Working Paper Series

No. 53

More on the dynamic Vickrey mechanism for multi-unit auctions: an experimental study on the emission permits initial auction

Anabela Botelho

Lígia M. Costa Pinto

Eduarda Fernandes

November 2013

Núcleo de Investigação em Microeconomia Aplicada

Universidade do Minho

Fundação para a Ciência e a Tecnologia

MINISTÉRIO DA EDUCAÇÃO E CIÊNCIA

More on the dynamic Vickrey mechanism for multi-unit auctions: an experimental study on the emission permits initial auction

Botelho, Anabela[a]; Pinto, Lígia M. Costa[b]; Fernandes, Eduarda[c]

[a,b,c] *NIMA, University of Minho, Braga, Portugal*

[a,b,c]NIMA, University of Minho
Address: Escola Economia e Gestao
Universidade do Minho, Gualtar
4710-057 Braga
Portugal
Emails: Botelho (botelho.anabela@gmail.com);
Fernandes (eduardafernandes6@gmail.com)

Pinto (ligiacpinto@gmail.com); (corresponding author)

More on the dynamic Vickrey mechanism for multi-unit auctions: an experimental study on the emission permits initial auction

The purpose of this paper is to contribute to the multiple-units auction literature, by testing the performance of the dynamic Vickrey auction (the Ausubel model), in an experimental setting, representing the functioning of an emission permits market with an Ausubel auction for the initial allocation of permits. Other features of the experiment include the possibility of banking and the inclusion of uncertainty, and the parameters were set so as to replicate an environment similar to the EU-ETS market.

Our results reveal that emission permits are not exactly allocated as theoretically predicted in the Ausubel auction although the differences are not statistically significant.

Comparison of our results with previous experimental studies on the same auction mechanism, although under very different conditions, indicate no relevant differences exist on the Ausubel auction performance, which is an important policy indication when decisions are being taken on the implementation of several auctions for multiple units, namely in the context of the EU-ETS.

Keywords: Multi-unit auctions; dynamic Vickrey (Ausubel) auction; emission permits; experiments.

Introduction

In contrast to the majority of the auctions experimentally tested in the literature that are single unit auctions, the CO_2 emission permits auction deals with multiple homogeneous units . This is a distinctive characteristic of CO_2 auctions and still remains a boundless field of investigation, as single unit auctions properties are not directly transposed to the multiple units' case.

Holt *et al.* (2007) report an extensive theoretical, empirical and experimental literature revision on this type of auctions. Moreover, these authors report their own results for a great number of experiments to test the performance of alternative auction mechanisms and support the decision adopted for the RGGI (*Regional Greenhouse Gas Initiative*). Holt *et al.* (2007) experiments' besides considering the particular case of a multiple unit auction also include the possibility of banking/ borrowing of the permits bought at the auction and a secondary market where those permits could be traded. These characteristics actually exist in implemented emission permit markets - as the EU ETS, for instance - and with a potential to influence participants' behavior at the auction, therefore its inclusion in the experimental design in order to make it valuable it is almost compulsory. From their experimental results, Holt *et al.* (2007) recommended the implementation of a static uniform price auction for the RGGI CO_2 emission permits auction.[1] Its simplicity, transparency and good allocation result were the basis for those authors recommendation. For the EU ETS, a study coordinated by Neuhoff and Matthes (2008) present a similar recommendation and the 2006 Ireland partial auction of CO_2 emission permits already implemented this format. In fact, sealed-bid uniform price

[1] Holt *et al.* (2007) experimentally tested five alternative auction formats for the RGGI: two static (unique and discriminative price auctions) and three dynamic (English, Dutch and Anglo-Dutch auctions). Price discovery, collusive behaviour avoidance, transparency, participants' comprehension, revenues and efficiency are some of the aspects considered for the different auction formats evaluation.

auctions are well known by regulated utilities in the EU ETS and, probably for that reason, it has been used by Ireland, Hungary and Lithuania in the first phase of the EU ETS.

However, these recommendations for the particular case of emission permits are opposed to multiple units' auction theory. Ausubel and Cramton (2002), for instance, demonstrate how inefficient unique price auctions are for the case of multiple units. As winning bids have a positive probability of affecting equilibrium price, participants have an incentive to reduce demand – and the larger dimension of participants is, the stronger and more profitable is this behaviour. Therefore, Ausubel and Cramton (2002) conclude that the simplicity and efficiency usually associated with this auction format are eliminated. Ausubel and Cramton (2002) compare this inefficiency to that of monopoly losses, as larger dimension subjects lose some units to the smaller, even if they have higher valuation for those units. List and Lucking-Reiley (2000) evidences' support this theoretical demand-reduction prediction for unique price auctions for multiple units, when compared to the Vickrey auction (Vickrey 1961). Furthermore, these authors collect evidence that show auction revenues are not significantly different in the two auction formats and for that reason, no trade-off exist between the Vickrey auction efficiency and the auctioneer revenues.

Considering Ausubel (2004) study and conclusions, the lack of consensus between theoretical recommendations and the empirical and experimental evidence about the best auction format to use under conditions similar to those of the EU ETS become even more acute. Ausubel (2004) recalls that existent multiple unit auctions do not respect two theoretical recommendations consensually agreed for single object auctions: 1) the need to guarantee an auction structure that allows winner paid price to be independent of the own winner's bid (the Vickrey auction); and 2) the use of an open format, in order to maximize the information available to participants, each moment a new proposal is made. English auctions are theoretically recommended for single objects precisely because they gather these two characteristics simultaneously, as pointed by McAfee and McMillan (1987) and Milgrom (1987), for instance. Ausubel (2004) successfully builds a model for homogenous multiple unit auctions that include those characteristics, therefore equivalent to the Vickrey auction but simpler to understand and administrate. This auction format even eliminates the problem identified under the Vickrey auction with reserve prices of having identical goods sold at different prices (Ausubel and Cramton (2004)). The efficiency of Ausubel (2004) auction format is not achieved with the biggest market participants buying the cheapest units in the market proposal, as happened under Ausubel and Cramton (2004) proposal, which additionally makes this model politically more acceptable and easily adopted. Hence, the Ausubel (2004) format seems the most theoretically adequate model to use in the case of an auction for the initial allocation of emission permits in general, and for the EU ETS in particular.

Although other previous experiments have tested the performance of the Ausubel auction, they all considered a very simplified environment, with few participants and few units being offered at the auction. That was the case, for instance, of Kagel and Levin (2001 and 2009), Engelmann and Grimm (2004), and Manelli *et al.* (2006). In addition, none of them, however, parallel the EU ETS structure, which justified our decision to experimentally test the use of the Ausubel (2004) auction within a different experimental design.

Our methodological choice to test the performance of the Ausubel (2004) auction for the specific case of the initial allocation of emission permits is based on the experiments' capacity to model each mechanism's structure, therefore, being the “cleanest” way of testing its performance, as Whitford (2007) labels them. Botelho *et al.* (2011) report the results of two experimental treatments, which aimed to test and compare the performance of a market institution similar to that of the EU ETS with a 100% auction versus a 100% free allocation of CO_2 permits. The current paper elaborates on the first stage of the 100% auction treatment reported in Botelho *et al.* (2011), which consisted of an Ausubel auction for the initial allocation of CO_2 emission permits. With this analysis we intend to contribute with additional knowledge about the performance of the Ausubel auction, and verify the sensibility of problems like overbidding behavior or demand reduction, previously identified on some of the other experimental studies by the authors just mentioned, to the parameters and experimental design used.

Our main finding is that there are no relevant differences between the Ausubel auction performance (with respect to prices, efficiency and revenues)when implemented under very complex conditions and when implemented in previously tested simpler laboratory experiments, which is an important policy indication when decisions are being taken on the implementation of several auctions for multiple units - namely, on the EU ETS.

The paper is organized as follows. In the next section, we describe the institutional rules of the experimental design implemented, with particular focus on the Ausubel (2004) auction format. Section 3 presents and discusses the experimental results and provides some comparisons with previous studies. Section 4 concludes discussing our main findings and pointing out some questions for future research.

Experimental setting

The experimental setting implemented to represent a CO_2 emission permits market which paralleled the EU ETS, as much as possible, and tested the performance of the Ausubel (2004) auction for permits initial allocation.[2] The experiment consists of the six stages below, which were repeated 10 times in each session - corresponding to the fixed number of periods for the market to function in each session:

Stage 1: Auction for initial emission permits allocation.

Stage 2: Banking decision concerning permits bought at the auction.

Stage 3: Re-sale (secondary) market.

Stage 4: Random fluctuation on emissions (Uncertainty stage).

Stage 5: Reconciliation market.

Stage 6: Possibility for re-banking decisions.

In addition to these tasks, subjects completed a risk elicitation task (in the vain of Holt and Laury (2002)) at the start of the experiment and a socio-demographic survey at the end. The institutional rules of these stages are next described though stage 1 in more detail. Used for the initial allocation of CO_2 emission permits, the auction is only one part of the institution represented – although the central part, in what concerns the present paper. The other stages of the market institution implemented in our experimental design are briefly described, as they might influence our auction allocation outcome.

[2] The experimental sessions run for this treatment occurred in May 2009 at Minho University, with Economics undergraduate students and were programmed in Ztree (Fishbacher (2007)).

The Ausubel auction

The first part of our experimental market for CO_2 emission permits reported in Botelho *et al.* (2011) as the 100% auctioning treatment was the Ausubel (2004) auction (or dynamic Vickrey model). This may be considered an example of a microeconomic system as defined by Smith (1982), constituted by a specific environment and institution. Our *microeconomic environment* consisted of the characteristics of eight participants $e = (e^1, \ldots, e^8)$, which could not be changed neither by the agents nor by the institutions where those interacted. This means vector $e^i = (u^i, T^i, \omega^i)$ characterized each subject i, with utility function u^i, for a specific technology T^i and a vector concerning the initial endowment of goods ω^i. Therefore, $\underline{e}$ constitutes a set of control variables fixed by the investigator. These were derived from different marginal abatement cost curves, corresponding to different productive/abatement technologies, representing the higher polluter countries of the EU-15. A private value setting was then represented, with subjects' valuation for each emission permit not being affected by the information of the other participants. Table A.1 of the Appendix presents parameters for the vector $e^i = (u^i, T^i, \omega^i)$.[3]

The *institution* $I^i = (M^i, h^i(m), c^i(m), g^i(t_0, t, T))$ of our microeconomic system ($S = (e, I)$), according to Smith (1982) nomenclature, defines each agent i property rights on communication and transactions, including de definition of messages he is allowed to send (M^i); each agent allocation rules as a function of messages previously sent ($h^i(m)$); cost imputation rules ($c^i(m)$); and, finally, the process adjustment rules $g^i(t_0, t, T)$, that includes a rule for the beginning $g^i(t_0, ., .)$, the sequence $g^i(., t, .)$ and the end of the exchange of messages $g^i(., ., T)$, as we next describe.

[3] For more details about the parameters used see Botelho *et al.* (2011).

At the beginning of each of the 10 periods of our experimental sessions, the auctioneer announces a relatively low first price (99 points). Auctioneer maximum price proposed (1319) was strictly higher than the highest marginal abatement cost of all subjects, therefore, strictly higher than the maximum valuation any participant could give to an auctioned emission permit (1301). Therefore, Ausubel's condition of non restrictive prices was respected, and last moment (*T*) was non-binding.

The discrete version, with incomplete information, of the Ausubel (2004) auction was implemented, with a price $p^t = t$ being announced by the auctioneer at each moment $t = 0, 1, 2, \ldots, T$ and subjects submitting the x_i quantities they wanted to buy at each price. At each moment $t = 0, 1, 2, \ldots, T$ the auctioneer verifies if $\sum_{i=1}^{n} x_i^t \leq M$ and only when that happens, current period t is considered the last of the auction, $L=t$. At that moment each subject i receives quantity x_i^* that respects conditions $x_i^L \leq x_i^* \leq x_i^{L-1}$ and $\sum_{i=1}^{n} x_i^* = M$. As long as excess demand is found and $t < T$ the auction proceeds to period $t+1$, with price p^{t+1} (a 20 points addition is made to the previous price) and the process is repeated. Therefore, an increasing price, after all bids are made, indicates there is still excess demand on the auction.

The number of units subjects acquire, $\{C_i^t\}_{i=1}^{n}$ are defined at any moment t according to Ausubel (2004):

(1) $C_i^t = \max\left\{0, M - \sum_{j \neq i} x_j^t\right\}$ for any $t=0,\ldots, L-1$ and $i=1,\ldots,n$

In the last period of the auction, *L*, this vector corresponds to:

(2) $C_i^L = x_i^*$, with x_i^* the final quantity of permits bought by subject *i*.

The vector of acquired ("clinched") units on current period *t*, $\left\{c_i^t\right\}_{i=1}^n$, corresponds to the difference between the quantity accumulated at moment *t* and moment *t-1*:

(3) $c_i^t = C_i^t - C_i^{t-1}$, with $t=1,\ldots,L$ and $c_i^0 = C_i^0$ for any $i=1,\ldots,n$

Our application is a dynamic multiple unit auction, with one seller allocating $M=88$ units of an homogeneous good to 8 buyers $N=\{1,\ \ldots,\ 8\}$. Each buyer *i* may be given any x_i quantity of the good (CO_2 emission permits, in this case), as long as $\sum_{i=1}^n x_i \leq M$. Buyer *i* utility for x_i equals the difference between its private value $U_i(x_i)$ and total payment y_i that he is obliged to do: $U_i(x_i)$- y_i. Although the Ausubel dynamic auction is possible to implement under different informational conditions, each buyer's (decreasing) marginal utility function is private information in our experimental design. Additionally, while the auction is open, no information is given about the amount of units still available nor about the number of units each participant already acquired (*clinched* units). The only (private) information released during the auction is the number of profitable units at each new price.

Our experimental design imposed a restriction on subjects' proposals/ bids at the auction: participants could bid more units than those needed – and therefore, have no value to them ($U_i(x_i)=0$) – but may not bid the total number of units offered in the auction ($x_i < 88$). The maximum number of units each subject could bid at the auction (x_i^t) was determined accordingly to the following budget restriction: $x_i^t = \frac{x_i^{activity} * p_{eq}}{p^0}$, with p^0=99 being the first price proposed by the auctioneer and p_{eq}=139 the equilibrium price of the Ausubel auction in the first period of our sessions. On the other hand, $x_i^{activity}$ corresponds to the number of units with positive value ($U_i(x_i)>0$), i.e., the number of units each subject needs to abate. If a participant buys more units than the ones he needs for the current period, $x_i^t > x_i > x_i^{activity}$, $x_i - x_i^{activity}$ units are automatically banked for the next period.[4]

The rules for the sequence of messages while the auction was open, $g^i(., t, .)$, included the above budget constraint and two other rules defined by Ausubel (2004):

(4) $x_i^t \leq x^{t-1}$, $\forall i = 1,\ldots,n$ and $\forall t = 1,\ldots,T$.

(5) $x_i^t \geq C_i^{t-1}$ for any $i=1,\ldots,n$ and $t=1,\ldots,T$.

Condition (4) corresponds to the monotonicity rule. That is to say, at each moment t bidders could not bid more than at the previous moment. On the other hand, bids at any moment t could not be less than the clinched units at the previous price (condition (5)).

The verification of one of the following conditions was the stopping rule, $g^i(.,.,T)$, of our auction:

(i) Auctioneer price reaches 1319;

(ii) Distribution of the total amount of units available at the auction ($\sum_{i=1}^{n} x_i = M$);

(iii) The price reached is such that $\sum_{i=1}^{n} x_i < M$.

[4] This may be considered a restrictive rule to subjects' behavior but it turned out to be non-binding. Only Subject 2 at Auction 1 session, in one period, bought more than the necessary permits. Additionally, this rule was included in the zTree programme but it was not explicitly included in the experimental instructions given to the participants - they were only told the maximum amount of units they could bid each period at the auction ($x_i^t > x_i^{activity}$).

When the auction closes each buyer is informed of the (own) amount of units bought and at what prices – as well as their total earnings in the auction.

The allocation rule of the auctioned units between each subject i $(h^i(m))$ are those defined in Ausubel (2004), and reproduced in equations (1) to (3). As it is clear from those rules, each subject's allocation depends on other participants' messages, not on his/her own messages. At each price p^t and for each buyer i, the auctioneer determines the residual demand (the sum of other subjects' quantity demand, excluding its own: $\sum_{j\neq i} x_j^t$), that is then compared with total supply, $M=88$. For any participant with $\sum_{j\neq i} x_j^t < 88$, the auctioneer allocates $M - \sum_{j\neq i} x_j^t$ units.

For the case when the stopping rule consisted of that pointed on (iii), *ie*, price is such that total demand is less than total supply, a *rationing rule,* was introduced in our experimental design. The use of this rule guarantees the allocation of the 88 units available, as predicted in the Ausubel (2004) theoretical model, respects the monotonicity rule and the allocation of the units already clinched at previous prices. This rule, similar to that of Mochón *et al.* (2005), starts identifying, for the price immediately before to the one that caused excess supply (therefore, a price where excess demand still existed), the subject with the higher non-satisfied bids. One bided unit is automatically withdrawn from this subject and total demand re-calculated. If demand is still higher than supply, the procedure continues by identifying the next subject with higher bids not yet acquired. Only when demand equals supply is this process stopped and the auctioneer allocates the emission permits according to the rules previously specified, bidders are informed of how many units they bought, at what prices and their respective earnings.[5]

[5] Although not for the Ausubel auction format, Burtraw *et al*. (2011) implemented a somewhat similar rule to deal with the possibility of unsold units in the last round.

Obviously, if total supply exceeds total demand at the first price the auctioneer proposes, some units will not be allocated. The rule we defined for these situations was that emission permits not allocated should be cancelled, which means that these permits are not carried forward to next periods within the session. In other words, if $\sum_{i=1}^{n} x_i < M$ at moment 0, each bidder would be allocated the number of units (x_i^0) submitted at the initial price, p^0. The $M - \sum_{i=1}^{n} x_i$ permits not sold would be canceled and a more restrictive than planned environmental target is achieved at the current period - and, as a consequence, total abatement costs are higher than predicted. This rule has no connection with the Ausubel (2004) model as the author mentions nothing about this possibility. On this topic, we found Holt *et al.* (2007) reflection on the alternatives for the non-allocated permits at an auction: *(i)* cancelling; *(ii)* future periods use; *(iii)* and contingency banking. These authors pointed out that all the options have advantages and disadvantages but recommend the cancelling of non-sold permits at the auction, particularly for recently created emission permits markets, with loose caps (which was the case for the EU ETS, at least in its first phases).

Finally, the cost imputation rule $(c_i(m))$ used in the auction implemented – according to Smith (1982) nomenclature - was as follows. At the end of the auction each bidder pays the total amount of units acquired at each of the clinching prices: $y_i = \sum p^t c^t_i$, with c^t_i the number of units bought by subject i at price p^t. Total earnings of each subject were determined through the difference $U_i(x_i)$-y_i.

The experiment included other tasks such as banking, uncertainty and a reconciliation market, however as the results of these tasks are not the object of the present paper we abstain from explaining each in detail.[6] It should however be noted

[6] A detailed description of the tasks can be found in Botelho et al. (2011).

that the presence of uncertainty coupled with the possibility of banking may change the behavior in the initial allocation Ausubel auction. Uncertainty about effective emissions abatement was included in our experimental design,[7] which means that the exact amount of emission permits each participant would need during the experimental session was also uncertain.

In this stage, each subject was informed about random variation on emissions drawn from a uniform distribution over the values (-1, 0, +1), following Godby *et al.* (1997) procedure, which means each period maximum noncompliance (or surplus) would be of one emission permit. At this point, information about consequences of these random variations for participants' earnings in the period, as well as possible ways to minimize losses or even make profits was also given.

Emission permits' price volatility and noncompliance were the main consequences of this stage. As a severe penalty for noncompliance was introduced,[8] the use of banked units emerges as a possibility to avoid this loss – on the last stage of each period. If the subjects did not bank any unit before (or did but intend to keep it for future periods), they might still try to obtain the necessary emission permit in the secondary market that opens after this uncertainty stage.

Subjects' banking behavior is expected to differ according to their attitudes towards risk. Risk neutral and risk averse subjects should bank one permit during the entire session, as a precaution against the possibility of a bad draw in the uncertainty stage (Stage 4 on each period of the session), while risk lover subjects are not expected

[7] Measurement errors, unpredicted factors that influence the availability of resources like energy or different kind of fuels, which represent, at the end, more or less pollution than planned at the beginning, are just some examples that justify this uncertainty.

[8] Similarly to article 16º of 2003/87/EC Directive, besides a monetary penalty – that we established as being an amount about four times the emission permits equilibrium price -, subjects were obliged to deliver one emission permit more on the period after being noncompliant.

to bank (at least for precautionary reasons). Following Godby *et al.* (1997) terminology, computed benchmarks for the first case were called *Market Equilibrium Benchmark* and for the second, *System Equilibrium Benchmark*.

The banking decision may impact on the next period initial auction: if emission permits are saved in the current period, it may imply less units being demanded at the auction, with consequences for the equilibrium price. Although a possible consequence of banking it is not a compulsory one under our experimental set as subjects may bid exactly the same units as if they decided not to bank at all. After the resolution of uncertainty, subjects could use a reconciliation market to sell surpluses or compensate deficits. After this stage subjects could again revise their banking decisions.

Each of our experimental sessions repeated the laboratorial market, consisting of the six stages just described, for 10 periods. Reduction of total abatement costs was each participant's objective, which corresponded directly into earnings, in lab points that were converted to Euro and paid individually at the end of the session.

Although constituted by several parts other than the initial auction, the next section will focus on this stage. However, the description just made for the other stages of our experiments may not be considered extemporary as those stages might influence the auction results or enlighten us about them. Moreover, subjects' behavior at the auction may be influenced for what happens on the other stages, therefore the analysis need to take that into account.

Results

Botelho et al (2011) analyzing the same data conclude that participants were mainly risk averse.[9] However, this attitude towards risk was not related to the specific characteristics of the subjects that constituted our sample. Additionally, both the non

[9] From the total 24 subjects participating in our experimental sessions only 1 was classified as risk lover.

parametric tests and the maximum likelihood estimates of the hurdle model of banking decisions revealed no association between subjects' risk preferences and their banking level, contrarily to what we theoretically expected, based on Godby *et al.* (1997).[10]

As the study of the Ausubel auction performance for the initial allocation of emission permits is the main goal of the current paper, we will now go through the results of the first stage of our experimental setting with some detail.

Effects on 1st Stage Prices

We start looking at auction closing prices registered in our three experimental sessions (Auction 1, 2 and 3)and compare them with the theoretical benchmarks. Note that we consider the auction closing price to be the last (and highest) price paid for the emission permits bought at the auction. This means that when the *rationing rule* is applied the auction closing price does not correspond to the price called by the auctioneer at the last round of the session but to the price called on the round immediately before (as previously explained, section 2.1).

Figure 1 represents both the theoretical benchmarks and the observed auction closing prices, averaged for the three experimental sessions run. [11] As it becomes clear, the session average auction closing prices are below our theoretical benchmarks, except for period 5 and 10, which, respectively, are slightly above and exactly correspond to the theoretical predictions. These differences between observed mean auction closing

[10] See Botelho *et al.* (2011) for more details on banking results and its statistical analysis.

[11] The *Market* and the *System Equilibrium benchmark* auction closing prices differ only on the last period of the session as we suppose subjects holding one emission permit at this point (due to precautionary reasons) reduce demand on the auction. The market equilibrium is the optimal path for risk neutral and averse subjects; the system equilibrium is the optimal path for risk loving subjects.

prices and our theoretical benchmarks are statistically significant for the usual levels of confidence (z=2.728; p=0.0064 and z=2.572; p=0.0101, respectively, for the *System* and *Market* benchmarks).

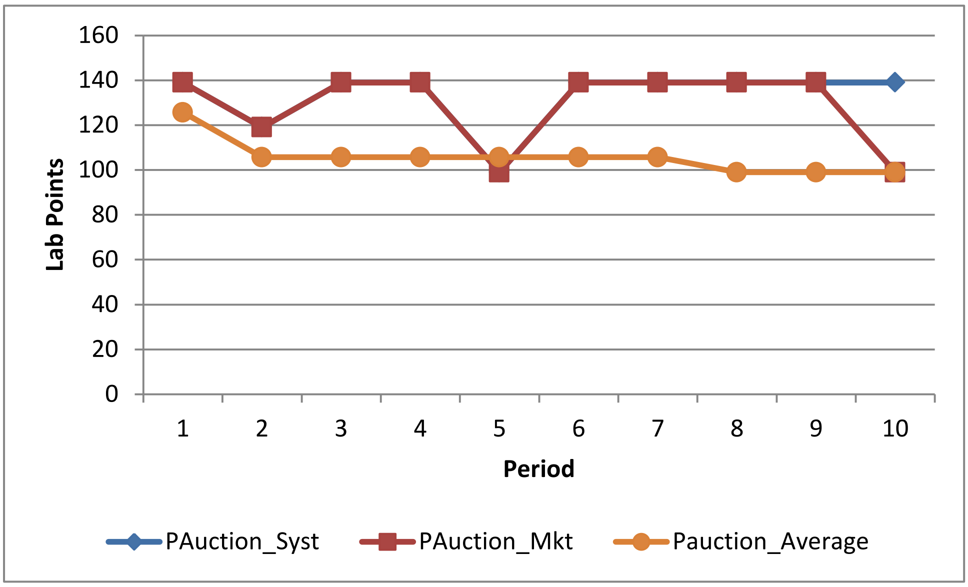

Figure 1 - Observed average auction closing prices and *System Optimum* and *Market Equilibrium benchmarks*

Effects on 1st Stage Revenues

Every auction, for the three sessions, closed with all (88) emission permits sold and, although with prices statistically different from the theoretical benchmarks, all sessions registered a value of about 90% of the potential revenue for the Ausubel auction (with values for Auction 2 around 95%), as shown by Figure 2. Considering *System Optimum* and *Market Equilibrium* references, on average, the three sessions attained 90,8% and 92% of the potential revenues, respectively.

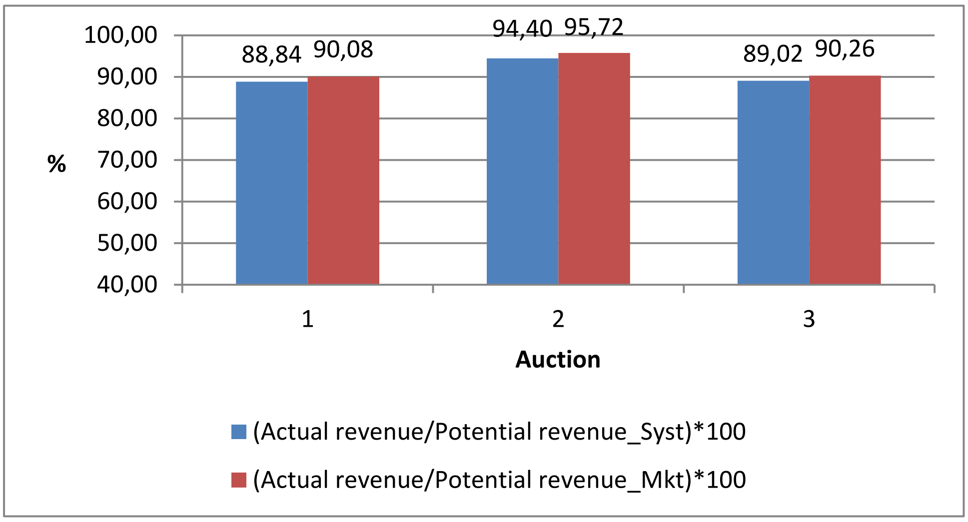

Figure 2 - Ratio between realized auction revenue, in each session, and potential revenue for *System Optimum* and *Market Equilibrium benchmarks*

Effects of 1st Stage Efficiency

More importantly, however, are the results concerning the efficiency of the implemented auction, ie, the CO_2 emission permits allocation between the different subjects (polluters/ emitters) and the consequent amount of abatement costs. As we can see In Table 1 and Figure 3, abatement costs are higher than our theoretical benchmarks, and this is statistically different according to the Wilcoxon nonparametric test. Auction 1 and 2 register an efficiency level relatively closer to the theoretically predicted for the Ausubel auction (about 12% and 7% more than the theoretical references, respectively) but, on average, the three sessions registered only an 85,3% and 85,6% efficiency level, considering *System Optimum* and *Market Equilibrium* references, respectively - which is a lower value than found in previous studies on this auction format, as next presented in Table 3.

Table 1 – Auction abatement cost benchmarks and observed values

	Abatement Cost Benchmarks		Observed Abatement Cost		
Period	*System*	Market	Auction 1	Auction 2	Auction 3
1	2288	2288	2457	2286	2403
2	2313	2324	2659	2328	4143
3	2288	2288	3121	2299	4143
4	2288	2288	2389	2299	2432
5	2390	2390	2377	2298	3617
6	2288	2288	2587	2299	2582
7	2288	2288	2831	2489	3005
8	2288	2288	2394	2748	2831
9	2288	2288	2599	2526	2389
10	2288	2360	2389	3074	2916
Total	23007	23090	25803	24646	30461

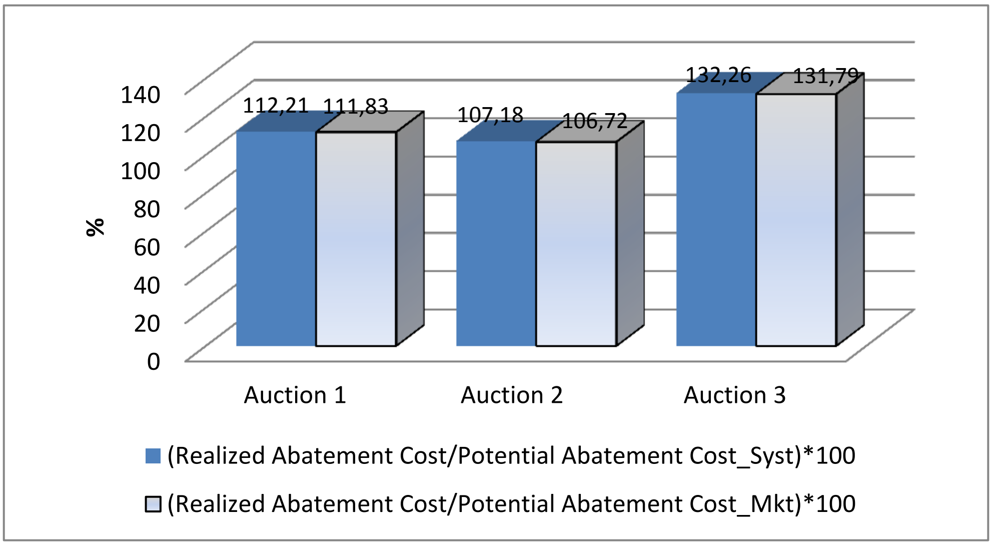

Figure 3 – Ratio between abatement costs after closing auction, in each session, and potential abatement costs for *System Optimum* and *Market Equilibrium* benchmarks

Differences between the realized and potential abatement costs must be explained by emission permits allocation that resulted from the auction, in each session. In fact, an auction performance indicator is precisely its allocation of emission permits among subjects, as an efficient auction model would award emission allowances to those subjects who value them the most (i.e., subjects with higher marginal abatement costs). Table 2 shows that, considering the results of the three experimental sessions, all the available units for sale at the auction were in fact sold but no exact correspondence exists between predicted allocations by subject type and those observed averaged over the 10 auction periods. Nonetheless, based on the nonparametric Mann-Whitney test we conclude that observed differences are not statistically significant, which means we cannot exclude the hypothesis that the implemented auction produces the sincere bids predicted.

Table 2 – Predicted and observed permit allocation in the Ausubel auction

	Subject Type								
	S1	**S2**	**S3**	**S4**	**S5**	**S6**	**S7**	**S8**	**Total**
System benchmark	4.9	10.8	15.2	4.0	15.0	15.9	16.1	6.1	88.0
Market benchmark	4.9	10.7	15.4	3.9	15.1	15.8	16.1	6.1	88.0
Observed	4.5	9.5	16.5	3.5	15.2	15.7	16.7	6.4	88.0

Note: Predicted outcomes are the averaged values of Table A.2 in the Appendix, over the 10 auction periods. For the observed permit allocation the same procedure was used: the average over the three sessions and 10 periods was calculated.

As Engelmann and Grimm (2004) point out, however, measuring efficiency in this way ignores the actual magnitude of potential efficiency losses due to misallocations. As those authors highlight, to allocate one unit to the "wrong" bidder may either cause huge or insignificant welfare losses, respectively, when his valuation is substantially or just slightly below the other bidders' valuation. Our biggest participants in the auction (S3 and S7), with lower marginal valuations, were allocated more than the efficient number of units while, on the contrary, participants with higher marginal abatement costs (like S1, S2 or S4, for instance) were allocated less than the efficient number of units. This misallocation is thus reflected on the ratio between realized abatement costs at the end of each auction and potential abatement costs even if, overall, we cannot exclude the implemented auction produced sincere bids.

Considering our experimental results for the efficiency and revenues of the implemented auction we might find evidence about the often voiced argument, at least for some auction formats, on the existence of some tradeoff between the auction revenues and the efficiency level obtained. In fact, taking the overall results of the experiment, realized revenues were considerably high but the same did not occur in terms of the efficiency observed for the implemented auction. However, our goal was to test the Ausubel auction format for the initial allocation of CO_2 emission permits under a very complex experimental setting, which included, among other stages, a secondary market for CO_2 emission permits re-sale. At that stage, as reported on Botelho *et al.* (2011), some allocation corrections effectively occurred, which resulted in a very efficient institution for a CO_2 emission permits market, with the inherent positive consequences on CO_2 emissions total abatement costs.

Based on the nonparametric Mann-Whitney test applied to per period means, for the conventional significance levels, we concluded that per period mean abatement costs are not statistically different from either the *System* or the *Market* benchmarks, *when considering the entire six stages of the market*. That is to say, that if we refer to abatement costs resultant of all the stages/ decisions taken each period of the session, including not only the auction allocation but also banking, secondary market participation, uncertainty resolution, reconciliation market participation and, finally, the re-banking decision, values are different from the ones reported In Table 1 and Figure 3 - which respect only to the abatement costs resultant from the emission permits allocation at the end of stage 1 of each period. Therefore, the utmost objective of the market institution represented is achieved: total abatement costs under an experimental setting mimicking the EU ETS that uses the Ausubel auction for the initial allocation of permits are minimized. Additionally, windfall profits resultant from the grandfathering of permits are avoided and, on the contrary, significant auction revenues are realized, which can be used to minimize pollution impacts.

Comparison with previous experimental results

Although not for the particular case of pollutants emission permits, Kagel and Levin (2001 and 2009), Engelmann and Grimm (2004) and Manelli *et al.* (2006) also experimentally tested the Ausubel (2004) auction format. Their results concerning the auction efficiency and revenues differed from each other, as we can see iIn Table 3. However, no clear evidence for the efficiency/revenue tradeoff argument can be identified from their values either, even if our experimental results concerning the Ausubel auction efficiency are clearly the lowest obtained - but close to those of Manelli *et al.* (2006). Our results for the auctioneer revenues' cannot be considered unsatisfactory, as actual average auction revenues are about 91% (92%) of potential auction revenues for the system (market) benchmark, which is quite high, even when compared with the previous experimental studies for the Ausubel (2004) auction, as shown in Table 3.

Table 3 – Comparisons of Ausubel (2004) auction results' in different experimental studies

	Botelho *et al* (2011)	**Manelli *et al* (2006)**	**Kagel & Levin (2001)**	**Engelman & Grimm (2004)**	**Kagel & Levin (2009)**	**Kagel & Levin*[12] (2009)**
Efficiency	0.853 (0.856)	0.871	0.9926	0.956	0.9863	0.9663
Seller Revenue	90.76 (92.02) (percentage of potential revenue)	52.2 (percentage of potential revenue)	100.25 (percentage of potential revenue)	84.74 (percentage of potential revenue)	-0.191 (difference from sincere bidding)	-1.717 (difference from sincere bidding)

Note 1: Results under Botelho *et al* (2011) report the *System Optimum* benchmark case and in parentheses the *Market Equilibrium* results.

Note 2: For Kagel and Levin (2001) we report their pooled results, concerning the number of computer rivals (one session with 3 and other with 5).

Note 3: Efficiency reported for Engelmann and Grimm (2004) consist of what the authors called *Relative efficiency* (the total welfare relative to the maximum possible welfare).

Note 4: Results reported for Kagel and Levin (2009), under both informational conditions, consist of the average results of the 3 sub-periods of their experiments (1-12; 13-24; and 25-36), where supply goes from 2 to 3 and again to 2 units.

Efficiency results obtained from Manelli *et al.* (2006) led them to conclude that sincere bidding transparency of English auctions for private value single units it is not a common characteristic for similar auction formats for the multiple units' case. These authors claimed participants do not reveal the true value for each unit but bided too high (overbidding behavior) however their conclusions are not corroborated by the other experimental studies mentioned in Table 3.

12 Kagel & Levin* (2009) stands for the experimental results of the Ausubel auction without drop-out information, which are also the informational conditions under our experimental treatment. Kagel & Levin (2009) refer to those authors results' when the full bid information Ausubel auction is implemented.

Although with similar goals, these studies present some differences in the experimental design, which may justify their results' divergence. Table 4 summarize the main characteristics of the experimental studies that we report on the Ausubel (2004) auction, as well as our own.[13]

Table 4 – Characteristics of some Ausubel (2004) auction experimental studies

	Botelho *et al* (2011)	**Manelli *et al* (2006)**	**Kagel & Levin (2001)**	**Engelman & Grimm (2004)**	**Kagel & Levin (2009)**
Informational rules	- No bid information.	- Aggregate bid information (full information but without disclosing the identity of the bidders).	- Full bid information.	- Full bid information (as there were only 2 participants in the auction).	- Two different experimental treatments: one with full bid information and other without.
Number of bidders in the auction	8 (invariant)	3 (invariant). Participant A, B, C	1 human participant + 3 or 5 (variant) computer rivals	2	4 (invariant)
Number of units sold (supply)	88	3	2	2	Either 2 or 3 (2 per period 1-12 3 per period 13-24 2 per period 25-36)
Individual's demand)	Dependent on the subject type (different for all the 8 participants) and period (according to banking decisions and penalties for	2 units	- 1 unit (computer bidders') - 2 units (human participants).	2	2

[13] Although some of these authors test the Ausubel auction for the private and common value case (as well as other auction formats), Table 4 refers only to the game of incomplete information (privately known marginal value function), as it is the only case we experimentally tested.

	Botelho *et al* (2011)	Manelli *et al* (2006)	Kagel & Levin (2001)	Engelman & Grimm (2004)	Kagel & Levin (2009)
	incompliance).				
Units' marginal valuation during the session	The same in all auctions.	Valuations for bidders A, B and C unchanged during the session. But participants changed roles at the beginning of every auction.	New random valuations at the beginning of each auction (both for human and computer bidders).	New random valuations at the beginning of each auction.	New random valuations at the beginning of each auction.
Overbidding possibility	YES	YES (and even buy all the available units at the auction).	YES	YES	YES
Procedure in the case of excess supply	*Rationing rule* mechanism that guaranteed all available units at the auction were allocated.	Auction closed with unassigned units not being allocated.	n.a.	n.a.	Parameters chosen eliminated potential excess supply problems.
Number of auctions	10	20	27	10	36
Re-sale after auction	YES	NO	NO	NO	NO
Intertemporal connection between rounds	YES[(a)]	NO	NO	NO	NO

(a) Due to the possibility of banking and the penalty structure implemented for incompliance, which resulted in different demand schedules at each auction

As we can see from Table 4, our experimental design is the one who provides the bidders at the auction with less information. That does not prevent us from obtaining efficiency results similar those obtained under richer informational experimental settings, as it is the case of Manelli *et al.* (2006) study. This seems to show that informational conditions are not determinants for the outcome of this auction model, contrarily to Kagel and Levin's (2009) conclusion on the importance of the feedback information for the superior performance of the Ausubel auction (in addition to the dynamic format characteristic).

If for the informational rules,our experiment appears as the simplest one of the reported above, the same does not happen for the rest of the items. The number of participants in our auction is higher and the number of units being sold is considerably larger than any in other experiment referred. This last aspect is particularly distinctive from all the previous experiments on the Ausubel auction, as usually there were only 3 units being sold and we auctioned a total of 88 units (representing emission permits). Adding also different individual demands for all the participants in the auction, due to its different dimension and cost structures, we definitely represented an experimental setting closer to several real life situations than the previous studies did.

All the experimental sets for the Ausubel auction allowed for non-profitable transactions, as signaled in Table 4 under the item " Overbidding Possibility", but only Manelli *et al.* (2006) allowed for the acquisition of the total amount of units auctioned (three), even if participants' valuations were only for two units. Although our experimental design included a restriction that did not allow subjects to buy the 88 units available at the auction ($xi<88$), participants could bid more units than those they need – and with no value to them ($Ui(xi)=0$) – as long as respecting the budget restriction rule imposed ($x_i^t = \frac{x_i^{activity} * p_{eq}}{p^0}$).This condition imposed in our experimental design is an intermediate situation between Kagel and Levin (2001) and Manelli *et al.* (2006) designs. [14]

Precisely because some participants used the possibility of buying all units available at the auction, an efficiency loss was registered by Manelli *et al.* (2006). With only three units being auctioned among three participants, an aggressive bidding behavior from one subject prevented her/his competitors to have access to any unit of the good being sold. This strategic behavior may not be considered too risky as the "only" negative consequence, if successfully buying all the units available for sale, would be the loss associated with the price paid for the third (worthless) unit. However, Manelli *et al.* (2006) consider this to be a much harder and risky behavior to use within an experimental setting with a higher number of units being auctioned. Precisely, in our experimental design it was too risky and expensive to use such a strategy (of bidding for the 88 available units!), therefore we would not expect our risk adverse participants to use such an extreme strategy - and our results show they effectively did not. Manelli *et al.* (2006) did not characterize subjects participating in their experiments concerning their risk attitudes so we cannot exclude this as a potential explanation for the different strategies observed. However, we tend to rather believe parameters are the key behind subjects' different behavior and agree with Manelli's *et al.* (2006) conjecture concerning their results' robustness/sensibility to the number of participants and units being auctioned.

Although our efficiency results are close to those of Manelli *et al.* (2006), as shown In Table 3, and some similarities may be found with our experimental design - for instance, the authors maintain units' marginal valuation during the session (although

[14] This budget restriction did not reveal to be binding in our experimental setting and was set in motion only for participant S2 in Auction 1.

subject's role is randomly changed during the session) -, it is clear from Table 4 that significant differences exist. Namely, under Manelli *et al.* (2006) experimental set, bidding for the third unit at the auction was worthless to the subjects because they had valuation for only two units but under our experiments bidding for more units than needed (units with zero marginal value) was not necessarily worthless for subjects because of the existence of a secondary market and the possibility of banking. In fact, within our experimental set, subjects could expect to use the "worthless" units to influence the resale market outcome, either in the current period or on the following ones (by using the possibility of banking). However, overbidding behavior was not present in our sessions, except in Auction 1 by a single subject.[15] This was, however, an outlier result in our experiments.

Therefore, even if *a priori* we could identify in our experimental design additional "incentives" to overbid at the auction stage, our results do not confirm the existence of such a problem for the experimental Ausubel auction implemented. If Manelli's *et al.* (2006) low efficiency results were due to overbidding behavior that was not the reason for the misallocation of emission permits registered in our experimental sessions.

A different type of problem, a demand reduction behavior by submitting extremely low bids, was pointed by Engelman and Grimm (2004) and registered also in some of our auctions.However, demand reduction registered within our experimental design might be associated with the existence of additional stages during the session, particularly, the possibility of banking. This intertemporal connection between rounds

[15] Subject 2 overbid 5 units on period 3 and 1 unit on periods 6 and 8. On period 3, besides buying 5 units at a loss at the auction closing price, Subject 2 bought a total of 16 emission permits at the auction, when its total pollutant emissions for the period were of only 13 - therefore, buying 3 more units than necessary ($x_i > x_i^{activity}$).

introduced by the possibility of banking, as well as the existence of a re-sale market for the permits bought at the auction, add new and different explanations to the demand reduction behavior, in comparison to that of Engelman and Grimm (2004), for instance. Effectively, we found this connection between subject's demand reduction in the auction and their banking decisions for more than one unit in previous periods. [16] Namely, in our auction 3 session', subject 2 submitted reduced bids on 6 out of 10 periods, in comparison to those that would be profitable, which therefore characterized as a demand reduction behavior. Additionally, we saw this same subject banking more than one unit on the periods before his demand reduction on the auction. Session results' suffered as a consequence of this demand reduction because subjects with the lowest marginal costs were allocated more units than optimal. This behavior helps explaining the poorest results of Auction 3 in terms of efficiency, as it was clear at Figure 3, where that session appeared as the one with the highest ratio between abatement costs after closing auction and potential abatement costs.

Conclusion

Experiments used to test the performance of the dynamic Vickrey mechanism for multi-unit auctions - the Ausubel (2004) model -, either by Engelman and Grimm (2004), Manelli *et al.* (2006), Kagel and Levin (2001 and 2009) or our own, differ on the experimental setting employed. Although different, the previous experiments on the Ausubel auction presented more similarities with each other than did ours. For instance, on all the previous experimental studies reported, the number of units supplied and demanded at the auction, as well as the number of bidders, is very reduced and inferior to those we included in our experiments. However, in comparison with those studies,

[16] Risk aversion may not be pointed as a possible explanation for such a behavior because even for risk adverse subjects' optimal banking behavior consists in keeping only one unit during the entire session.

the major difference of our experiment is the fact of analyzing the Ausubel' (2004) auction performance for the initial allocation of pollutant emission permits. Trying to parallel the EU ETS case, which constitutes a novel contribution to the analysis of the performance of plicy oriented experimental investigations in the area of multi-unit auctions. Nevertheless, our experimental results confirm many of the previous experimental results suggesting that the Ausubel auction format under evaluation may be used under complex institutional settings, such us the EU ETS, and still result very effective.

Results obtained in our experimental sessions, however, indicate that the Ausubel auction implemented do not guarantee emission permits to be efficiently allocated, to the subjects who value them the most. Although theoretically efficient for the allocation of multiple units, the Ausubel auction did not produce the CO_2 emission abatement cost reduction expected. The existence of a secondary market after the auction, though, allowed emission permits to be efficiently reallocated, which resulted in a clear reduction of total abatement costs. Overall, the institution represented in the lab realized almost all the potential earnings, which means it produces the predicted efficiency results.

The ability for the dynamic Vickrey auction to overcome the demand reduction problem existent on unique price auctions for multiple units, pointed by Ausubel and Cramton (2002), and questioned by Engelman and Grimm (2004) experimental results is, to some extent, also questioned by our results. However, the demand reduction registered within our experimental design (though observed for a single subject) might be associated with the existence of additional stages during the session, particularly, the possibility of banking. This intertemporal connection between rounds introduced by the possibility of banking, as well as the existence of a re-sale market for the permits bought at the auction, addd new and different explanations to the observed demand reduction behavior.

Still, the overbidding problem identified by Manelli *et al.* (2006) experimental study on the Ausubel (2004) auction was not present in our experiments. Most of the participants in our experiment were risk averse and this may explain why the bidding strategy present at Manelli *et al.* (2006) experiments' was not identified in our sessions. However, as those authors did not include any procedure for the elicitation of subjects' risk aversion attitudes, we cannot argue for sure that differences in our results are a consequence of diverse subject's pool characteristics. This constitutes an important methodological contribution of the present paper for this kind of experiments: the use of a Multiple Price List, or any other instrument, to elicit subjects' risk aversion attitudes and, therefore, obtain a more complete characterization of the participants in the experiments. Additionally, it adds arguments to the ongoing discussion about the importance of parameters for the experimental results. In fact, even if participants in Manelli *et al.* (2006) experiments' were as risk averse as our participants, the use of the same strategy in our experiments could be much more harming because potential losses were much higher. With more subjects in the auction and considerably more units being auctioned (88 instead of only 3) overbidding it is not an attractive strategy but an extremely risky one, which gives reason to claims on experimental economics literature saying parameters do matter!

Our experiments implemented the simplest version of the Ausubel (2004) auction concerning its informational conditions. Although not for the particular case of Emission Permit Markets, Kagel and Levin (2009) experimental study highlighted the importance of revealing information about the drop outs that occur at each price, while the auction is open, as well as about the clinched units. These authors concluded not only the dynamic characteristics of the Ausubel auction influence and explain its superiority in comparison to the Vickrey's format but also the informational conditions under which it is implemented (complete *versus* incomplete). Only additional experimental sessions would be able to confirm their results for the case on emission permits initial allocation and this is a direction for future research: to replicate our experimental setting for the Ausubel (2004) auction (parallel to the EU ETS), including different informational conditions.

Another line for future research is to experimentally test and compare the performance of the Ausubel (2004) auction with alternative auction formats, namely, the uniform price proposed by Montero (2008) for the allocation of the commons (as the emission permits auction is an example for such application).

Given the growing importance of emission permits markets as an environmental policy instrument worldwide to halt, or at least diminish, GHG emissions, further research about this instrument and the relevance of institutional rules for its performance is more than justified. We have focused on the EU ETS because it is currently an example for other countries/ regions of the world considering the use of emission permits markets to achieve their environmental objectives. China, for instance, has stated on its 12^{th} Five-Year National Economic and Social Development Plan (2011-2015) the objective to cut CO_2 emission per unit of GDP in 2015 by 17% based on the level of 2010, establishing an ETS, among other measures. Therefore, additional experiments like the one reported on this paper are necessary, as many other aspects/ variables can be evaluated in this way, before implementing such a program in reality.

ACKNOWLEDGMENTS

We thank FCT for research support under grant POCTI/ECO/45435/02. Financial support from NIMA is also appretiated.

References:

Ausubel, Lawrence M., 2004. "An Efficient Ascending-Bid Auction for Multiple Objects", *American Economic Review* 94 (5), 1452-175.

Ausabel, L. M., Cramton, P., 2004. "Vickrey auctions with reserve pricing", *Economic Theory* 23, 493-505.

Ausubel, L. M., and Cramton, P., 2002. "Demand Reduction and Inefficiency in Multi-Unit Auctions." *University of Maryland, Working Paper*, 27 July 2002.

Botelho, A., Fernandes, E. and Pinto, L. C., 2011. "*An Experimental Analysis of Grandfathering Versus Dynamic Auctioning in the EU ETS",* in Isaac, R. M., and Norton, Douglas A. (Eds.), *Research in Experimental Economics*, Volume 14, Emerald Group Publishing Limited, 37 – 76.

Burtraw, D., Goeree, J., Holt, C., Myers, E., Palmer, K., and Shobe, W., 2011. "Price Discovery in Emissions Permit Auctions", *",* in Isaac, R. M., and Norton, Douglas A. (Eds.), *Research in Experimental Economics*, Volume 14, Emerald Group Publishing Limited, 11 – 36.

"DIRECTIVE 2003/87/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 13 October 2003 establishing a scheme for greenhouse gas emission allowance trading within the Community and amending Council Directive 96/61/EC" *Official Journal of the European Union*, L 275/32, 25.10.2003

Engelmann, D., Grimm, V., 2004. "Bidding Behavior in Multi-Unit Auctions – An Experimental Investigation and some Theoretical Insights", *Center for Economic Research and Graduate Education - Economic Institute, Prague, Working Paper 210.*

Fischbacher, Urs, 2007. "z-Tree. Zurich Toolbox for Ready-made Economic Experiments", *Experimental Economics* 10(2), 171-178.

Godby, Robert William, 1996. "An Experimental Economic Examination of Market Power in Emission Permit Markets", Doctor of Philosophy Thesis at McMaster University. Hamilton, Canada.

Godby, R. W., Mestelman, S., Muller, R. A., and Welland, J. D., 1997. "Emissions Trading with Shares and Coupons when Control over Discharges is Uncertain", *Journal of Environmental Economics and Management* 32 (2), 359-381.

Holt, C., and Laury, S. K., 2002. "Risk Aversion and Incentive Effects", *American Economic Review* 92 (5), 1644–1655.

Holt, C., Shobe, W., Burtraw, D., Palmer, K. and Goeree, J., 2007. "Auction Design for Selling CO_2 Emission Allowances Under the Regional Greenhouse Gas Initiative", *Final Report for RGGI*, October 26, 2007.

Kagel, J. H., and Levin, D., 2001. "Behavior in Multi-Unit Demand Auctions: Experiments with Uniform Price and Dynamic Vickrey Auctions." *Econometrica* 69 (2), 413-454.

Kagel, J. H., Levin, D., 2009. "Implementing Efficient Multi-Object Auction Institutions: An Experimental Study of the Performance of Boundedly Rational Agents", *Games and Economic Behavior*, 66 (1), May 2009, 221-237.

List, J. A., Lucking-Reiley, D., 2000. "Demand Reduction in Multiunit Auctions: Evidence from a Sportscard Field Experiment", *The American Economic Review*, Vol. 90 (4), 961-972.

Manelli, A. M., Sefton, M., and Wilner, B. S., 2006. "Multi-unit auctions: A comparison of static and dynamic mechanisms", *Journal of Economic Behavior & Organization* 61, 304-323.

McAfee, R. P.; McMillan, J., 1987. "Auctions and Bidding", *Journal of Economic Literature* 25 (2), 699-738.

Milgrom, P. R., 1987. "Auction Theory", in T.F. Bewley, ed., Advances in economic theory: Fifth world congress; Econometric Society monographs series, No.12. Cambridge: Cambridge University Press, 1-32.

Mochón, A., Quintana, D., Sáez, Y. and Isasi, P., 2005. "Analysis of Ausabel Auctions by Means of Evolutionary Computation", *The 2005 Congress on Evolutionary Computation*, Vol.3, Issue 2-5, 2645-2652.

Montero, J.-P., 2008. "A Simple Auction Mechanism for the Optimal Allocation of the Commons," *The American Economic Review*, vol. 98(1), 496-518, March.

Neuhoff, K., Matthes, F. (coordinating authors); Betz, R., Dröge, S., Johnston, A., Kudelko, M., Löschel, A., Monjon, S., Mohr, L., Sato, M. and Suwala, W. (contributing authors), 2008. "The Role of Auctions for Emissions Trading", *Climate Strategies*, October 6, 2008.

Smith, Vernon L., 1982. "Microeconomic Systems as an Experimental Science", *The American Economic Review*, 923-955.

Vickrey, W., 1961. “Counterspeculation, Auctions, and Competitive Sealed Tenders”, *Journal of Finance* 16, 8-37.

Whitford, A. B., 2007. “Designing Markets: Why Competitive Bidding and Auctions in Government Often Fail To Deliver”, *The Policy Studies Journal* 35(1), 61-85.

Appendix

Table A.1 - Marginal abatement costs

Units	Belgium (S1)	Spain (S2)	Germany (S3)	Greece (S4)	France (S5)	Italy (S6)	U.K. (S7)	Netherlands (S8)
1	76	37	4	59	21	17	6	32
2	177	90	11	149	56	42	15	76
3	291	152	18	255	100	72	25	127
4	413	220	27	374	151	105	37	182
5	543	294	36	503	208	140	50	241
6	678	372	46		270	177	63	304
7		454	56		337	216	77	369
8		539	67		408	257	92	436
9		627	79		483	300	107	506
10		719	91		561	344	123	
11		813	103		643	389	140	
12		909	115		729	436	157	
13		1008	128		817	484	174	
14			142		908	533	192	
15			155		1002	583	210	
16			169		1099	634	228	
17			184		1199	686	247	
18			198		1301	739	266	
19			213			792	286	
20			228			847	306	
21			243				326	
22			259				346	
23			274				367	

Units	Belgium (S1)	Spain (S2)	Germany (S3)	Greece (S4)	France (S5)	Italy (S6)	U.K. (S7)	Netherlands (S8)
24			290				388	
25			307				409	
26			323				431	
27			340					
28			356					

Table A.2 - Predicted Allocation of Permits in the Ausubel Auction

Period	Subject Type							
	S1	S2	S3	S4	S5	S6	S7	S8
1	5	11	15	4	15	16	16	6
2	5	10	16(15)	4	15	15(16)	16	7
3	5	11	15	4	15	16	16	6
4	5	11	15	4	15	16	16	6
5	4	10	17	4	15	15	17	6
6	5	11	15	4	15	16	16	6
7	5	11	15	4	15	16	16	6
8	5	11	15	4	15	16	16	6
9	5	11	15	4	15	16	16	6
10	5	10(11)	16(15)	3(4)	16(15)	16	16	6

Note: Values in the cells are *Market* benchmarks (within brackets are *System* benchmarks when different from the Market).