?index=4910&type=0, accessed May 4, 2010).

[21] For example, FCC rules prohibits bidders that are eligible to compete for the same licenses from communicating with each other during the auction about bids, bidding strategies, or settlements unless the nature of the relationship is declared to the commission.

regional markets than national ones, since the largest single emitters in the U.S. tend to be regionally concentrated electric power utilities.

- *Monitoring market conditions and managing supply*: It may be important for the market oversight body to take steps to manage expectations about future prices. For example, if expectations about prices for future vintages of allowances are not stable, there may be extreme fluctuations in the prices for current vintages as the demand for allowances that will be used for banking varies. One option for managing these risks would be to "jump start" the market by issuing some allowances of a variety of vintages for free. Trading of these allowances would then provide signals as to the relevant prices. Indeed, this feature has been the rule rather than the exception among U.S. auction proposals to date – with a majority of allowances given for free to emitters and a minority auctioned, but with the balance shifting more toward auctioning over time. Another, perhaps complementary, risk-management option would be to develop a schedule of supply increases associated with various price hurdles.[22] Under such a scheme, market prices above fixed hurdle levels for a set period of time would trigger the release of fixed numbers of additional allowances. Alternatively, additional discretion could be given to market authorities in the form of a strategic allowance reserve (Murray, Newell and Pizer 2009).[23]

[22] For example, under RGGI, regulated power plants may use CO_2 offset allowances to satisfy 3.3 percent of their CO2 compliance obligation, but this amount may be expanded to 5 percent and 10 percent if CO2 allowance prices reach thresholds of $7 and $10 per allowance, respectively. See http://www.rggi.org/docs/RGGI_Offsets_in_Brief.pdf, accessed July 24, 2010.

[23] Such a reserve was included in the Waxman-Markey cap-and-trade bill (HR 2454), which passed the U.S. House of Representatives in 2009. This strategic reserve is designed to contain prices between $10 and $21 per ton, via a "soft collar": a *fixed* supplement of allowances is triggered when the price exceeds the reserve price. However, there is no guarantee that prices will fall within the target range.

CONCLUSION

Auction design fundamentals, as well as the fine details, are of crucial importance for the success of a U.S. carbon allowance market. This article has evaluated the leading carbon allowance auction formats and has discussed some additional features that could address potential shortcomings of these auction designs.

Although there are still unanswered questions, we believe the existing evidence suggests that a uniform-price sealed-bid auction with a sensibly-chosen price collar is best-suited to auction CO_2 permits and is most likely to achieve the objectives of: (i) distributing the allowances efficiently; (ii) creating reliable price signals that can be useful for long-term planning and policy; and (iii) ensuring that prices are high enough to provide meaningful incentives to reduce emissions while low enough to avoid too much economic pain. We have emphasized that there is the *possibility* that such an auction could be vulnerable to collusive and/or the more troubling "collusive-seeming" bidding behavior, which would jeopardize the auction's ability to meet its first two objectives. Fortunately, it appears that this potential problem can be alleviated by augmenting the auction rules to encourage participation by both "speculators" and "environmentalists." Even if such bidders were to demand only a small fraction of the total supply of allowances being auctioned, their presence would disrupt large bidders' ability to coordinate and engage in collusive-seeming bidding.

The auction format recommended here can be included as a component of a national cap-and-trade program for the United States. However, regardless of which auction format is ultimately selected, it is essential to continually monitor and evaluate the auction's performance and to remain open to design changes that research and experience suggest would improve the auction's effectiveness.

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