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ARTICLE INFO

Erling Moxnes and Carla Susana Assuad (2012). GHG taxes and tradable quotas, experimental evidence of misperceptions and biases. *Environmental Economics*, 3(2)

RELEASED ON

Tuesday, 10 July 2012

JOURNAL

"Environmental Economics"

FOUNDER

LLC “Consulting Publishing Company “Business Perspectives”



NUMBER OF REFERENCES

0



NUMBER OF FIGURES

0



NUMBER OF TABLES

0

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GHG taxes and tradable quotas, experimental evidence of misperceptions and biases

Abstract

The Kyoto Protocol required individual countries to reach certain emission targets by 2012. The research question is: could misperceptions cause countries to choose policies that imply unnecessarily high abatement costs when trying to reach similar targets? The first hypothesis is that decision makers (voters and politicians) do not consider long lifetimes of equipment that emit CO₂ and therefore ignore the benefits of early and natural replacements. In a closed economy laboratory experiment with economics students, T1, the author find postponed policies and costs exceeding benchmarks by 58 percent. Only 25 percent of the participants reach the target. The second hypothesis is that tradable quotas may not solve this problem. In a symmetric five-country treatment, T2, the author finds costs to be higher than in T1, while more participants reach the target. Unwarranted tax differences between symmetric countries motivate inefficient quota trade. The results point to a need for information policies and may be seen to favor uniform taxes over tradable quotas.

Keywords: taxes, permits, carbon market, misperception, climate policy, laboratory experiment.

JEL Classification: H23, Q48, Q54, Q56, Q58, C90.

Introduction

Countries should have found cost-effective ways to decrease greenhouse gas (GHG) emissions to comply with their Kyoto Protocol targets by year 2012 and should find cost-effective ways to deal with targets that may be established for subsequent years. The targets can be achieved either by domestic emission reduction or by buying quotas (or equivalents) in international markets. Policy makers have to choose between these policy options and decide to what extent and when to use them. In democracies these choices may be constrained by limited information and misperceptions among politicians and not the least among their voters.

To explore the possibility of misperceptions we perform a laboratory experiment where subjects are asked to make these difficult policy decisions during 12 years preceding 2012. The GHG tax rate is the only policy option to reduce domestic emissions. The tax rate is a simple and natural choice because it represents a money equivalent of all possible policy options and because it represents a cost-effective policy instrument (Hoel, 1998; Hoel and Karp, 2002; IPCC, 2001, 1995). In treatment T1 subjects set taxes in a closed economy with no interaction with other subjects. In treatment T2 we allow for trade of emission quotas between five symmetric nations. Each country is represented by one subject who sets domestic GHG taxes and who trade in the international quota market.

The main challenge for decision makers is to take account of long delays in the process of reducing GHG emissions. Retrofits are delayed by time needed to perceive benefits, to plan, finance, and to

carry out reconstruction. Replacements of inefficient GHG emitting equipment are delayed by long equipment lifetimes and infrequent natural replacements. Appropriate policies must take account of these delays. If policies to reduce GHG emissions are put in place too late, the adjustments will be unnecessarily costly due to lost opportunities for cheap replacements.

Few journal articles deal with these dynamics when discussing policies for emission reductions or when designing laboratory experiments¹. The most relevant paper in this regard is Lecocq et al. (1998). They studied the impact over time of GHG emission abatement policies using an energy model with two sectors (a flexible housing sector and a rigid transportation sector). They conclude that economical emission reductions require early actions; a conclusion that was repeated by Ruth et al. (2004). This is a key insight for the problem we pose in this study. Without this insight, people may resort to a simple feedback strategy to reduce emissions: start out with low taxes to allow early learning about tax elasticities while postponing costly reductions; then increase taxes until emissions fall below the given target for 2012.

Do politicians and voters understand and take account of the delays when forming opinions? It does not seem likely that people get much guidance from the ongoing debate where the dynamics of replacement are hardly ever mentioned. It seems overly optimistic to assume that insights from the excellent and technical article by Lecocq et al. (1998) have

¹ Some studies focus on estimating curves of marginal abatement costs based on aggregate macroeconomic models or engineering approaches (Criqui et al., 1999; Ellerman and Decaux, 1998). Other studies analyze and compare different climate policies using cost-effective and cost-benefit analysis (Kolstad, 1996; Nordhaus, 1994; Yohe and Wallace, 1996). Laboratory experiments have been used to study market efficiency (Bohm and Carlen, 1999), however, these experiments do not include dynamics.

spread to a wide audience, hardly any citations to the article is one indication. Furthermore, to the extent that people are aware of delays, they usually underestimate their lengths (Sterman, 2000). Even worse, information about delays is not used properly to improve decisions (Brehmer, 1989, Diehl and Sterman, 1995; Sterman, 1989a). The likely reason for this is that people tend to operate with correlational mental models that do not take account of delays (Cronin et al., 2009; Moxnes, 1998b). These misperceptions of delays are related to misperceptions of dynamic systems in general where accumulation processes and feedback effects are misrepresented (Funke, 1991, Moxnes, 1998a; Sterman, 1989a).

Investigations also indicate that people misperceive certain aspects of tax systems. For instance, people do not differ clearly between marginal and average tax rates (De Bartolome, 1995). Eriksen and Fallan (1996) found that people's attitudes towards taxation were influenced by their knowledge about the tax system. Our study adds dynamic aspects to previous studies of taxes. If we reveal biases, that should motivate further research to find ways to correct these.

The laboratory experiment is designed as follows. Information about abatement costs is given to subjects in terms of a curve showing the long-term marginal costs of emission reductions. In treatment T1 subjects are asked to reach a given emission target by 2012 by setting a GHG tax each and every year from 2000 to 2011. Before each new decision, subjects receive feedback about current emissions. They do not receive explicit information about the delays; rather they are encouraged to think of the experiment as capturing all important factors. This design is motivated by the lack of attention to delays in literature and debates. As a separate test of this design, a few subjects received additional information about delays (treatment T1^D). Trade in quotas is not allowed in T1.

Starting from the T1 design, treatment T2 adds quota trading between five identical countries (subjects). Since the game is symmetric, the optimal tax rates are the same as in T1 and there should be no trade. In both treatments the discount rate is the same and players are punished if they do not comply with the target in 2012. Subjects get paid according to how well they perform. The experiment was carried out with economics students who we presume are familiar with the economics jargon of the experiment.

The main question pertains to the participants' understanding of the dynamics of the system. Do the subjects increase taxes early enough to keep costs at a minimum? Will they reach the emission target? Will quota trade influence average tax rates and lead to differences between players (nations)? We find that people tend to set taxes below the benchmark

and many do not reach the emission target, consistent with misperceptions of delays. Average tax rates are not much influenced by trade, however trade leads to greater variation in tax rates between players and thus to unwarranted trade.

The paper is organized as follows. Section 1 describes the underlying simulation model and the experimental design. Section 2 contains the results and the final section discussions and conclusions.

1. The experimental design

We start by presenting the underlying simulation model, which calculates the consequences of GHG taxes in terms of emissions and costs. The model, programmed in Powersim Constructor, is available from the authors upon request.

2.1. Model. Domestic emissions of GHGs are reduced either by replacing worn out capital equipment by new and more efficient equipment or by retrofitting existing equipment. Normally GHG emissions are also influenced by the level of economic activity. However, to simplify, we assume constant economic activity.

Total emissions at a given point in time equals

$$E = E_0 \frac{E_0 - N}{E_0} \times \frac{E_0 - R}{E_0}, \quad (1)$$

where E_0 are the initial emissions in the country, N are the reductions in emissions due to replacements of old with new and more efficient equipment, and R are the reductions in emissions due to retrofits¹. Replacements are a vital component in the model, an attribute that is not usually captured in detail by GHG emission models (Lecocq et al., 1998). Emission reductions through replacements of old by new equipment is in principle modelled as follows

$$\frac{dN}{dt} = N^* \frac{1}{\tau_N} - N \frac{1}{\tau_N}, \quad (2)$$

where N represents the current total emission reductions and N^* is the desired reduction of emissions for the entire capital stock – for a given tax rate. Initially $N = 0$. Due to the lifetime of equipment τ_N , only $1/\tau_N$ of the old equipment is scrapped and replaced by new equipment each year. The average lifetime is set equal to 20 years reflecting lifetimes of refrigerators, automobiles, ships, production equipment, infrastructure etc. Since we have assumed no economic growth there is no need to correct the equation for growth.

¹ Retrofits diminish the potential for reductions through replacements and vice versa. For instance, better insulation of a house through retrofits, reduces the economic potential for further reductions through replacements of inefficient ovens. A linearized version (additive effects) would be more correct for some other examples. The exact formulation is not very important since the GHG tax influences both retrofits and replacements.

Using equation (2) as it is, implies that as soon as N^* increases, the scrapping rate N/τ_N will also increase. This implies a very wide distribution of capital lifetimes including immediate scrapping of some of the new equipment. To get a more narrow distribution belonging to the Erlang family we introduce six cohorts with equal lifetimes of $\tau_N/6$. Now the outflow of emission reductions only depends on emission reductions in the oldest cohort. Similarly, the flow of emission reduction from one cohort to the next depends on the emission reduction in the younger cohort. In general, the outflow from a cohort i is $N_i/(\tau_N/6)$. This outflow becomes the inflow to cohort $i + 1$. The sum of emission reductions equals the sum of reductions in all cohorts, $N = \sum_{i=1}^6 N_i$.

The model implies that some replacements do not have a lasting effect within the time horizon of our study. For instance, an automobile replaced in 2000 may have to be replaced again in 2011. However, this effect is limited by a relatively high fraction of equipment with long lifetimes.

The desired equilibrium emission reduction in new equipment N^* is influenced by the tax rate. The higher the tax rate the greater the desired reduction. The relationship between the tax rate and N^* reflects the set of technologies assumed to be available over the period up to 2012. We have ignored time needed to develop and market new technologies. Hence, we have removed another cause of delays and another reason to increase taxes at an early stage.

We assume that retrofits have a lasting effect (irreversible) within the time horizon of the experiment. This is so because it is most economical to retrofit equipment or constructions with very long lifetimes such as buildings; early scrapping and replacement will have prohibitive costs. This also implies that the potential for retrofits is not restricted by the frequency of replacements.

Since it takes time to decide, plan and carry out retrofits, actual retrofits follow desired retrofits by a delay. The delay is captured by the following equation:

$$\frac{dR}{dt} = \max(0, (R^* - R) / \tau_r), \tag{3}$$

R^* is the desired level of retrofits for a given tax rate and τ_r is the average delay time, equal to 2 years – a low and conservative estimate. The max-function ensures irreversibility. For instance, insulation that has been added to a house will not be removed even though the tax rate and R^* drops again. Since the model does not explicitly allow for behavioral changes in response to tax increases, retrofits could be seen to cover changing habits as well, where the retrofit costs represent adjustment costs.

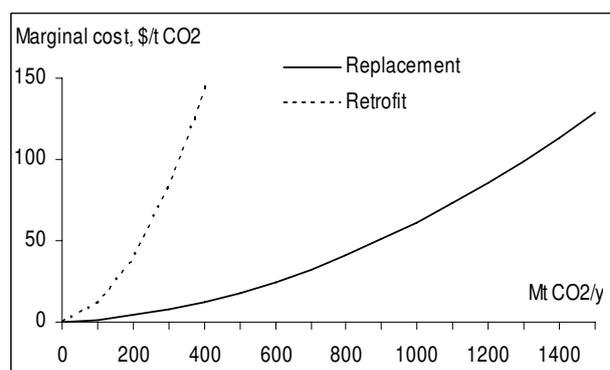


Fig. 1. Marginal cost curves for replacements and retrofits

Figure 1 shows the assumed marginal costs of emission reductions through replacements and retrofits. To establish these curves we first made the assumption that at a given marginal cost, replacements will contribute four times as much emission reduction as retrofits. This is a rough estimate built on our interpretations of Springer and Varilek (2004) and Lecocq et al. (1998).

To establish the absolute cost levels, we calibrated the above curves such that the marginal costs for combined emission reductions corresponded roughly to data for EU (Criqui et al., 1999; Ellerman and Decaux, 1998). Figure 2 shows the combined marginal cost curve shown to the participants. The curve reflects interest rates and the fact that some replacements have to be repeated before 2012. Hence, this cost curve should give a more consistent indication of the needed tax level than typical estimates found in literature, estimates that do not take interests and replacements into account. In this regard the experimental design is conservative. Figure 5 shows that the cost curve gives a good indication of the needed tax level in later years.

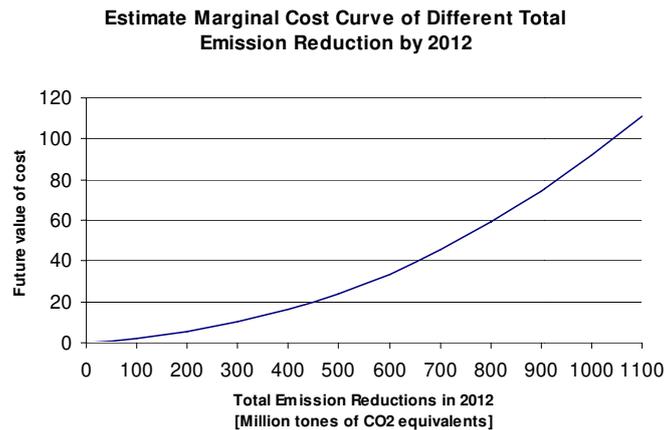


Fig. 2. Future value marginal cost curve shown to the participants

The marginal cost curves in Figure 1 are used to find the desired emission reduction N^* and R^* as functions of the tax rate. We simply assume that desired emission reductions are found where marginal costs equal the tax rate set by the participants. Again this is a conservative design since there are reasons to assume that in reality most people underinvest in energy conservation. The marginal cost curves are integrated to find total costs each year. Yearly costs accumulate over time and interests on accumulated costs are added. The interest rate is set equal to 4% p.a. For those who do not reach their target for emissions by 2012 we add a punishment of \$200 per ton in the last year.

The above model is the same in both treatments. In T2 there is in addition a mechanism for trade between groups of five players. Each player decides on a bid-offer curve each year. These curves are such that at high hypothetical prices, subjects offer quotas and at low hypothetical prices they bid for quotas. A computer routine calculates the equilibrium price given the bid-offer curves of all five players. Once the equilibrium price is established, the quotas are assigned according to the bid-offer curves for the individual players. The trading mechanism resembles a real world system where players give reservation prices to a broker who operates in an ideal market. For both treatments the simulator uses Euler integration and a time step of one year.

1.2. Experimental design. The experiment starts in year 2000 with initial emissions for each player of 4000 Mt/y (million tons of CO₂ equivalents per year). The goal for each participant is to reach a target of 3000 Mt/y by 2012 with as low costs as possible. These numbers are somewhat representative of the Kyoto treaty requirements for the EU¹.

¹ The European Union (EC-12) must reduce emissions in 2012 to 92% of their 1990 emissions. According to EPPA (Criqui et al., 1999; Ellerman and Decaux, 1998) this target for EC-12 emissions is 2773 Mt/y. In EPPA the projected emissions for 2012 are 3901 Mt/y. Compared to the projected emissions, EC-12 should reduce emissions by 1128 Mt/y.

Figure 3 shows the player interface for T1. The upper box displays the current year. Players enter their tax rates in the second box. After the tax rate has been entered, they click a button that makes the simulator advance one year, new decisions are made and so on. The third box gives information about the current emissions, and relates these to the target. First when the game is over, the fourth box gives numerical information regarding total costs and subject payoffs.

YEAR		2012
Decision	Tax Next Year [\$/ton CO2 eq.]	
	<input type="text" value="50"/>	
Information	Current Yearly Emissions	<input type="text" value="3198"/>
	Target for emissions in 2012	<input type="text" value="3000"/>
	Need for Domestic Reduction in 2012	<input type="text" value="198"/>
When game is over	Total Cumulative Cost [Million \$]	<input type="text" value="60242"/>
	Your Pay off is	NOK <input type="text" value="120"/>

Fig. 3. Treatment 1 interface

Subjects were randomly seated in cubicles. In T1 subjects operated in isolation. In T2 they were playing in groups of five, but did not get to know who they were competing with, only that all countries were identical. They were paid privately one by one. The Appendix shows the exact instructions given to and read aloud to the participants.

Figure 4 shows the interface for T2. It is similar to the interface for T1, with the following exceptions. In the information box there is also information about the players¹ holding of emission quotas. If a player has bought quotas, the need for reductions in 2012 is diminished. A negative holding of quo-

tas implies that the need for further reductions increases. A graph is added in the upper part of the interface. By use of the mouse, players move the line in this graph to form bid-offer curves. The program requires that the curve is monotonically decreasing.

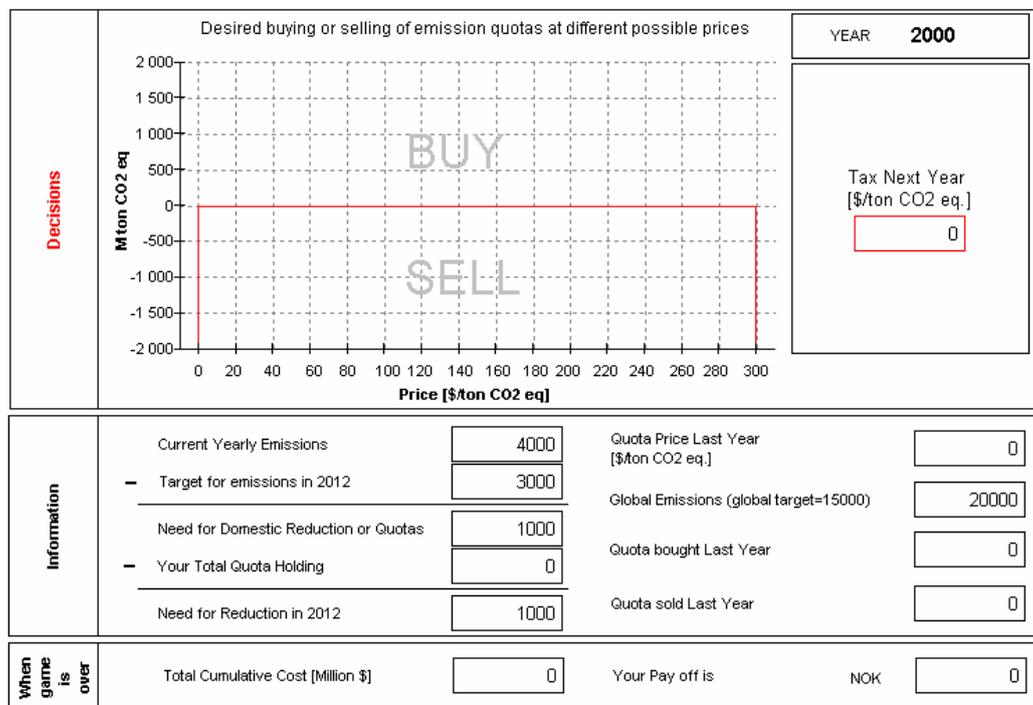


Fig. 4. Treatment 2 interface

The participants were told that the underlying computer model was realistic with the exceptions of no economic growth and no technological improvement. Both assumptions should simplify the task. The instructions did not quantify or mention delays, neither for retrofitting nor for replacements, except for in one special version of T1. In this version T1^D the participants received the following extra information to make them aware of delayed retrofits and that it is only scrapped equipment that is replaced:

“Think of emission reductions as taking place through two different processes. First, with emission taxes in place, emissions from installations with very long lifetimes are reduced by adding insulation in existing houses and by other types of retrofits. This process takes several years. Second, with emission taxes in place, old emitting equipment that is scrapped is immediately replaced with more expensive equipment that emits less CO₂”.

Finally, participants were asked to fill in data for the current year in a handout table to keep a record of history, and as a backup of decisions made.

¹ To guard against errors we used two different optimization packages: Powersim Solver, <http://www.powersim.no/>; and SOPS, <https://www.uib.no/rq/dynamics/research/software>. Both programs and methods gave the same numerical results.

1.3. Benchmarks. To identify the optimal sequence of taxes, subjects have to solve a complex dynamic optimization problem with limited information about the underlying model. We start by assuming full information and use numerical methods to find the optimal sequence of taxes and quota prices. Figure 5 shows the results.

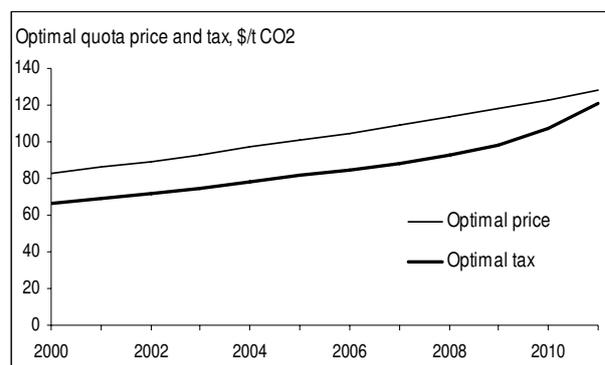


Fig. 5. Benchmarks for taxes and quota prices

The tax and the quota price differ because they represent emission reductions of unequal quality. The quota is a right to emit in 2012 and its price increases with the interest rate (4% p.a.) from beginning to end. The tax is somewhat lower because the tax also leads to emission reductions in short-lived capital equipment. These particular replacements have to be re-

peated before 2012. Thus, with regard to the target in 2012, the early reductions in short-lived equipment are of no value. Another consequence of this is that the path for taxes increases faster than the path for quota prices. Since the T2 game is symmetrical, in optimum there is no trade and consequently the trading institution does not influence the optimal tax.

In the experiment players do not have information, tools, and most likely the ability to optimize. However, we will illustrate how a simple feedback strategy can be used to get very close to the optimal tax sequence. The feedback strategy, however, does require a minimum of qualitative understanding of the delays involved in emission reductions.

Step 1: Set the initial tax.

Start by setting the tax close to the discounted marginal cost at a 1000 Mt/y reduction (about \$90/t/y). To illustrate the adjustment process we choose a tax on the low side, 40 \$/t/y.

Step 2: Keep the tax fixed for three years.

Keep the tax and observe development. The reductions in the first three years are 140, 89, and 62 Mt/y, respectively. The effect drops off as retrofits approach their desired level given by the fixed tax rate. Modestly extrapolating this tendency, an average emission reduction of 50 Mt/y per year over the remaining 9 years yields a total future reduction of 450 Mt/y. Together with the total reduction during the first three years, 291 Mt/y, we project a total reduction of 741 Mt/y in 2012. This is not enough to reach the target of 1000 Mt/y; the tax rate must be increased. A simple linear extrapolation suggests that a tax increase of around 25 percent is needed to reach the target. Since the known marginal cost curve is curving upwards, it seems appropriate to increase the tax rate somewhat more.

Step 3: Repeat

Repeat step 2 with data for new three year periods until the final year is reached.

This quite simple procedure leads to a result close to the optimal cost level for any reasonable starting point.

1.4. Hypotheses. The experiment is motivated by the following hypotheses. In T1 the null hypothesis is the benchmark tax. Alternatively a simple feedback strategy largely ignoring delays implies too low taxes in early years. As a consequence, observations of excessive emissions in later years lead to rapidly increasing taxes. In T2, the null hypothesis is the benchmarks for taxes and quota prices. Alternatively the quota price could be anchored on some salient source of information. The likely candidates are discounted

punishments (200\$/t in 2012) and discounted marginal costs at the desired emission reduction of 1000 Mt (90\$/t). Regarding taxes in T2, one alternative hypothesis is that high quota prices in early years inspire higher taxes in T2 than in T1. Conversely, the existence of a quota market is seen as an easy way out and thus leads to lower taxes in T2 than in T1. We will also explore to what extent variation in taxes among players leads to unwarranted trade. The consequences of all possible biases are summed up in our observations of total costs and emissions in 2012.

1.5. Subjects. The experiment was carried out at the University of Bergen (UiB), Norway, and Universidad Nacional Sede Medellin, Colombia, with bachelor and master students from economics departments. We chose this group for two reasons: they were accessible and likely to understand the economic jargon of the instructions. Student subjects are not perfect representatives of neither the average voter nor the typical decision maker. However, previous studies suggest that misperceptions of dynamic systems are widespread and occur even among experts (Moxnes, 1998a). An a priori assumption that politicians make perfect decisions is negated by numerous examples of policies that fail. Whether this is because of lacking skills among politicians or tactics to win votes from unskilled people is of minor importance here.

Thirty eight subjects from Norway and 43 from Colombia completed the experiment. T1 was accomplished by 28 subjects, T1^D by 8 subjects, and T2 by 40 subjects (an additional group in T2 was discarded because one of the subjects had seriously misunderstood the instructions). To avoid learning effects, no subject participated more than once. The experiment was carried out in 2005, with the exception T1^D which was carried out at the University of Bergen in 2009.

2. Results

We start out by pooling Colombian and Norwegian subjects. In T1 results do not differ much between these subject groups, while in T2 there are significant differences¹. We return to a discussion of these differences later.

Figure 6 shows that the median tax for subjects in T1 is lower than the optimal tax in all years except for the last three; *p*-values show that differences are

¹ In T1 the average difference over all years between median taxes for Colombian and Norwegian subjects is only 2\$/t/y. Median taxes are significantly higher for Colombian subjects in the first year (Mann-Whitney U test, *p* = 0.05). A similar test shows that total costs do not differ between the subject groups. In T2 median taxes do not differ between the two groups in any year (Mann-Whitney U test, *p* > 0.08). Median quota prices differ in all years from 2004 to 2010 (Mann-Whitney U test, 0.02 < *p* < 0.06).

statistically significant except for the years 2007 to 2009 (sign test). We focus on the median because this is the most relevant indicator for democratic decisions¹. Hence we reject the null hypothesis of equality with the benchmark except for the years from 2007 to 2009.

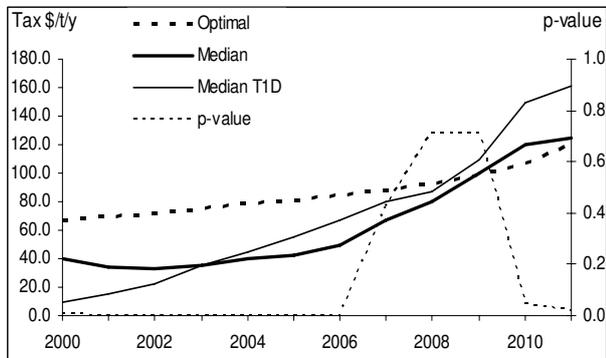


Fig. 6. T1, optimal and median tax and p-values for difference between the two plus median tax for T1^D

Figure 6 also shows median taxes for the 8 subjects that received the additional information about delayed retrofits and the role of replacements. Except for the first and the last year (Mann-Whitney U test, $p = 0.02$) there are no significant differences between T1 and T1^D. The extra information does not lead to higher taxes.

Figure 7 shows that the median tax for subjects in T2 is below the optimal tax in all years. The p-values (sign test) show that the difference is significant in all years. Hence, equality with the benchmark is rejected for all years when a trade option exists.

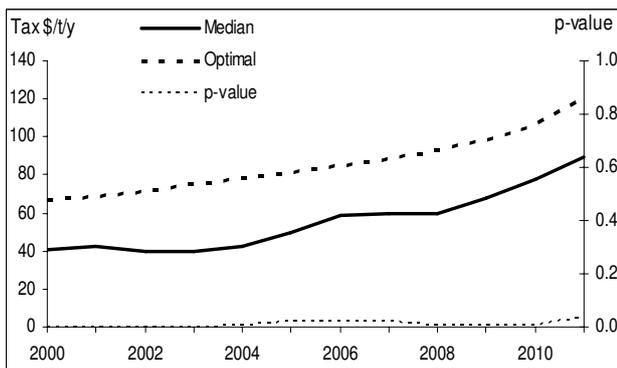


Fig. 7. T2, median, average and optimal tax together with p-values

Figure 8 compares taxes from T1 and T2. The main difference is higher taxes in T1 towards the end of the period. P-values (Mann-Whitney U test) show that the difference is borderline and significant in 2010.

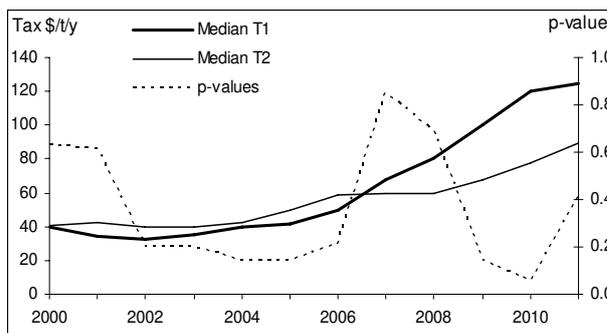


Fig. 8. Median tax in T1 and T2 and p-values

Figure 9 shows that the median quota price exceeds the benchmark quota price in all years. P-values (sign test) indicate significant differences in 7 out of 12 years. If all observations are taken together as independent observations, the median difference between observed and benchmark price is significantly greater than zero (sign test and very low p-value).

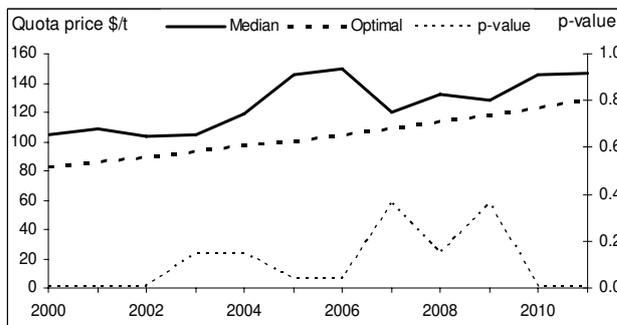


Fig. 9. Average, median and optimal quota price in T2 and p-value

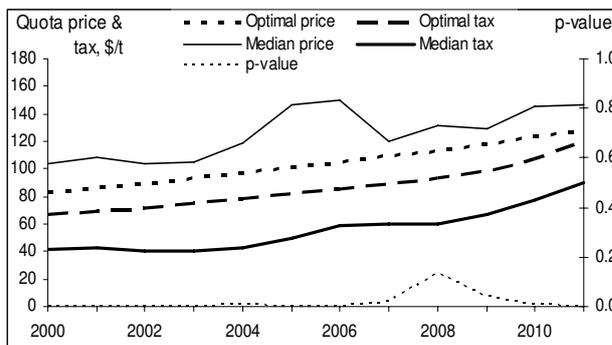


Fig. 10. Benchmark band between optimal quota price and tax, observed band between median quota price and tax, and p-value for difference between band widths

For treatment T2, Figure 10 shows a quite narrow band between benchmark quota prices and benchmark taxes. The band between observed median quota prices and observed median taxes is much wider. In all years, except for 2008, the band for observations is significantly wider than that for benchmarks, measured by median differences (sign test). The graph shows that the quota price exceeds its benchmark with approximately the same amount as the tax is below its benchmark.

¹ Except for the first few years, the average is very close to the median. The average is significantly different from the optimal tax from 2002 to 2008 (t-test).

Table 1 shows that median emissions in 2012 are significantly higher than the target in T1 (sign test). The sample median in T2 is higher than in T1, however, it is not significantly higher than the target. The lowest and the highest emission values

show that the variation is much greater in T2 than in T1; the standard deviations are respectively 137 and 357 Mt/y. The averages are nearly identical, and both are significantly higher than the target (t-test).

Table 1. Domestic emissions in 2012 to be compared to target of 3000 Mt/y

Treatment	Median	p-value sign test	Lowest	Highest	Standard deviation	Average	p-value average
T1	3061	0.002	2925	3457	137	3105	0.0004
T2	3174	0.08	2110	3723	357	3118	0.04

Table 2 shows that in T1, 25 percent of the subjects reduces emissions below the target, exclusively by domestic reductions. In T2, 35 percent reduces below the target, a number that increases to 53 percent when their holdings of quotas are taken into account. Hence, while total emissions are not much influenced by quota trade, more players reach their targets. Yearly data shows that much of this effect comes in the last year.

Costs in T1 vary from 4 to 168 percent above the benchmark costs. The highest costs were obtained by subjects who kept taxes at a low level. However, high costs were also achieved by a few players who set taxes much too high in the first few years. Costs in T2 are considerably higher than in T1 and they vary more. The subject in T2 with the lowest costs benefited mostly from quota trade, but did also have the lowest domestic emissions among those that he or she traded with. The subjects with the second and third lowest costs had the second and the first lowest emissions in their respective groups.

Table 2. Fractions of subjects reaching their emission targets

Treatment	By domestic reductions	By use of quotas
T1	25 %	n.a.
T2	35 %	53 %

Note: n.a. – not available.

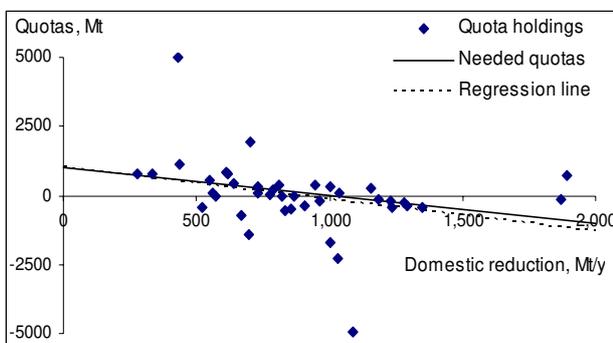


Fig. 11. Quotas versus domestic reductions, T2

Since average and thus total emission reductions are almost identical in the two treatments, the main

reason for cost differences must be greater variation in domestic emission reductions among subjects in T2 than in T1 and/or less than perfect quota trade. To distinguish these two effects consider Figure 11, which shows individual quota holdings in 2012 versus domestic emission reductions in 2012. Since the game is symmetric, the ideal situation is that all individuals reduce domestic emissions by 1000 Mt/y and engage in no trade. All observations to the left or to the right of the 1000 Mt/y point represent inefficiencies where total emission reductions are reached with higher than necessary average marginal costs, recall the convexity of the cost curve.

Given that subjects do choose different tax rates and domestic emission reductions, the straight solid line indicates the need to buy (positive) or sell (negative) quotas to reach the emission target. The larger the domestic reductions are, the lower the need to buy and the higher the need to sell. The dashed “Regression line”, which is not significantly different from the “Needed quotas” line, suggests that subjects on average aim for the needed quotas¹.

All data points above the “Needed quota” line represent subjects that have bought quotas in excess. This is an inefficient adaptation since subjects get no credit for exceeding the emission target. Those below the line lack quotas to reach their targets. This is also inefficient. Although the situation did improve in the last trading period, many subjects would have benefited from more arbitrage in the last years. In the following we report average costs with imperfect and with assumed perfect arbitrage.

Table 3 shows total individual costs. First the medians and the averages are shown with actual and imperfect arbitrage. In T1, median and average exceed the benchmark costs by respectively 52 and 59 percent. In T2, the corresponding numbers are 93 and 206 percent. All cost overruns are highly significant except for the average in T2, where costs are widely distributed.

¹ $Quota\ holdings = -1.18 * Domestic\ reduction + 1038$, p-values for differences from zero are 0.05 and 0.07, respectively. The line for “Needed quotas” has a slope equal to -1.0 and a constant equal to 1000.

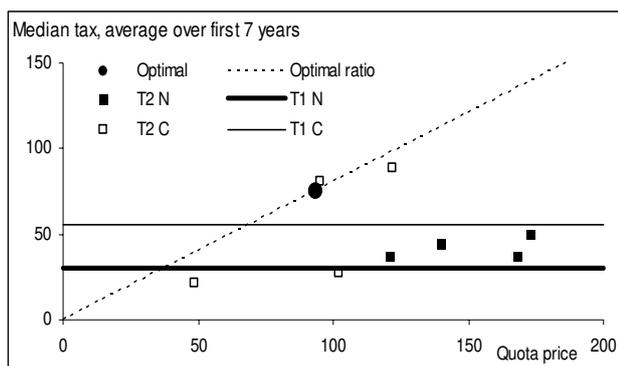
Table 3. Individual costs compared to benchmark costs of M\$44674

Treatment	Median	Average	Average with perfect arbitrage
T1	68061	70703	69563
	+52 %	+58 %	+56 %
T2	86293	136756	78735
	+93 %	+206 %	+76 %

Then we construct average costs under the assumption of perfect arbitrage¹. In T1, perfect arbitrage would have reduced the average by only 2 percentage points, reflecting that few players reduced emissions below the target. Thus, in T1 most of the excess costs are caused by too low taxes.

In T2 perfect arbitrage reduces the average costs by 130 percentage points. Clearly imperfect arbitrage counts for much of the inflated costs in this experiment. Even with perfect arbitrage, costs are still 76 percent above the benchmark. These excess costs are caused by generally too low taxes and by unwarranted variation in tax levels among players.

To see if the T2 results with perfect arbitrage are sensitive to the four most extreme positions shown in Figure 11 (one high and one low quota and two very high domestic reductions), we remove the three groups that contain these four individuals. The effect is not large; the average cost with perfect arbitrage is reduced from 76 to 72 percent above the benchmark cost. It is also interesting to note that most of the cost increases due to lack of arbitrage are caused by two of the groups who account for 76 percent of the 130 percent cost increase.



Note: All numbers are averages over the first 7 years. C = Colombia and N = Norway.

Fig. 12. Median taxes versus quota prices for all groups in T2; median taxes for individuals in T1; and optimal ratio between tax and quota price

Finally, we take a more detailed look at differences between Colombian and Norwegian taxes and quota

prices. Figure 12 shows averages over the first seven years of the experiment, which are important years to ensure low cost emission reductions. We see that in T1 median taxes are higher for Colombian subjects (T1 C) than for Norwegian ones (T1 N). In T2 median taxes for Colombian groups (T2 C) are quite symmetrical around the median for the individuals (T1 C). For Norwegian subjects group taxes (T2 N) are slightly higher than individual taxes (T1 N). With one Colombian exception all quota prices are higher than the optimal (93 \$/t). With one minor Colombian exception, all ratios of median taxes to quota prices are lower than the optimal ratio (all except one data point fall below the dotted line for optimal ratio). With the low number for data points for T2, one cannot make firm claims about differences between the two countries. The most interesting result is that there is variation among groups.

Discussion and conclusion

We discuss taxes, quota trade, and compare them to real markets.

Tax. In treatment T1, subjects were asked to set yearly emission taxes to reach a target for a nation’s GHG emissions in 2012. The subjects started out with taxes below the benchmark and increased them too late to avoid average costs 58 percent above benchmark costs. Only 25 percent reached the target. What are the likely explanations of this mismanagement?

The main hypothesis that motivated this research was based on previous findings that people tend to misperceive dynamic systems in general (Rouwette et al., 2004) and delays in particular (Sterman, 1989b). In the experiment there is a delay in retrofitting emitting equipment and emitting equipment have long lifetimes. For these reasons Lecocq et al. (1998) pointed out the importance of early tax increases, as in our benchmark. Our results suggest that the dynamics of the system are not well understood.

At the outset this may not seem surprising since we did not make the subjects aware of the inherent delays in the model; we only referred to the underlying model as being realistic. However, we omitted information about delays to increase external validity; the public debate hardly ever mentions these delays and there are hardly any journal articles that deal explicitly with these delays. We also felt confident that the results would not change much if we had mentioned delays; according to Brehmer (1989): “... the same effects are obtained when subjects are told about the possibility of delays beforehand as when they are not” A likely explanation is that when making decisions in dynamic systems people operate with simplified mental models where information about delays does not fit in. In accordance

¹ First we subtract the actual punishments paid. Then we add punishments under the assumption that perfect arbitrage has taken place in year 2012.

with these expectations, we found no effect of information when repeating the experiment with explicit information about the dynamics of emission reductions (T1^D).

An alternative explanation to misperception is that the subjects disliked taxes and did not use this instrument as a matter of principle. We cannot rule out this completely. However, we note that in treatment T1 the experiment forced the subjects to use taxes as the only available policy instrument to reach the emission target. Consequently, all subjects did make use of taxes. Even in treatment T2, where they had the quota option, all subjects set positive taxes in nearly all years. Hence the introduction of a second policy option did not lead to systematically lower taxes, as one may suspect if players were averse to using taxes.

We also observe that the introduction of a quota market in treatment T2, had little effect on median taxes, except that the market option seemed to reduce some of the “panic” increase in taxes in the final years. The considerably higher quota prices did not serve to reveal and correct biases in the tax. Hence we did not observe that “rationality stimulated by market-like discipline extends to the non-market setting” as found by Cherry et al. (2003). Two possible explanations come to mind. First, dynamic systems are more complex to deal with than lotteries. Second, setting taxes for one fixed deadline does not allow for repeated trials – as is also the case in reality. Cherry et al. (2003) comments that “Repeated exposure to competition and discipline was needed to achieve rationality.”

Quota market. In treatment T2, subjects were availed with a five player international quota market in addition to the tax option. The median quota price came out higher than the benchmark in all years. Initially, the quota price seems to be predominantly anchored on the undiscounted cost of a 1000 Mt/y emission reduction seen in the cost graph, \$90 per ton. Five out of eight markets started out with quota prices in the range from \$90 to \$110 per ton. Total emissions ended up above the target with the same amount as in T1. Total costs ended up considerable higher than in T1.

There are two reasons why total costs are higher in T2 than in T1, greater spread in taxes and imperfect arbitrage. First, greater spread in taxes among players led to 20 percentage points higher average costs in T2 than in T1, assuming perfect arbitrage. The greater spread in T2 is likely to be explained by differences among players with respect to: propensity to speculate in quotas (which are assets that may invite to speculation (Smith et al., 1988), expectation formation, perceptions of tax effects, risk attitude etc.

Second, insufficient arbitrage in the last year contributed to large cost additions, and particularly so for

two of the groups. Some players speculated in buying and others in selling quotas in the early years. A desire among buyers to sell at a considerably higher price than quotas were bought may have prevented them from selling for a long period. This parallels Smith et al. (1988) who find that asset buyers delay sales until there are few or no potential buyers left. Similarly, those who sold quotas early on may have waited for instances of low prices to repurchase quotas. All this implies that there should be a large potential for trade in the last year. In accordance with this, the average trade volume over all markets was the second highest in the last year, only lower than first year’s trade.

However, last year trade was far from sufficient to meet the potential for arbitrage. Holders of excess quotas did not offer the entire holding at low prices, nor did those in need of quotas bid what they needed at prices that approached the punishment. With five players and thus limited competition such strategies may seem rational. Thus, while trade in the last year equilibrated supply and demand as in previous years, an idealized target of selling all excess quotas or satisfying all excess needs for quotas was not met.

The trading institution may have influenced this outcome. Repeated auctions in the last year would most likely have brought quota holdings closer to optimal levels. Thus, the experiment is likely to have overestimated costs due to lack of arbitrage. This is predominantly a problem affecting the last year and with little effect on other results. Even taxes in 2011 were set before the results of last year’s bid-offer curves were revealed.

Real markets. EU has played a leading role in reducing GHG emissions. They also publish detailed data for their member countries. We focus on the EU-15 countries, ignoring the member states that have joined EU recently. First we consider policy differences as a source of inefficiency. Figure 2 in EEA (2007) shows that there is considerable variation in the gaps between targets and projections for 2010 based on existing policy measures. At the one end, Luxembourg and Austria are projected to lag behind their targets by respectively 39.9 and 30.2 percent of the target. At the other end, Sweden and the United Kingdom are ahead of their targets by respectively 10.4 and 10.7 percent. Under the assumption that the original targets for the individual EU countries were based on a fairness principle, it should be equally difficult or costly for the countries to reach their targets. If so, different achievements reflect differences in national abatement policies rather than in marginal costs. This could be explained by differences with respect to political culture, attitudes towards the environment, awareness of policy efficiencies etc. Accordingly, one can observe

that countries choose different policy measures and different strengths of these. While this line of reasoning suggests that policy differences are likely, clearly, it does not rule out cost differences as one of the explanations for different achievements.

Secondly, we consider delayed abatement policy implementations as a potential source of excessive costs. The column for “2010 projections from 2006” in Figure 1 in EEA (2007) shows that of the lacking 8.0 percent reduction of expected total emissions by 2010, existing measures make up only 0.6 percent. Additional measures are expected to make up 4.0 percent, carbon sinks 0.8 percent, and Kyoto mechanisms (trade) 2.5 percent. Notes to Figure 2 in EEA (2007) bear signs of hurry towards the end of 2007: “In July 2007 Spain adopted a plan of urgent measures against climate change” and “... Denmark plans to reach its target by initiating new national climate initiatives, although these have not been identified yet”. Clearly these measures will be implemented much too late to benefit from efficiency improvements through natural replacements.

Thirdly, will Kyoto targets be met? According to the Marrakesh Accords (and later confirmed in the Bonn Agreement), a “significant element” of national efforts to reduce GHG emissions should be made up by domestic actions. Taking this to mean 100 percent (and ignoring the modest expected use of carbon sinks), 12 out of 15 EU-15 countries are currently projected not to meet their targets. However, cheap emission quotas from Eastern Europe could be used to fill these gaps. Since the unused quotas in Eastern Europe result from unexpected and radical reductions in their heavy industries, this is an escape route implying that EU ends up delivering less than what was intended when signing the Kyoto protocol.

Finally, taxes do not seem to be widely used to reduce GHG emissions even though research points to taxes as a preferred option (Hoel, 1998; Wellisch, 1995). This suggests that when taxes are not the only option for domestic emission reductions, people and politicians behave as if they are averse to taxes (Vollebergh et al., 1997). For most EU-15 countries energy and CO₂ taxes are generally low¹. Reported tax rates are not applied over all economic sectors and in some sectors energy is subsidized. Searching for tax rates in 2008, we found only one CO₂ tax in EU that clearly exceeded the historical quota price of around 20 EUR per ton. Hence average taxes are far below the experienced quota prices. Efficiency losses result since quotas and alternative policies typically limit themselves to large point emissions.

We conclude that there are similarities between our experiment and reality, a similarity that deserves further study. The experiment shows that there is a tendency to misperceive the importance of delays when determining abatement policies, a type of misperception that is known from previous experiments (Brehmer, 1989; Moxnes; Jensen, 2009, Sterman, 1989a). Consequently information about the consequences of delays is needed in policy processes where delays are currently not a theme. To reach emission targets with minimum costs, early policy interventions are needed as suggested by Lecocq et al. (1998) and Schwoon and Tol (2006). Furthermore, our results provide an argument in favor of uniform national abatement policies (e.g., a uniform GHG tax) to prevent quota trade motivated by differences in national policy measures. With an international quota system in place, information is needed that points out the profit potential offered by quota prices that exceed marginal domestic abatement costs.

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¹ In Table 1 Baranzini et al. (2000) compare taxes on energy products between countries. While there are significant taxes on petroleum for transportation – mostly for other reasons than CO₂ emissions – taxes on oil for industrial uses, coal, and natural gas are generally small or non-existent.

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Appendix

1. The Kyoto treaty experiment. The purpose of the Kyoto treaty is to reduce world emissions of greenhouse gases to limit potential future climate change. According to the Kyoto treaty, the countries that have signed the agreement must reach certain targets for their greenhouse gas emissions by the year 2012. The targets can be reached in two ways: (1) countries can reduce their domestic emissions; or (2) they can buy emission quotas from other countries, which in turn must reduce their domestic emissions below their agreed targets to make up for the quotas they have sold.

In this laboratory experiment the world is split in 5 identical countries (or regions). You will each be playing the leader in one of these countries, making all decisions for the country by yourself. Your *goal* is to reach the target with the lowest possible cost.

Each year you have *two decisions* to make: You set a tax rate for emissions of greenhouse gases in your own country and you make bids to buy or to sell emission quotas in a market where all 5 countries interact. From one year to the next, the computer calculates how much the domestic emissions have been reduced due to the tax and the amount of quotas you have bought or sold in the market and at what price.

The experiment starts in year 2000 and the emission goal should be reached by 2012. You cannot reach the target without incurring costs. At the end of the game you will receive a payoff that depends on your total costs. The payoff can vary from NOK 70 for very high total costs to NOK 150 for very low total costs.

Your total costs depend on three factors:

1. Domestic emission reductions cost money for those who have to make the reductions. The tax income for the government is of no concern here; just assume that it is returned to the tax payers as reductions in other taxes. It is assumed that all emission-reduction projects that cost less than the tax rate will be implemented each year. Thus, the higher the tax rate, the larger the costs for domestic emission reductions and of course the larger the emission reductions.
2. If you buy emission quotas in the market you generate a cost. If you sell quotas, you decrease your costs.
3. If you do not reach the emission target by domestic reductions or quotas in 2012 you will be punished with an extra cost of 200 \$/ton CO₂ equivalent for the excessive emissions. Note here that Greenhouse gases are measured in equivalent units of CO₂ (tons of CO₂ equivalents).

Think about the costs as being paid by loans for which you have to pay a 4 percent interest per year. Thus, your total costs in 2012 will include both the direct costs and the interests you have to pay on the loans. Hence, an early reduction in emissions will be more costly than a later and otherwise similar reduction.

To simplify the experiment we assume that there is no economic growth. Furthermore, all emissions reductions must take place with equipment that exists today, there is no technological improvement over time. Your emissions in year 2000 are **4000 million** tons of CO₂ equivalents. Your emission target for year 2012 is **3000 million tons** of CO₂ equivalents. Thus, the needed reduction is **1000 million** tons of CO₂ equivalents.

The experiment is based on studies that have estimated the lowest possible marginal costs of total domestic emission reductions by 2012. The minimum costs require that an optimal sequence of taxes is used. See future values of the minimum marginal costs in the graph below. For your information, a tax of 130 \$/ton CO₂ equivalent corresponds to approximately a doubling of current energy prices.

See Figure 2 in the paper. Each year the computer computes the emissions reductions that follow from chosen tax rates. You should assume that the computer program is highly realistic except for the simplifications already mentioned.

2. How to play. The PC screen is divided in three sections: decisions for the present year, information about the last year, and total costs and payoffs in year 2012. The game progresses in the following sequence: Look at information from last year, make decisions, press the button “Accept Decisions”, the game progresses to the next year, you look at the new information and so on.

Do not press “Accept Decisions” before you have checked your decisions – there is no return once you have advanced to the next year.

3. Decisions. You set the tax rate by entering a number in the Tax box. You make bids for quotas by clicking on the curve and then dragging it to where you want it. At sufficiently low quota prices (to the left in the diagram) you will probably like to buy quotas – if so, the curve should be in the buy region (higher than zero). At sufficiently high prices you will probably like to sell quotas and the curve should be in the sell region (lower than zero). You have to specify the entire curve, such that the computer program knows how much you want to buy or sell at all possible quota prices. The curve may be flat or declining, it cannot bend upwards at any point (if you do, you get an error message and have to change it). An upward bending curve is like saying that you want more quotas the more expensive they are - that does not make sense.

When all players have entered their curves (and their taxes and have clicked on “Accept Decisions”), the computer program finds the quota price that equilibrates the market, that is, total sales equal total purchases.

Information in the last year: Current Yearly Emissions; Target for emissions in 2012; Need for Domestic Reduction or Quotas; Your Total Quota Holding; Need for Domestic Reduction in 2012; Quota Price Last Year; Global Emissions (sum of emissions for all five players); Quotas bought Last Year; Quotas sold Last Year;

Information in 2012: Total Cumulative Cost; Your Pay off.