Two Patterns of Price Dynamics were Observed in Greenhouse Gases Emissions Trading Experiments: An Application of Point Equilibrium[#]

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ABSTRACT

This paper compares efficiencies of double auction and bilateral trading in GHG emission trading experiments with the addition of two rules, abatement irreversibility of GHG emissions and non-compliance penalty, to Hizen and Saijo (1998). Using a new concept of equilibrium, we found that (i) Results were grouped into two cases. In one case, excessive reductions occurred at the early stage of the experiment and efficiency was relatively low. In the other case, excessive reduction did not occur at the early stage of experiment and efficiency was relatively high. (ii) In both cases, efficiency of double auction was higher than that of bilateral trading. (iii) Emissions trading lowered emissions reduction costs. (iv) Excessive emissions reduction occurred in almost all the sessions.

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1. Introduction

The third Conference of Parties (COP3) to the United Nations Framework Convention on Climate Change was held in Kyoto in December 1997, and adopted the Kyoto Protocol.[1] The Protocol establishes national emission targets for greenhouse gases (GHGs) for developed countries including economies in transition. In effect the Protocol calls for an emissions reduction of 5.2% from 1990 levels for developed countries as a whole, with for example Japan to attain 94% of 1990 emissions, USA 93%, EU 92%, Russia 100%, during the period 2008 and 2012. In order to achieve this goal, the use of Kyoto mechanisms, which include international emissions trading, joint implementation, and the Clean Development Mechanism, was authorized. At the COP6 held in Den Hague in November 2000, the parties reviewed the details of the Kyoto Protocol in preparation for its ratification, but the conference failed to agree on the details of the Kyoto mechanisms.[2] Whatever the final outcomes of the negotiation process may be, design of the mechanisms is important from an economics viewpoint.

This paper focuses on emissions trading in Kyoto mechanisms. The purpose of this paper is to explore, by employing an experimental method, what type of institutions can efficiently attain the targets of the Kyoto Protocol related to GHG emissions reduction. Bohm (1997), an initiator of GHG emissions trading experiments, reported a bilateral trading experiment among four Nordic countries, using experienced public officials or experts appointed by the Energy Ministries. The resulting prices were very close to the competitive equilibrium price with an efficiency of allocation of 97%, which is extremely high. Muller and Mestelman (1998) and Godby, Mestelman and Muller (1998) provide many new findings on general emissions trading experiments. Among others, experimental economists have found that: (i) allowing banking permits over time smooths contracted prices across time periods, and (ii) a trader who has some market power other than in the emissions trading market can influence the emissions trading market, and hence the introduction of the emissions market reduces the efficiency of the whole economy.[3]

Our experimental design focuses on three important features that have not been analyzed so far in previous experiments. These are the effects of non-compliance penalty, abatement irreversibility and the time lag effect of investment.

[1] See http://www.unfccc.de/index.html

[2] President Bush announced that the USA would not ratify the Kyoto Protocol in March 2001.

[3] The experiments by Bohm and Carlén (1999) show that the market power problem is not as serious as Muller and Mestelman (1998) and Godby, Mestelman and Muller (1998) suggest since participants in an emissions trading market can buy *and* sell the permits.

For non-compliance penalties, when a party cannot attain the Kyoto target an important issue in the negotiation process of the design of the Kyoto Protocol has been what type of penalty would be appropriate.[4] In our experimental design, we impose a monetary penalty when a party is under non-compliance. When a party ends with non-compliance, it has to pay a penalty which is about three times higher than the competitive equilibrium price, but when a country ends with over-compliance, the permits left over have no value.

With abatement irreversibility, once a party invests a certain amount for abatement, it cannot revert to the original situation. This is shown by movement on the marginal abatement cost (MAC) curve. When a party moves from a certain point on the MAC curve to another point through abatement investment, it cannot return to the original point. In other words, the shape of the MAC curve is changed by the investment decision.

For the time lag effect of investment, even though a party decides on abatement investment at a given point, the actual abatement will be done later. In order to take account of this effect, a party in our experiment can only decide on abatement investment within the first half part of the period. Abatement investment decisions cannot be made after the half point of the period.

We have two types of experimental controls. The first one is the trading method, which is either bilateral trading or double auction. The second control is the disclosure of contract information (i.e., price, quantity, and who are the buyer and the seller). Therefore, there are four treatments: bilateral trading with open information, bilateral trading with closed information, double auction with open information, and double auction with closed information. However, since all proposals in double auction are open to the public, we actually have three treatments. Each treatment has four sessions and hence we have twelve sessions in our experiment.

Although the Hizen and Saijo (2001) experiment uses the same MAC curves, the experimental designs are different. Hizen and Saijo designed their experiment so that firstly, non-compliance and over-compliance would not occur in order to exclude their effect; secondly, so that subjects could move on the MAC curves freely; and thirdly, so that subjects could make abatement investment decisions throughout the period. Under this design, they observed the following: (i) the efficiency of both bilateral trading and double

[4] Japan insists that the target of a party is just a challenge and hence no penalty should be imposed when it cannot attain it. However, most of the countries including the US, the EU and developing countries oppose the idea and advocate strong penalty including monetary punishment.

auction is quite high, regardless of the control of contract information[5]; (ii) marginal abatement costs are equalized over time in both institutions; (iii) contracted prices roughly converge to the competitive price over time in a double auction, but not quite so in bilateral trading.

However, in our experiment we found results that were different from those of Hizen and Saijo and others. First, two patterns of price dynamics were observed with the help of a new equilibrium concept called a *point equilibrium*. At each point of time in a session, the normative equilibrium price depends on the previous decisions of abatement investment. For example, assuming that at a certain point in time a party conducts excessive abatement investment more than that of competitive equilibrium, after other parties have already conducted investments at exactly competitive equilibrium, the total amount of reductions would then exceed the competitive equilibrium reductions, and hence the competitive equilibrium price at *this point* should be less than the competitive equilibrium price *before* conducting a session. Therefore, we have two sequences of price dynamics. One is actual data and the other is "should be" price pattern derived from the actual price data. This "should be" price at each point of time is named the point equilibrium price.

In one of the two patterns, the point equilibrium price dropped at an early stage of the transactions.[6] Due to fear of non-compliance, some subjects conducted excessive domestic reductions at an early stage which caused excess supply of emissions permits, and hence the point equilibrium price went down. Five sessions fall into this pattern. The efficiency of this pattern was relatively low. In the other pattern, that is seven sessions out of twelve, excessive reductions did not occur at an early stage and the point equilibrium price pattern was very close to the competitive equilibrium. Its efficiency was relatively high, but substantially lower than that of Hizen and Saijo.

Secondly, we observed that efficiencies of double auction were higher than those of bilateral trading in each price pattern. That is, the treatment of transaction methods did not give us a clear-cut distinction on efficiency, but the two patterns did. On the other hand, no clear distinction on efficiency was observed between bilateral trading and double auction in Hizen and Saijo.

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[5] The efficiencies of emissions trading are high. They are between 91.9% and 99.9% for bilateral trading and between 99.4% and 99.7% for double auction.

[6] Baron (2000) observed the same price dynamics in his experiment. Since he conducted just one session only, it is hard to generalize the result. However, the price pattern of sulfur dioxicde market in the U.S. showed the same price dynamics around the beginning of the first few years.

Third, although efficiencies of sessions were not very high, in eleven sessions out of twelve the emissions reduction costs of emissions trading were lower than those of domestic reductions only.

Fourth, excessive emissions reduction occurred in almost all the sessions regardless of the treatment. Out of 48 subjects in bilateral trading 8 subjects were under over-compliance and 3 subjects were under non-compliance. Out of 24 subjects in double auction 5 were under over-compliance and none was under non-compliance. The remaining subjects complied with the targets exactly.

This paper is organized as follows. In Section 2, the experimental design and procedures are described. The point equilibrium is explained in Section 3. Section 4 shows two types of efficiency. In Section 5, we analyze the results using the point equilibrium. The final section contains concluding remarks and policy implications.

2. Experimental Design

We recruited at least six students for each session through campus-wide advertisements at Osaka University. These students were told that there would be an opportunity to earn money in a research experiment. Two or three days after recruitment, we conducted the sessions. In the recruitment and experiment, we did not use the term "emissions trading".

In each session, subjects were seated at desks in a relatively large room and listened to a tape-recorded voice giving instructions. In this part, each subject received a sample graph, which was actually an MAC curve. See Figure 1. The horizontal axis represents the amount of an abstract commodity and the vertical axis represents the marginal cost. Each subject was told that she would start from the initial position (20 units in the figure) and should finish with more than or equal to the goal (70 units in the figure). "Your initial position" is her initial emissions and "your goal" her target of the Kyoto Protocol. When she moves one unit to the right (left) along the curve from the initial position, she obtains (loses) one unit of goods in exchange for paying (getting) 100 units of money. In our experiment, we called one unit of reduction of emissions "producing the unit" and one unit of increment of emissions "returning the unit to an experimenter." In this paper we use the terms emissions or reductions rather than the terms that were used in our sessions.

Abatement irreversibility was then explained to subjects. See Figure 2-1. The horizontal axis represents the amount of emissions and the vertical axis represents marginal abatement cost. The downward sloping curve is an MAC curve. Point *a* corresponds to the initial position of the party. If the party decides to invest in emission reductions and moves from *a* to *b* on the MAC curve, the shaded area is the abatement cost of moving from *a* to *b* and the position moves from the initial position to the new position given in Figure 2-2. The MAC curve is considered as representing marginal *cost* when a party reduces one unit of emissions, but it can be regarded as representing marginal *benefit* when it increases one unit of emissions. If abatement investment is *reversible*, the benefit of one more unit of emissions is the height of point *b*. That is, the abatement investment is fully recoverable by increasing the emissions. If it is totally unrecoverable, the benefit of emitting one more unit should be zero. In our experiment, we take a middle point of these two extremes. After any amount of emission reduction investment, the benefit of emitting one additional unit is always the height of the initial position. Further benefit of emissions decreases along the right hand side of point *a* of the MAC curve in Figure 2-1. Therefore, the new MAC curve after moving to the new position becomes the curve depicted in Figure 2-2. That is, the shape of the MAC curve changes after abatement investment. On the other hand, it would not change shape in the case of abatement reversibility.

After instruction on abatement irreversibility, we taught subjects basic strategies depending on price level. See Figure 3 for an example. Figure 3 gives the case where the Kyoto target is on the left hand side of the initial position. Assume that the price level is at *p*. Since the price of permits is high, the party should reduce her emissions until MAC is equalized to the price, that is, from *a* to *b*, and then sell the difference between the Kyoto target and the new position, that is, from *b* to *c*. Two other cases such as p' and p'' were explained to subjects. Several more cases were shown to subjects with the target on the right hand side of the initial position.

A marginal abatement cost curve can be regarded as an excess demand curve for emissions permits in the following manner. See Figure 3. If the Kyoto target is the new origin, then the left hand side of the MAC curve becomes the supply curve of the permits and the right hand side becomes the demand curve. That is, the party becomes a supplier of permits when the price level is high enough, and it becomes a demander of permits when it is low enough. Thus the MAC curve is an excess demand curve for permits when the Kyoto target point is the origin.[7]

[7] See Saijo (2000) for a theoretical analysis.

After instruction on basic strategies, all subjects took an examination to check their understanding of the instructions. The best six subjects continued the session, and the rest of the subjects were asked to leave the room with $13.16 ($1=114 yen). Each subject was then assigned a subject number from 1 to 6 and received her own marginal abatement cost curve. They were given fifteen minutes to strategize before the sixty minutes' trading period started.

The six subjects played the roles of Russia, Ukraine, USA, Poland, EU, and Japan. Figure 4 shows the MAC curve of each party. In the figure, their MACs are shifted so that their Kyoto targets are the origin, that is, each curve is an excess demand curve for emissions permits of the party, and the dot on the curve shows its initial position. During the experiment, we did not use any country names. Because we did not use any terms related to emissions trading, subjects faced a situation where trading and production of an abstract commodity were conducted with an abstract price or at an abstract production cost.

We have three types of treatments in our experiment: bilateral trading treatment with contract information (price, quantity, and subjects' numbers) closed, bilateral trading treatment with contract information open, and double auction treatment with contract information open. In double auction, all proposals are open by nature, so we did not have a double auction treatment with contract information closed. Since we conducted four sessions in each treatment, we had twelve sessions. In what follows, "Bc" represents the bilateral trading treatment with contract information closed, "Bo" the bilateral trading treatment with contract information open, and "D" the double auction treatment For example, "Bo3" indicates session 3 of the bilateral trading experiment with contract information open.

In bilateral trading, each subject could move around the room freely to find a subject with whom to transact. During negotiations, subjects were not allowed to talk. Only numbers (price and quantity), and "yes" and "no" symbols on their negotiation sheets, were exchanged, in order to avoid information leakage. Once a pair reached agreement, they reported the price, quantity, and their subject numbers to an experimenter. In Bo sessions, the experimenter announced this information and wrote it on a black board.

In our double auction, an auctioneer called on the subject who raised her hand the earliest. Then the subject provided her subject number, sell or buy decision, the quantity and the price per unit. For example, a subject said, "Subject five wants to sell ten units at one hundred dollars per unit." The auctioneer projected the proposal on an OHP screen. After the proposal, the subject who raised her hand the earliest could trade with the proposer. The accepted quantity had to be smaller than or equal to the proposed quantity. We imposed the "improvement rule" on proposals, that is, asks (bids) must be successively lower (higher).[8]

To reduce or increase emissions, a subject informed the experimenter of the amount of emissions reductions or additional emissions. These could be conducted only in the first half of the sixty minute trading period.[9] That is, after half an hour, the point on the MAC curve is fixed for the rest of the period. If a subject ended the experiment under non-compliance, she had to pay a penalty of 300 per over-emissions unit. On the other hand, if a subject ended it with over-compliance, the permits left over had no value.

It took approximately three hours for each session. The mean payoff per subject was $34.61. The maximum payoff was $66.34, and the minimum payoff was $17.54.

3. Point Equilibrium

Due to changes of MAC curves caused by abatement investment irreversibility described in Section 2, the normative competitive equilibrium price also changes. See Figure 5. This figure is similar to Figure 2, but the position of the Kyoto target is explicitly expressed. That is, the downward sloping curve is regarded as a demand curve for emissions permits. On the other hand, the supply curve is derived from the MAC curves of other parties. This is an upward sloping curve in the figure. The competitive equilibrium before any abatement investment is e and the competitive equilibrium price is p^*. If a demander conducts abatement investment and moves from point a to point b, *after* this investment the normative competitive equilibrium would no longer be at e, but should be e' and the new competitive equilibrium price becomes p'. At each point of time, the normative competitive equilibrium changes as abatement investments proceed. We describe the normative competitive equilibrium given previous actions of subjects at a certain time as the *point equilibrium* at the time.

If it were also the case with abatement reversibility, the competitive equilibrium price and the point equilibrium price would always coincide with each other throughout the period. On the other hand, since the shapes of MAC curves change as time proceeds in

[8] See p. 41 of Davis and Holt (1993).
[9] Each session has just one period that is sixty minutes.

our experiment, they do not always coincide with each other although they do at the starting point. Therefore, there are three price sequences in a session. The first is a sequence of real price data. The second is the normative competitive equilibrium price sequence which is constant throughout the period. The third is the point equilibrium price sequence. The first and second sequences are usually compared in the analysis of experimental economics literature. We will show in section 5 that the introduction of the point equilibrium price sequence enriches our analysis of price dynamics.

4. Two Definitions of Efficiency

We define efficiency as follows:

$$\frac{\text{The sum of surplus extracted in the experiment}}{\text{The sum of surplus extracted at competitive equilibrium}}$$

This is a standard measure of efficiency. Efficiency in experiments is usually measured as the percentage of the realized sum of surplus to the maximum possible sum of surplus extracted from an institution. The maximum is attained at the competitive equilibrium and the sum of surplus extracted at the competitive equilibrium is 6990. We employ two types of efficiency measures depending on how we measure "the sum of surplus extracted in the experiment."

The first one is to measure "the sum" as the sum of the actual payoffs obtained during the experiment. When a subject ended with over-compliance, the permits left over have no value, and when a subject ends with non-compliance, she must pay a penalty.

There are two problems with the above measure of efficiency. First, the permits left over under over-compliance will have some value since the Kyoto protocol allows banking of permits and over-compliance really means a reduction of GHGs beyond the targets of the Kyoto protocol. Therefore, it would be natural to assign the left-over permits some value. Second, the penalty from non-compliance would be handed to an international body and would then be distributed to some parties. Therefore, the total sum of penalty would not be a source of loss of efficiency.

Taking into account the above two facts, we modify efficiency in the following manner. In the case when some subjects are under over-compliance and nobody is under non-compliance we take the subject who has the highest marginal emission benefit and reevaluate one unit of over-compliance with this value. That is, hypothetically, a subject with the highest marginal emission benefit can obtain benefit by using one unit of over-compliance. Next we take the subject who has the second highest marginal emission benefit and do the same as above until reaching the last unit of over-compliance. We note however that the shape of the marginal abatement cost curve (or the marginal emission benefit curve) of each subject will have been changed due to abatement irreversibility at the end of a session. Re-evaluation should therefore be carried out with this reshaped marginal emission benefit curve.

In the case when some subjects are under non-compliance, and nobody is under over-compliance we take the subject who has the lowest marginal abatement cost, and replace one unit of non-compliance with this value. That is, hypothetically, a subject with the lowest marginal abatement cost can reduce one unit of emission instead of paying one unit of penalty of another subject. We then take the subject who has the second lowest marginal abatement cost, and repeat the above procedure until reaching the last unit of non-compliance.[10]

Figure 6 shows an example when at the end of a session subject A was under over-compliance and subject B complied with the target exactly. Both marginal abatement cost curves have kinks at the end positions of the session due to abatement irreversibility. The amount of over-compliance for subject A is 0-*m*, and the end position of subject B is exactly at the Kyoto target. The subject who has the highest marginal emission benefit is subject B. That is, the height of *i* is bigger than the height of *k.* Hence, the benefit from emitting from *i* to *n* is the area *0-q-n-i.* At *n,* the marginal benefit of subject B becomes exactly the same as that of subject A at *k*. From this point, the benefit can be obtained from both subjects A and B, and it is the area *q-m-k-j-n*. In total, the over-compliance of 0-*m* generates the benefit depicted by the area *0-m-k-j-i*.

The re-evaluation of over-compliance in Figure 6 can be interpreted as a hypothetical trade after the end of the session. Immediately after the session Subject A emits the amount *m-l* and hence obtains the benefit *l-m-k-j*. Subject A then sells the amount 0-*l* to subject B at the price *p.* Subject A then obtains the benefit 0-*l-j-p,* and subject B obtains the net benefit *p-j-i*. In total, the sum of the surplus is exactly the same as the area *0-m-k-j-i*.

5. Results

[10] We did not have a session where both a subject with over-compliance and a subject with non-

5.1 Analyses Using Efficiency Table

In this section we analyze experimental results using Table 1, efficiency table, which provides a summary of the sessions.

The first row in the table shows the two treatments, i.e., bilateral trading and double auction. The second row indicates the names of the sessions. For each subject, in the first cell of the first column, the top left number represents the subject number and the number in the parentheses is the maximum possible surplus, or profit, that the subject can obtain if every subject trades permits at the price 119 which is the midpoint of the competitive equilibrium prices 118-120. The middle shows the name of the subject. The number in the first parentheses of the bottom is the corresponding initial position in Figure 4. The first number in the second parentheses of the bottom is the position in Figure 4 where it should reduce its emissions at the price 119. The second number is the amount of non-compliance. If the subject follows the transaction at the competitive equilibrium, this should be 0. For example, Russia, whose subject number is 1, can make the maximum surplus 2555 at the price 119 when she reduces her emissions from her initial position -32 to the point -55, and sells her permits until the amount of non-compliance becomes 0. From the second column, for each subject the top shows the surplus a subject achieved, the middle shows the ratio of the surplus she achieved to the surplus she extracts at the competitive equilibrium, the first number in the bottom shows the final position in Figure 4, and the second number at the bottom shows the amount of non-compliance at the end of the session. In the case of over-compliance, this number is negative. In session Bc3, for example, Russia achieved surplus of 620, the ratio of this surplus to the surplus she extracts at the competitive equilibrium is 620/2555 = 0.243, she reduced emissions to the point -65, that is, 10 units of over-reduction, and the amount of non-compliance was -22, that is, 22 units of over-compliance. In order to show over-compliance, we put a bold square around the cell. On the other hand, if a subject is under-compliance, we put a bold square with gray shading in the cell. The second row from the bottom indicates the sum of the surplus each subject extracted and the efficiency of the session. The bottom row indicates the sum of the surplus after modification shown in section 4 and the modified efficiency of the session. In session Bc1, for example, the sum of the surplus is 5112 and the efficiency is 5112/6990 = 0.731 where 6990 is the sum of the surplus at the competitive equilibrium. The surplus after modification is 5612 and the modified efficiency is 5612/6990 = 0.803.

compliance co-existed.

Using the table, we demonstrate that on average the market achieves positive efficiency and positive modified efficiency, that is, on average the emissions trading reduces the total costs of the Kyoto target at the market level compared with the case of domestic reductions only. At the subject level, almost all subjects extract positive surplus from the market on average, that is, they reduce the costs of the Kyoto target on average.

Result 1. (i) *On average efficiency and modified efficiency achieved in the market are positive.*
(ii) *On average each subject except the USA extracts a positive surplus from the market.*

Support. (i) Efficiency was positive in eleven out of twelve sessions and the modified efficiency was positive in all sessions. Both the mean of efficiency and the mean of the modified efficiency are statistically larger than 0 at the 1% significant level[11].
(ii) Among twelve sessions, Ukraine and the USA achieved a positive surplus in nine sessions, the EU in ten sessions, Japan in eleven sessions, and Russia and Poland in all sessions. The mean of the surplus each subject except the USA extracts is statistically larger than zero at the 5% significant level. The USA extracted a negative surplus only in three sessions, but the average of twelve sessions was negative, which is not statistically different from zero. ■

Next we make comparisons between the efficiency of bilateral trading and that of double auction, between the modified efficiency of bilateral trading and that of double auction, between the efficiency of bilateral trading with closed information and that of bilateral trading with open information, and between the modified efficiency of bilateral trading with closed information and that of bilateral trading with open information.

Result 2. (i) *A difference between the efficiency of bilateral trading and that of double auction was not observed.*
(ii) *A difference between the modified efficiency of bilateral trading and that of double auction was not observed.*
(iii) *A difference between the efficiency of bilateral trading with contract information closed and that of bilateral trading with contract information open was not observed.*
(iv) *A difference between the modified efficiency of bilateral trading with contract information closed*

[11] Unless otherwise indicated, t-tests are used in this paper.

and that of bilateral trading with contract information open was not observed.

Support. (i) The difference between the mean of the efficiency of bilateral trading and that of double auction is statistically insignificant.
(ii) The difference between the mean of the modified efficiency of bilateral trading and that of double auction is statistically insignificant.
(iii) The difference between the mean of the efficiency of bilateral trading with contract information closed and that of bilateral trading with contract information open is statistically insignificant.
(iv) The difference between the mean of the modified efficiency of bilateral trading with contract information closed and that of bilateral trading with contract information open is statistically insignificant. ■

As shown in Result 2 (ii), when we analyze all sessions together the difference between the modified efficiencies of the trading institutions is not observed. However, when we classify the sessions into two groups according to their dynamic processes, such as the path of point equilibrium price, a difference between the modified efficiency of double auction and that of bilateral trading is observed.[12] In the following section, we classify the sessions into two groups and characterize each group.

5.2 Classification of the Sessions by their Dynamic Processes

Since Table 1 does not give us the dynamic processes of transactions, emissions reductions, and additional emissions as time passes, we use figures where these dynamic processes are illustrated with the point equilibrium price path. As an example, see Figure 7, the figure of session Bc1. In this figure, the horizontal axis represents minutes and the vertical axis represents MAC and price. Squares in the figure show transactions. The left-hand (right-hand) side letter of a square represents the initial letter of the seller (the buyer) and the number under the square the quantity traded. Lozenges (triangles) show the emissions reduction (additional emissions). The letter attached to a lozenge (triangle) represents the initial letter of the subject who conducted emissions reduction (additional emissions) and the number under the lozenge (triangle) the amount of emissions reduction (additional emissions). The gray (or green) horizontal line shows the competitive

[12] As for the effect of price disclosure, no significant effects were observed even after the classification.

equilibrium price ranging from 118 to 120. The black (or dark red) line represents the point equilibrium price path up to 30 minutes. It has some thickness until 14 minutes, then becomes 120 until just before 30 minutes, and then drops to 85. The dotted line is the point equilibrium price path after 30 minutes, which is zero if over-compliance occurs, 300 if non-compliance occurs, and 0-300 if complied exactly. Figures of all sessions are given in Appendix 1.

From these figures we notice that the pattern of the point equilibrium path up to 30 minutes varies considerably from session to session: in some sessions it drops early and in others it is almost the same as the competitive equilibrium price. That is, the pattern of the point equilibrium path characterizes the sessions. As a measure of these path patterns we introduce the concept of *discrepancy area*, which is the area of the region enclosed by the midpoint of the competitive equilibrium price up to 30 minutes, i.e. 119, and the sequence of the midpoints of the point equilibrium prices up to 30 minutes. This area becomes larger the earlier the discrepancy between the competitive equilibrium price and point equilibrium prices happens and/or the larger this discrepancy is. An example is given in Figure 8. The discrepancy area in this session is the area which is shaded. In this session, the point equilibrium price dropped early and the degree of the drop was large, so that the discrepancy area is large. See Figure 7 again. In session Bc1, on the other hand, the discrepancy between the competitive equilibrium price and the point equilibrium prices happened just before 30 minutes, so that the discrepancy area is almost zero.

Using this new concept and the dynamic processes of transactions and emissions reductions, we obtain the following result.

Result 3. *The sessions are grouped into two, that is, sessions Bc3, Bo1, D2, D3 and D4, and sessions Bc1, Bc2, Bc4, Bo2, Bo3, Bo4 and D1.*

Support. When we use cluster analysis after normalizing the discrepancy area and the modified efficiency, first, the twelve sessions are divided into two groups, i.e., session Bo1 and the other eleven sessions, and second, the eleven sessions are divided into two groups, i.e., sessions Bc3, D2, D3 and D4, and the remainder. That is, cluster analysis divides the 12 sessions into three groups: the largest group consists of sessions Bc1, Bc2, Bc4, Bo2, Bo3, Bo4, and D1, the second largest group consists of sessions Bc3, D2, D3 and D4, and the smallest group consists of session Bo1.

Next, we describe each group's dynamic characteristics. First, we examine the largest group, i.e., sessions Bc1, Bc2, Bc4, Bo2, Bo3, Bo4 and D1. Consider session Bc1 as an example of the group and see Figure 7 again. In this session, low contracted prices at the early stage caused insufficient emissions reduction for suppliers such as Russia, Ukraine and Poland. Therefore, just before 30 minutes the USA and EU, who could not buy enough permits, reduced their emissions to levels where their MACs exceeded the point equilibrium price 120. These excessive reductions caused the point equilibrium price to drop to 90. This type of dynamic process also applies to the other sessions that belong to this group. That is, relatively low contracted prices at the early stage caused insufficient emissions reduction of suppliers and in many cases, demanders conducted excessive reductions just before 30 minutes in order to avoid a non-compliance penalty. Although this caused efficiency losses the losses were not big. We name this group the constant point equilibrium price case, the constant price case for short.

We now examine the second largest group, i.e., sessions Bc3, D2, D3 and D4. Consider session D2 as an example of the group and see Figure 8 again. In this session because of the relatively high contracted prices around the first 10 minutes, Japan and Russia conducted excessive reduction at around 10 minutes. Although this caused the point equilibrium price to drop, the contracted prices did not drop immediately due to inertia of contracted prices. Accordingly, Ukraine and the USA continued to reduce their emissions at around 15 minutes at the MACs based on the former contracted prices, so that the point equilibrium price dropped even further. This type of dynamic process also applies to the other sessions that belong to this group. That is, high contracted prices and/or expectation of high contracted prices in the future at the early stage caused some subjects to reduce their emissions to levels where their MACs exceeded the competitive equilibrium price. Accordingly, the point equilibrium price immediately decreased, but contracted prices did not drop immediately due to inertia. Therefore some subjects continued to reduce their emissions to levels where their MACs exceeded the new point equilibrium price, not knowing that the point equilibrium price had decreased. These excessive reductions caused the point equilibrium price to decrease even further. This cycle caused great efficiency losses. [13]

In the third and smallest group, session Bo1, the USA reduced her emissions at extremely high MACs at the early stage and as a result the point equilibrium price dropped heavily. However the contracted prices remained at about the same level as the contracted

[13] A similar pattern of price sequence is observed in Baron (2000).

prices at the early stage because of inertia of the contracted prices and as a result subjects continued to conduct excessive reductions. These dynamic processes are the same as those of the second largest group, so that we combine these two groups into one and name it the early point equilibrium price decrease case, the early price decrease case for short.

As a result, the total sessions are divided into two by cluster analysis using two variables, i.e., modified efficiency and discrepancy area, and by reclassification according to the dynamic processes of transactions and emissions reduction. ■

Figure 9 shows a scatter diagram of 12 sessions where the horizontal axis represents modified efficiency and the vertical axis represents the discrepancy area. The number above the session name is modified efficiency and the number below the name of the session is efficiency. Where the two efficiencies are the same, only the modified efficiency is included. The figure shows that the sessions which belong to the constant price case are densely located around the southeast corner and the sessions that belong to the early price decrease case are further away from the corner. This visual impression confirms the cluster analysis described above.

The characteristics of each of the two groups are described below.

Result 4. (i) *In sessions Bc1, Bc2, Bc4, Bo2, Bo3, Bo4 and D1 (the constant point equilibrium price case), relatively low contracted prices at the early stage caused insufficient emissions reduction of suppliers, and in many cases demanders conducted excessive reductions to avoid a non-compliance penalty just before 30 minutes. Although this caused efficiency losses, these were minor.*
(ii) *In sessions Bc3, Bo1, D2, D3 and D4 (the early point equilibrium price decrease case), at the early stage high contracted prices and/or expectation of high prices in the future caused some subjects' excessive reductions, which caused the immediate drop of the point equilibrium price. However contracted prices did not drop immediately due to the inertia of contracted prices so that some subjects continued to reduce their emissions to levels where their MACs exceeded the new point equilibrium price, which then caused the point equilibrium price to decrease even further. This cycle caused great efficiency losses.*

We now compare the two groups.

Result 5. (i) *The modified efficiency of the constant price case is higher than that of the early price decrease case.*

(ii) *The discrepancy area of the constant price case is smaller than that of the early price decrease case.*

(iii) *The time at which the point equilibrium price becomes lower than the competitive equilibrium price in the constant price case is later than that in the early price decrease case.*

(iv) *The amount of net over-reduction, i.e., the sum of the permits left over at the end of a session, is smaller in the constant price than in the early price decrease case.*

Support. (i) The mean of the modified efficiency of the constant price case is statistically larger than that of the early price decrease case at the 5% significant level.[14]

(ii) The mean of the discrepancy area of the constant price case is statistically smaller than that of the early price decrease case at the 1% significant level.[15]

(iii) The mean of the time when the point equilibrium price becomes smaller than the competitive equilibrium price in the constant price case is statistically later than that in the early price decrease case at the 1% significant level.

(iv) The mean of the amount of net over-reduction in the constant price case is statistically smaller than that in the early price decrease case at the 1% significant level. ■

5.3 Comparison of Trading Institutions

In this section, we compare how the trading institutions generate different results in the two groups. First, we compare the probabilities of the two trading institutions resulting in the constant price case and compare the probabilities of the two trading institutions resulting in the early price decrease case.

Result 6. *Bilateral trading is more likely to result in the constant price case and less likely to result in the early price decrease case than double auction.*

Support. In bilateral trading, six of eight sessions, 75%, resulted in the constant price case and two of eight sessions, 25%, in the early price decrease case. In double auction, one of four sessions, 25%, resulted in the constant price case and three of four sessions, 75%, in the early price decrease case. The probability that a bilateral trading session results in the constant price case is statistically higher than the probability that a double auction session

[14] We use a nonparametric Mann-Whitney U test because the difference between the variances is statistically significant at the 5 % level.

[15] See footnote 13.

will at the 10% significant level. The probability that a bilateral trading session results in the early price decrease case is statistically lower than the probability that a double auction session does at the 10% significant level. ■

Finally, we observe the difference between the modified efficiency of double auction and that of bilateral trading within each group.

Result 7. *In both groups, the modified efficiency of double auction is higher than that of bilateral trading.*

Support. Within the early price decrease case, all of the double auction sessions attained higher efficiency than any other bilateral trading sessions. In the group, the mean of the modified efficiency of double auction is statistically higher than that of bilateral trading at the 5% significant level. Within the constant price case, the double auction session also attained higher modified efficiency than any other bilateral trading sessions.[16] ■

Our primary objective in this paper is to demonstrate which is the better market institution, double auction or bilateral trading. However when we compare all sessions in Result 2 (ii), a significant difference between the modified efficiencies is not observed. However, from Results 6 and 7, we determine the reason why the difference is not observed, namely that although double auction attains higher modified efficiency than bilateral trading in each group, the early price decrease case, which is likely to result in low modified efficiency, occurs more frequently in double auctions, so that the two effects offset each other and we cannot observe a significant difference. Besides the existence of the two groups, i.e., Result 3, these characteristics of each institution concerning two groups, i.e., Result 6 and 7, are the main findings of this paper.

6. Concluding Remarks and Policy Implications

Two patterns of price dynamics were found in the experiment. In the constant point equilibrium price case, relatively low prices at an early stage caused insufficient emissions reduction of suppliers, and demanders therefore conducted excessive reductions immediately before the end of the investment period. Efficiency was relatively high in this

[16] We cannot do a statistical test because the sample size of double auction is one.

case. On the other hand, in the early point equilibrium price decrease case, due to fear of non-compliance, some subjects conducted excessive domestic reductions at an early stage, and hence, the point equilibrium price dropped at the early stage of the transactions. However contracted prices did not drop immediately because of price inertia. The efficiency of this pattern was relatively low. In each pattern, the modified efficiency of double auction sessions was higher than that of bilateral trading. However, this does not necessarily imply that double auction is better than bilateral trading since we found just one double auction session in the constant point equilibrium price case where the modified efficiency is higher than that of the early point equilibrium price decrease case.

For efficiency before modification, we found that most of the parties realized a benefit from emissions trading compared with that of domestic reductions only.

Furthermore, we found over-reduction of GHGs in both patterns. Although this reduced market efficiency, it greatly contributed to reducing GHGs, which would be beneficial to future generations as under the Kyoto Protocol the banking of emissions permits is allowed, and hence permits generated from over-reduction would be used in later years.

It is not easy to determine policy implications from the results of our experiment, but it seems that a strategy based on "carrying out reduction investment immediately responding to the market price" was not successful. Rather, it seems that a party should *gradually* purchase emissions permits if the market price is cheaper than the marginal abatement cost, and it should *gradually* carry out abatement investment otherwise. In order to verify this statement, however, further experiments are needed.

Experimental economists have found that double auction is one of the best institutions for trading. However, in an environment incorporating investment decisions explicitly such as in our experiment, it seems that double auction is not always the best institution. For example, in bilateral trading, the market price does not move in one direction since information such as price and quantity is not centralized and it therefore takes a considerable amount of time for it to be disseminated to the participants. Further study is also needed on this matter.

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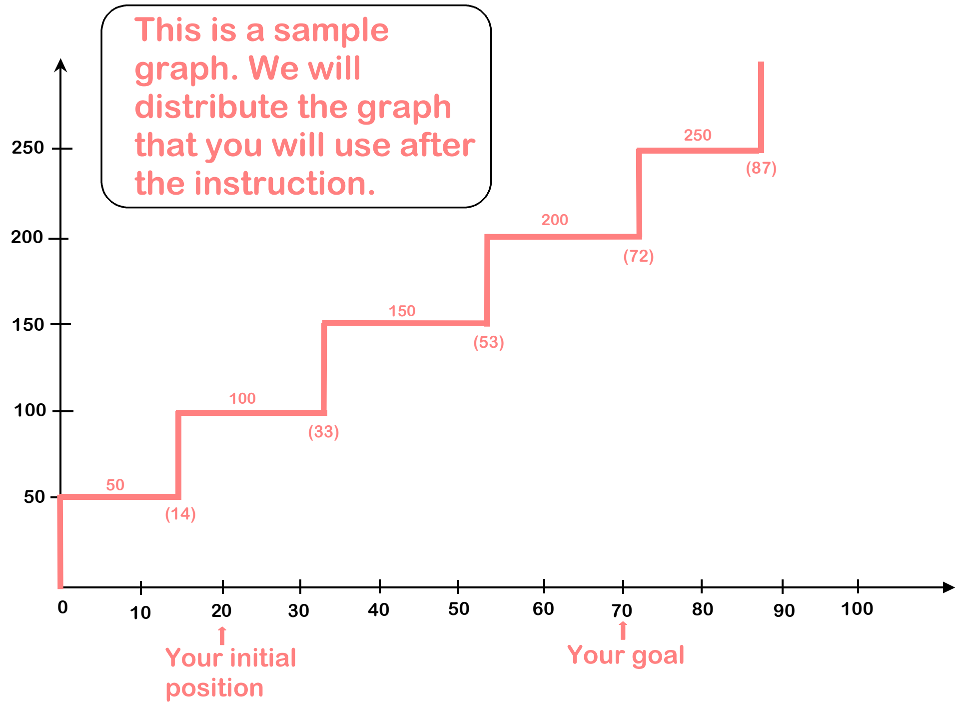


Figure 1. A Sample Graph

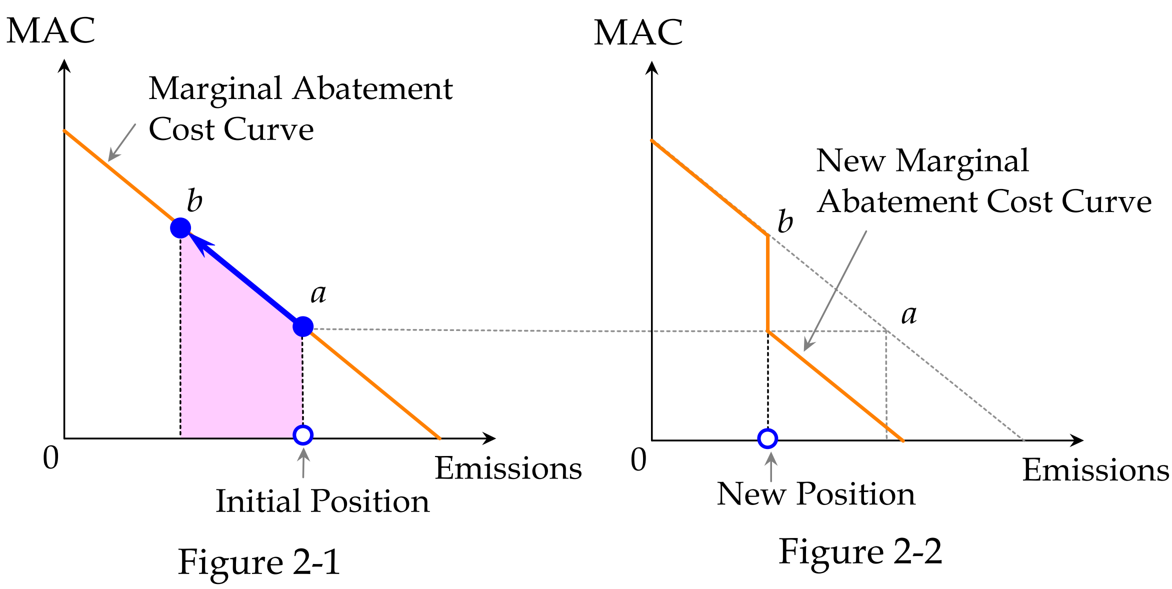


Figure 2. Abatement Irreversibility

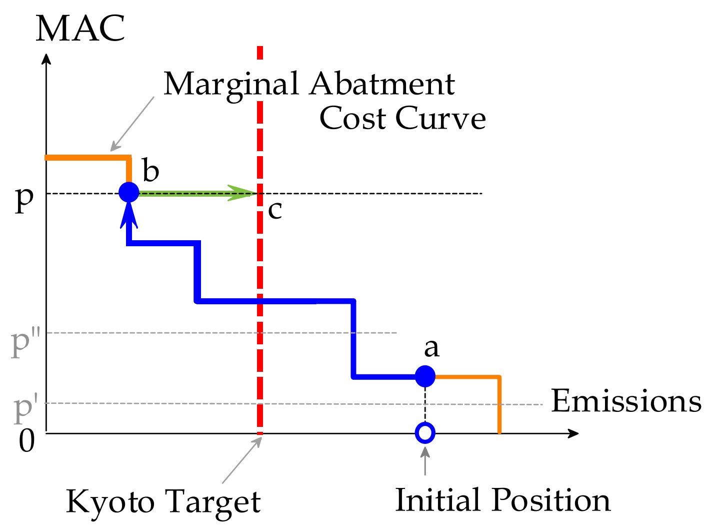
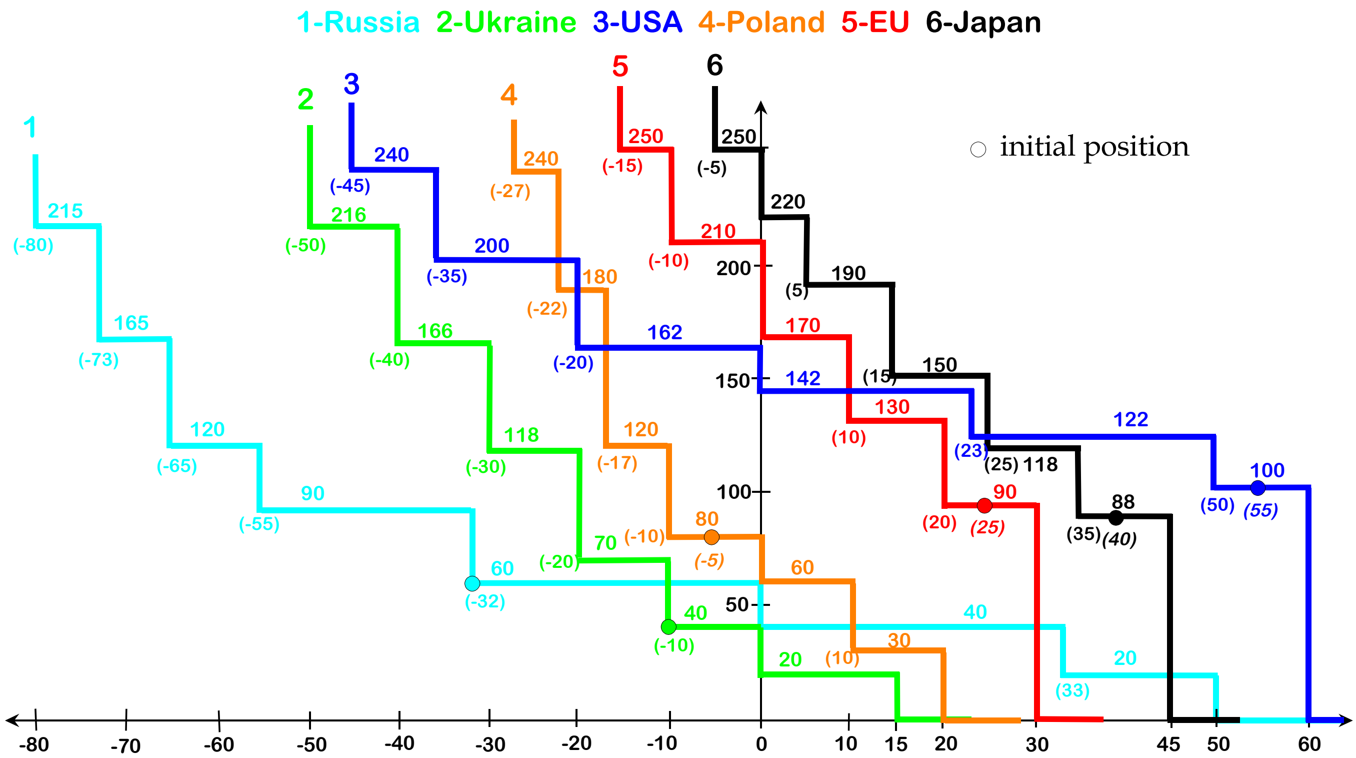


Figure 3. A Possible Strategy



No country names were given to subjects in the experiment.

Figure 4. All Marginal Abatement Cost Curves

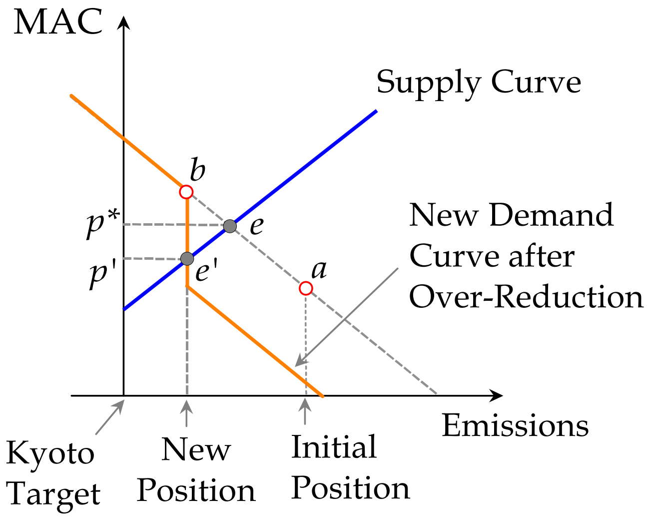


Figure 5. Point Equilibrium

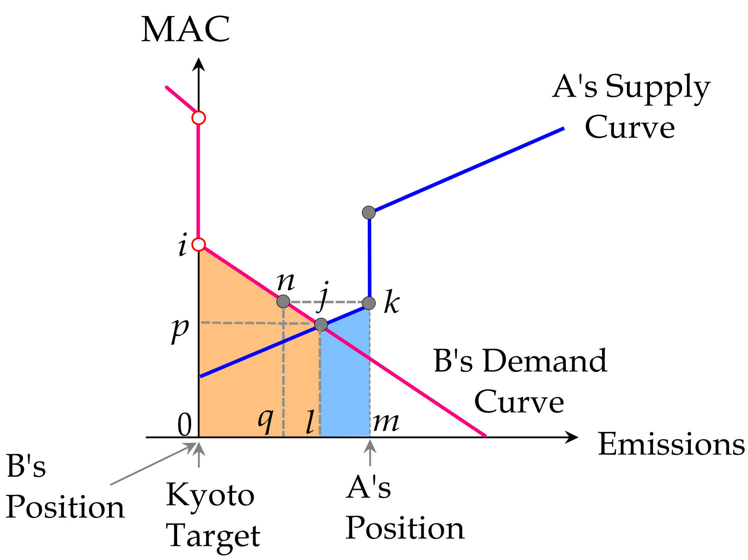


Figure 6. Re-evaluation of Permit Surplus

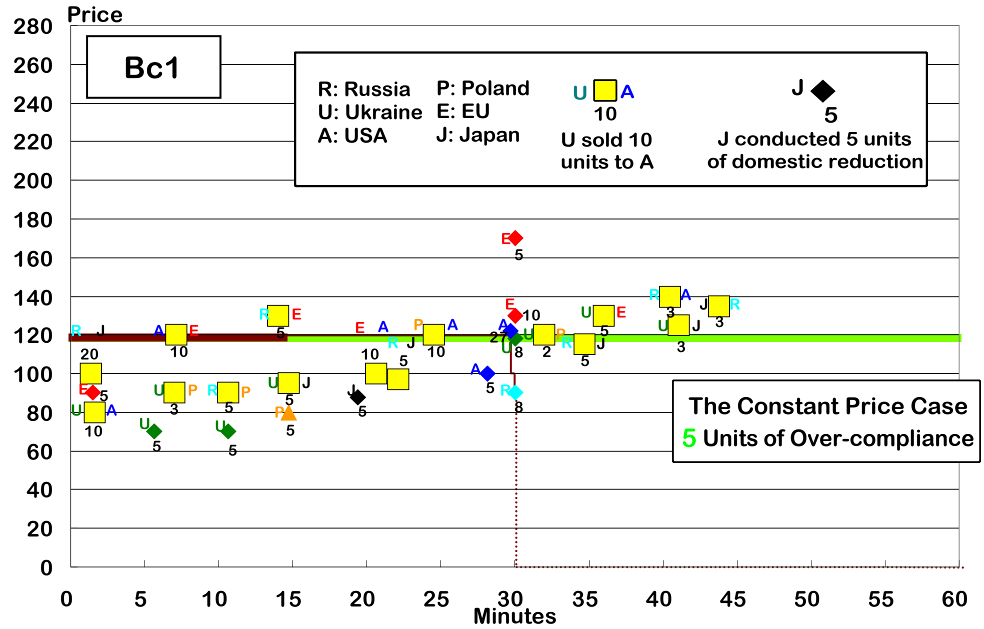


Figure 7. The Constant Price Case

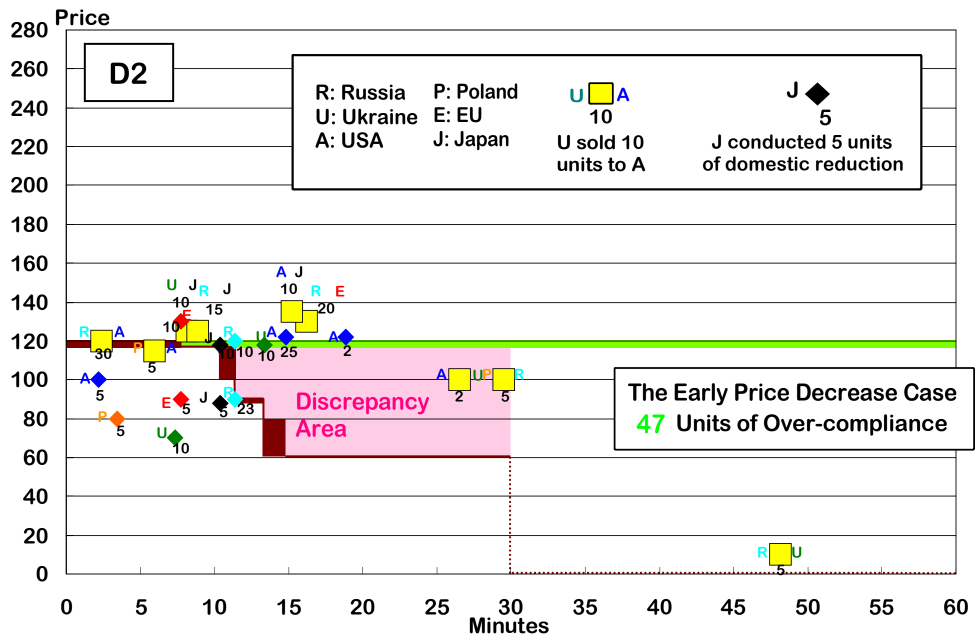


Figure 8. The Early Price Decrease Case

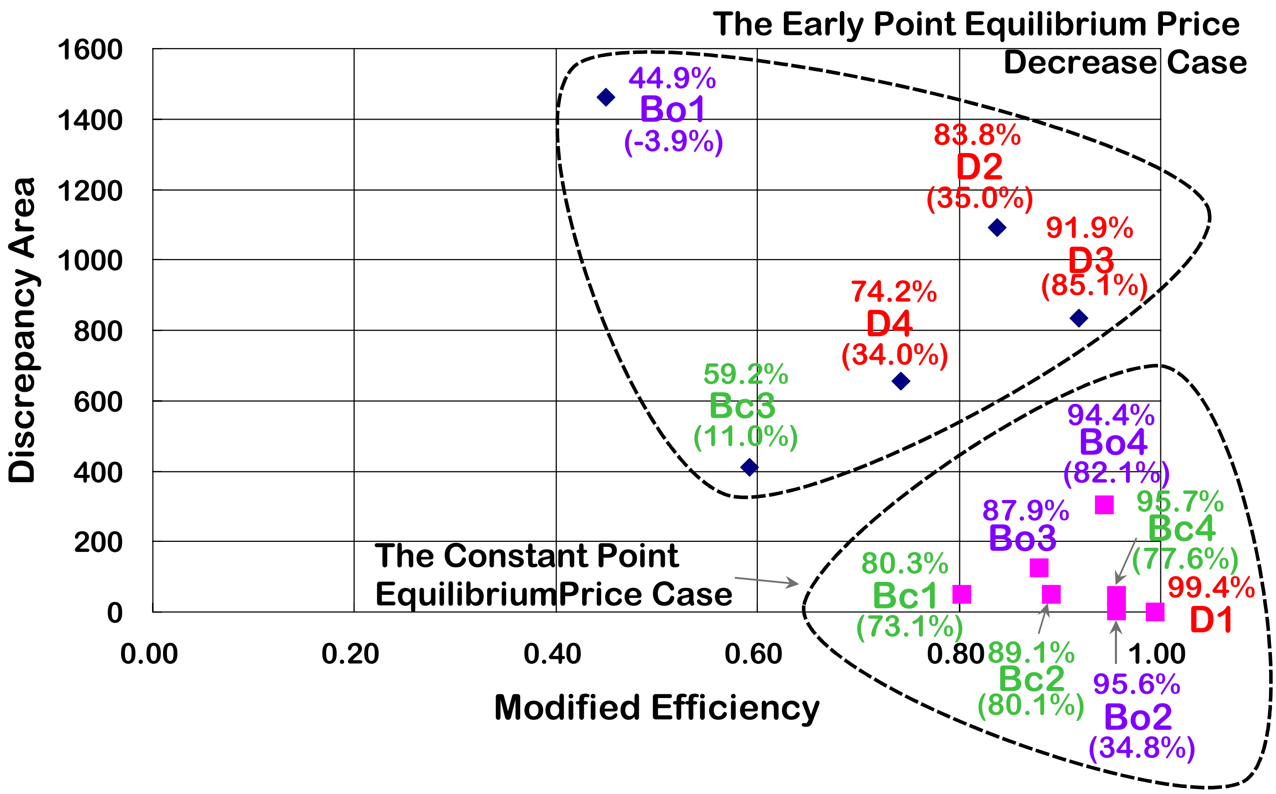
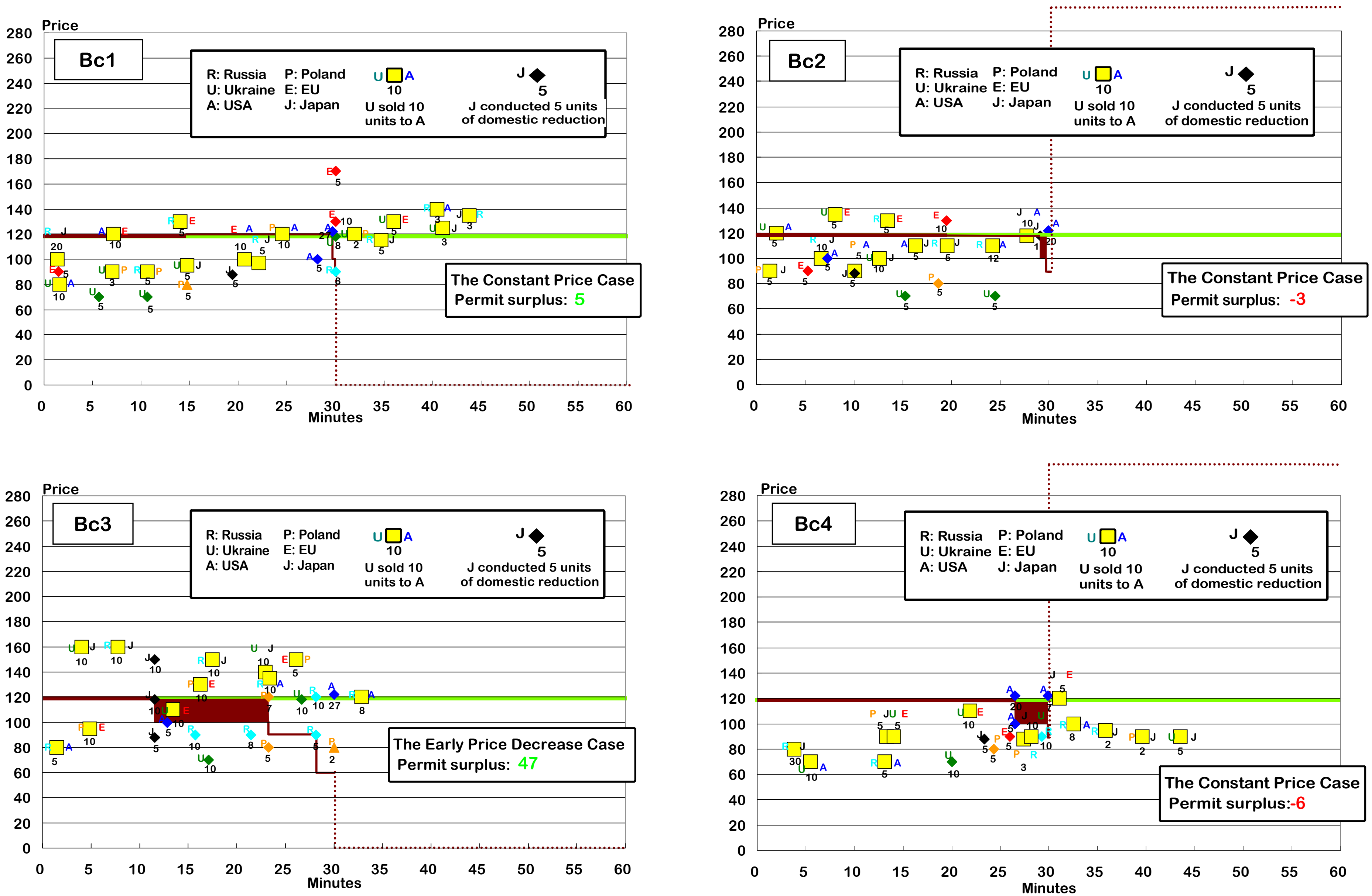


Figure 9. Two Groups

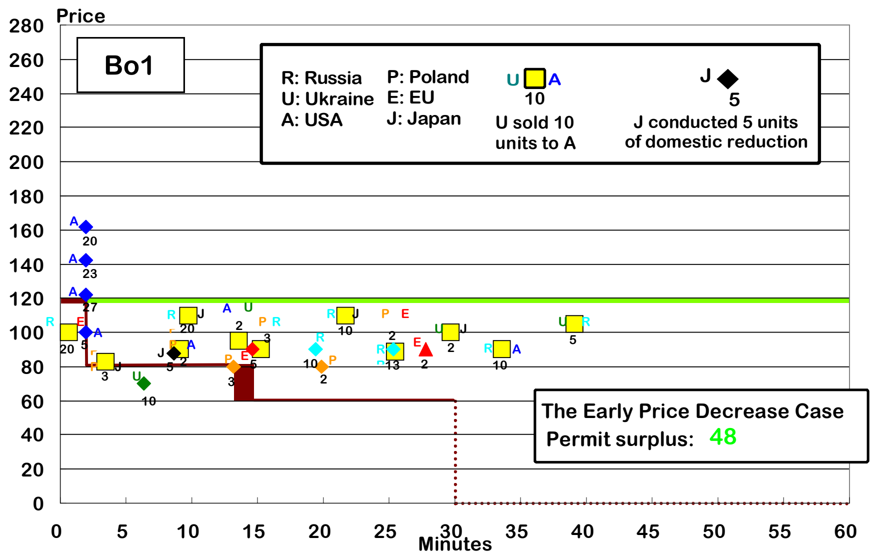
	Bilateral Trading								Double Auction			
Session No. / Subject No.	Bc1	Bc2	Bc3	Bc4	Bo1	Bo2	Bo3	Bo4	D1	D2	D3	D4
1 (2555)	1535	1600	620	656	1415	384	1825	1465	1425	2435	1360	2060
(Russia)	0.601	0.626	0.243	0.257	0.554	0.150	0.714	0.573	0.558	0.953	0.532	0.806
(-32)(-55,0)	-40, 0	-32, 0	-65, -22	-42, 0	-55, -3	-52, 0	-33, 0	-52, 0	-55, 0	-65, 0	-44, 0	-60, 0
2 (1290)	766	1175	1820	700	-565	2625	1285	2200	1195	-30	850	-1925
(Ukraine)	0.594	0.911	1.411	0.543	-0.438	2.035	0.996	1.705	0.926	-0.023	0.659	-1.492
(-10)(-30,0)	-28, 0	-20, 0	-30, 0	-20, 0	-20, -15	-20, 0	-25, 0	-20, 0	-30, 0	-30, -27	-20, 0	-30, -37
3 (610)	1046	220	556	1416	-4130	-4094	481	316	890	641	769	-404
(U.S.A.)	1.715	0.361	0.911	2.321	-6.770	-6.711	0.789	0.518	1.459	1.051	1.261	-0.662
(55)(50,0)	23, 0	*30, 3*	23, 0	23, 0	-20, -30	*50, 23*	23, 0	23, -2	40, 0	23, 0	23, 0	23, 0
4 (390)	240	100	20	94	77	500	300	450	165	275	375	763
(Poland)	0.615	0.256	0.051	0.241	0.197	1.282	0.769	1.154	0.423	0.705	0.962	1.956
(-5)(-10,0)	-5, 0	-10, 0	-17, 0	-10, 0	-10, 0	-10, 0	-13, 0	-10, 0	-10, 0	-10, 0	-11, 0	-17, 0
5 (620)	-650	375	850	850	1002	975	630	965	760	-900	770	682
(EU)	-1.048	0.605	1.371	1.371	1.616	1.573	1.016	1.556	1.226	-1.452	1.242	1.100
(25)(20,0)	5, -5	10, 0	25, 0	20, 0	20, 0	20, 0	20, 0	20, -2	20, 0	10, -10	20, 0	20, 0
6 (1525)	2175	2130	-3100	1710	1931	2040	1625	340	2515	25	1822	1200
(Japan)	1.426	1.397	-2.033	1.121	1.266	1.338	1.066	0.223	1.649	0.016	1.195	0.787
(40)(25,0)	35, 0	25, 0	15, -25	*35, 6*	35, 0	25, 0	25, 0	30, -5	35, 0	25, -10	25, -5	25 , 0
Sum (6990)	5112	5600	766	5426	-270	2430	6146	5736	6950	2446	5946	2376
Efficiency	0.731	0.801	0.110	0.776	-0.039	0.348	0.879	0.821	0.994	0.350	0.851	0.340
Sum (6990)	5612	6230	4136	6686	3140	6680	6146	6596	6950	5856	6426	5186
Modified	0.803	0.891	0.592	0.957	0.449	0.956	0.879	0.944	0.994	0.838	0.919	0.742

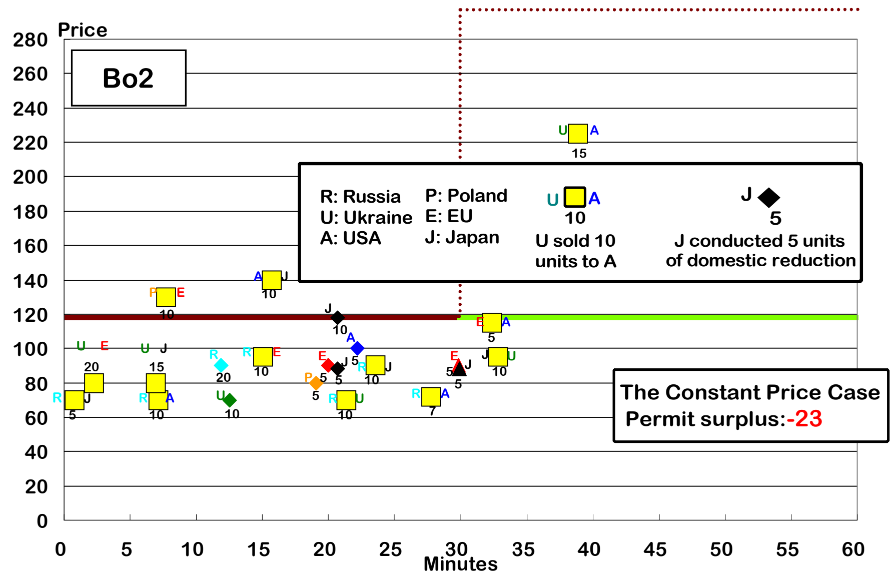
Table 1. Efficiency Table

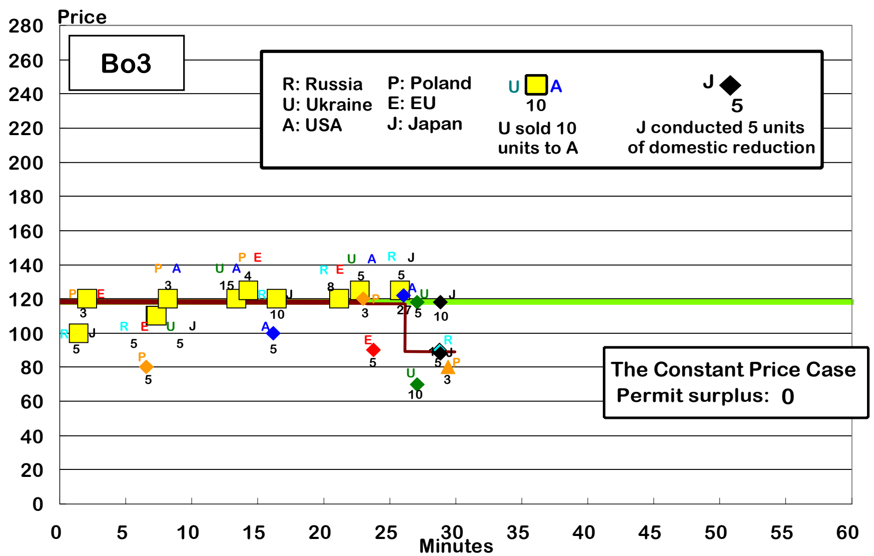
Appendix 1. Price Dynamics (Bc sessions)

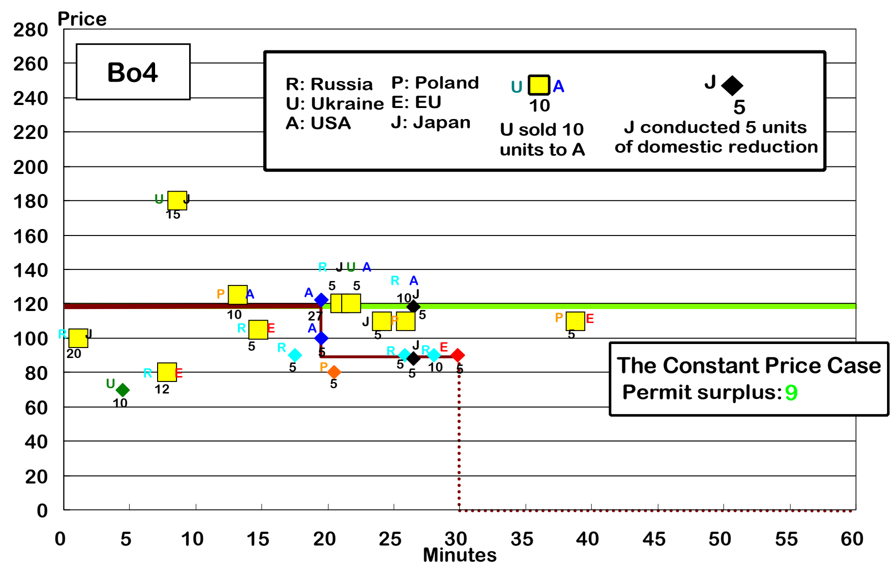


Appendix 1. Price Dynamics (Bo sessions)









Appendix 1. Price Dynamics (D sessions)