Environment and Development Economics 5 (2000): 203–220

Theory and Applications

Intertemporal flexibility in a tradeable CO_2 quota system

HEGE WESTSKOG
Centre for Development and the Environment (SUM), University of Oslo

ABSTRACT. The paper compares the total costs of abating CO_2 emissions in two different intertemporal trading systems. In addition, the paper gives an analysis of how abatement costs are distributed among different countries/regions. It is shown that the total cost of implementing a climate treaty is considerably reduced in a system where both banking and borrowing of quotas are allowed compared to a system where quotas only can be banked. The analysis also shows that the total cost of implementing a climate treaty can be reduced in a banking system by compensating the developing country parties for participating in the CO_2 emission reductions such that their net costs of making emissions reductions after sale/purchase of quotas equal zero.

1. Introduction

Greenhouse gas emissions resulting from the use of fossil fuels and other human activities are threatening to raise global temperatures. To prevent this, international cooperation induced through international agreements for reducing emissions of climate gases such as CO_2, is required. A first step towards an agreement to reduce the emissions of greenhouse gases was made in 1988 with the establishment of the Intergovernmental Panel on Climate Change (IPCC). IPCC's goal is to obtain a better scientific understanding of the climate change problem. It was IPCC that provided the scientific material needed for the work with the Framework Convention on Climate Change (FCCC). The historic FCCC was signed by 154 countries at the UN Conference on Environment and Development (UNCED) in Brazil in 1992. The main objective of the FCCC was to stabilise the atmospheric greenhouse gas concentration at a level that would prevent dangerous anthropogenic interference with the climate system. The Kyoto protocol agreed to by the FCCC parties in December 1997 in Kyoto, is the first international agreement where the parties committed themselves to reduce emissions of climate gases.

The Kyoto Protocol makes it possible for the parties to reduce their greenhouse gas emissions through quota trade, by banking excess quotas for the future by participating in 'Joint Implementation' projects and projects defined as the 'Clean Development Mechanism'.[1] In this paper, the abatement cost of a CO_2 quota trading system where banking of quotas is allowed is compared with a system where both banking and borrowing of quotas are permitted. With borrowing of quotas, an agent is allowed to increase its emissions in excess of the quotas it holds against future abatement of emissions. Borrowing of quotas are not permitted by the Kyoto protocol, the parties can only bank quotas for future use. By comparing the costs of abating CO_2 emissions in these two intertemporal trading systems, an estimation of the efficiency loss by only allowing banking of CO_2 quotas in an agreement to reduce emissions of CO_2 is obtained.

The Kyoto protocol is not the main focus of the paper. The time horizon assumed in this paper is longer than the agreement period in the Kyoto protocol and the emission reduction goals for different parties are not the same. The relevance of the results to the cost effectiveness of the Kyoto protocol will however be commented on.

In this paper, the question of burden sharing between countries/regions is also raised. It is analysed how the costs of abating CO_2 emissions are distributed among different countries/regions in the two intertemporal trading systems. In the conducted sensitivity analyses, it is also discussed how different ways of initially allocating CO_2 quotas between agents influence the distribution of abatement costs between countries/regions.

In all the calculations conducted below it is one energy-economy model that is used, which is the model used by Kverndokk (1992). This model is built on the work by Manne and Richels (1991).

Recently some authors have discussed the advantage of introducing intertemporal flexibility in a CO_2 quota trading system. Richels *et al.* (1996) compare different ways of implementing a specific target for abatement of CO_2 emissions.They show that flexibility in where and when CO_2 emission reductions are made can reduce the costs of CO_2 abatament by more than 80 per cent compared to a situation with no interregional and intertemporal emission trading. Kosobud *et al.* (1994) examine the implications of a long-run objective of stabilizing greenhouse gas concentrations at low or moderate risk levels by the year 2100. Their stabilization scenarios are interpreted as the end result of introducing a quota system where both banking and borrowing of quotas are permitted. The quotas are issued all at once for the volume of property rights carved out of atmospheric space as determined by an international agreement. Their models permit estima-

[1] The FCCC divides the parties into Annex 1 countries (these countries are referred to as Annex B countries in the Kyoto Protocol) and non-Annex countries. The countries on the Annex 1 list are the European Community, 24 members of the OECD in 1992 and 12 European States that are undergoing a transition to market economies. The non-Annex countries are developing countries signatories, and they are under no obligation to reduce their greenhouse gas emissions. It is only the Annex 1 countries that can participate in quota trade and 'Joint Implementation' projects. However, by the so called 'Clean Development Mechanism' the Annex 1 countries could invest in projects in non-Annex countries to help them achieve sustainable development, and at the same time contribute to the reduction goal of the Annex 1 parties.

tion of the gains of consumer energy welfare brought about by long-run stabilization scenarios when compared with temperature-equivalent near-term freeze or reduction actions. The gains, while small in terms of total energy welfare discounted over a very long-run horizon, are not trivial when comparing alternative policy choices.

This paper has a different focus than the two articles mentioned above. While both Richels *et al.* (1996) and Kosobud *et al.* (1994) compare the costs of abating CO_2 emissions in a system where both banking and borrowing of quotas are permitted with a quota system with no intertemporal flexibility, the issue of intertemporal cost effectiveness is further studied in my paper when comparing two intertemporal trading systems. In addition, burden-sharing issues are also raised. However, it should be observed that all the analyses mentioned above including this one, focus on the abatement costs of reducing climate gases. The trade-offs between the benefit of avoiding damage from climate change and the abatement costs of doing this are not studied. This is mainly because of the severe difficulties of calculating the damage of climate change. Hence, it is only the cost effectiveness of a certain emission reduction goal that is studied, the efficiency of the goal in itself is not questioned.

In the next section, the details on the abatement cost function and the climate treaty studied in this paper are given. In section 3 the abatement costs of a banking system of quotas are compared to a system where both banking and borrowing of quotas are permitted. Sensitivity analyses are conducted in section 4, while concluding remarks are given in section 5.

2. A comparison of two different intertemporal trading systems

Below the costs of abating CO_2 emissions in two different intertemporal CO_2 quota trading systems are studied. A system where only banking of quotas is permitted is compared to a system where agents can both bank and borrow quotas.[2] It is assumed that some agents have agreed to reduce emissions of CO_2. In both systems considered in this paper they agree to set the target level for CO_2 emissions at Q^0, within a time horizon consisting of T periods. Quotas according to the target level Q^0 are distributed to the agents participating in the agreement in each period t. Each quota specifies an emission allowance for that respective period.

In a banking system, quotas that are not used by an agent in a period t, may be sold to other agents or deposited in an emission bank for future use. An agent also has the possibility of purchasing quotas from other agents in each period. When both banking and borrowing of quotas are permitted, agents can in addition to banking and trading quotas with other

[2] In this paper, it is assumed that it is only CO_2 emissions that are included in a climate treaty. By doing this, the analysis is simplified. Most studies of a climate treaty also do the same. If more gases are included, different data and models than the ones used in this study have to be used, since the abatement cost function will differ with different greenhouse gases. This will obviously be an area for further research. The Kyoto Protocol for instance, includes methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons, and sulphur hexafluoride apart from CO_2 emissions.

agents, pollute more than the amount of quotas they hold in each period, and borrow quotas according to the shortage of quotas in that period.[3] However, it is required that their cumulative deficit is repaid by the end of the time horizon for the agreement consisting of T periods. Observe that an agent in this system can both bank *and* borrow, i.e., an agent can find it profitable to bank quotas in one period and borrow quotas in another period.

An agent will sell/purchase a quota if the price of a quota is higher/lower than its marginal abatement cost. Banking/borrowing of quotas will occur if, *ceteris paribus*, the present value price of a quota increases/decreases. Several factors can lead to an increasing or a decreasing present value price of quotas:

- A positive discount factor will, *ceteris paribus*, lead to a decreasing present value price of quotas;
- Technological progress in abatement will, *ceteris paribus*, lead to a decreasing present value price of quotas;
- Economic growth which increases the demand for fossil fuels, will, *ceteris paribus*, increase the present value price of quotas;
- Changing the amount of quotas initially allocated to an agent in a period without reducing the amount allocated to other agents in that period will, *ceteris paribus*, change the present value price of quotas. For instance, if more quotas are allocated to an agent in the first period without changing the amount of quotas allocated to other agents in that period, this will, *ceteris paribus*, increase the present value price of quotas.

It is assumed that all agents trading on the tradeable CO_2 quota market are price takers. The agents have perfect information of each other's abatement costs. In addition, it is assumed that the agents have perfect foresight about future quota prices. A competitive quota market where both banking and borrowing of quotas are permitted will result in a cost-effective distribution of abatement across agents and across periods (see Rubin, 1996 for a discussion of this issue). However, when restricting intertemporal trade by only allowing banking of quotas, cost effectiveness across periods will depend on how quotas are allocated across periods. If quotas are allocated such that no borrowing will occur in a system where this activity is permitted, cost effectiveness will also be secured in a system where only banking is allowed. On the other hand, if quotas are allocated such that agents will find it profitable to borrow quotas in a banking and borrowing system, there will be cost ineffectiveness across periods in a system where only banking is permitted (see Cronshaw and Kruse, 1996 for a further discussion of this issue).

[3] It is possible that an international agreement will restrict the possibilities for borrowing by introducing a limit on these activities. In this study, it is assumed that if borrowing is permitted, there is no limit for these activities as long as the agent's cumulative deficit is repaid by the end of the agreement period. If the possibility for borrowing is restricted, this will only make the difference in total abatement cost between the banking and borrowing system and the banking system smaller.

Restricting intertemporal trading by only allowing banking of quotas can be done to reduce the temptation to free ride by agents participating in the climate agreement. Internationally no supranational authority exists, and a change of government can make a country change their policy towards cooperation in an international CO_2 agreement. Further, it can be expected that the temptation for a country to free ride, i.e., stop cooperating, increases with the amount of quotas borrowed, since this amount must be repaid by the end of the agreement period. Hence, restricting intertemporal trading by only allowing banking of quotas can be done to reduce this temptation.

2.1. The abatement cost function

The abatement cost function, used in the simulations below, is based on the work by Kverndokk (1993). He uses an abatement cost function derived from an income function for a country.[4] Each agent's abatement cost function is defined as: $C_{jt} = C_{jt}(a_{jt})$, where a_{jt} denotes abatement by agent j in period t.[5] The abatement cost function is increasing and convex ($C'_{jt}(a_{jt}) > 0, C''_{jt}(a_{jt}) > 0$) and can be written in terms of relative abatement

$$C_{jt}(a_{jt}) = \frac{\gamma_{jt} Z_{jt}}{b_{jt}} \left(\frac{a_{jt}}{Z_{jt}} \right)^{b_{jt}} \tag{1}$$

where γ_{jt} signifies the shadow price of CO_2 which can be interpreted as the switch price of CO_2 (i.e., the tax on CO_2 emissions which leads to a total substitution away from fossil fuels to non-fossil fuels backstop technologies). b_{jt} denotes the constant elasticity of costs (i.e., increasing abatement in a country by 1 per cent increases costs by b per cent) and Z_{jt} denotes the business as usual emission by agent j in period t.

The marginal abatement costs are hence as follows

$$\frac{\partial C_{jt}}{\partial a_{jt}} = \gamma_{jt} \left(\frac{a_{jt}}{Z_{jt}} \right)^{b_{jt}-1} \tag{2}$$

For a further discussion of the properties of the abatement cost function and how it is derived, see Kverndokk (1993).

The numerical specifications of γ_{jt}, Z_{jt}, and b_{jt} can be found in Kverndokk (1992). He uses the data source from Manne and Richels (1991) who analyse the abatement costs of different CO_2 emissions targets for five different countries/regions—USA, other OECD countries (OOECD), the former Soviet Union and Eastern Europe (SU-EE), China, and rest of the world (ROW). The model used in their calculations is the intertemporal model Global 2100, covering the period 1990 to 2100. The same grouping of countries and the same time horizon are used in the simulations discussed below. It is assumed that the different agents operating on the

[4] An income function for a country expresses the maximum income a country can obtain under different CO_2 reduction requirements.

[5] It is in the following assumed that the abatement costs in one period do not depend on abatement decisions in previous periods.

competitive market for quotas are the governments in each country. Hence, a region defined in the Global 2100 model is assumed to be an aggregated 'agent' consisting of the different governments in this region.

In the Manne and Richels' (1991) Global 2100 model three key demand parameters are crucial to the debate of energy and environmental futures—potential GDP growth, the elasticity of price-induced substitution (ESUB) and autonomous energy efficiency improvements (AEEI). ESUB describes the possible substitutability between the inputs of capital, labour, and energy and is set to 0.4 for the USA and OOECD and 0.3 for the other regions. AEEI is set to 0.5 per cent annually for the USA and OOECD, 0.25 per cent for SU-EE in the first part of the twenty-first century and 0.5 per cent in the second half. For China and ROW it is set to 1.0 per cent and 0.0 per cent respectively in the first part of the twenty-first century and 0.5 per cent for both in the second half of the century. On the supply side Manne and Richels divide energy inputs into two categories—electricity supply (there are nine different sources where five are existing and four non-existing) and non-electric energy supplies (there are assumed to be eight different sources here). (Details can be found in Manne and Richels, 1991.)

Further, Manne and Richels assume that the unconstrained carbon emissions grow at an average rate of 1.4 per cent per year within the time horizon studied here. This is low by historical standards. It is derived from an assumption of a slowdown in population growth during the twenty-first century and a diminishing rate of GDP growth, and hence a slowdown in the demand for energy (see the study of Manne and Richels (1991) for a further discussion of this issue).

Kverndokk (1993) explains how the different numerical specifications of γ_{jt} and b_{jt} are derived from the Manne and Richels' (1991) study. The γ_{jt} values in year 2000 are calculated as the price per ton of carbon which makes the costs of the fossil energy supplies similar to, or higher than, the costs of the non-fossil backstop in 1990. The switch prices of all different countries/regions decrease linearly to a common value of \$300 per ton of carbon in 2100.

Given the time series of Z_{jt} estimates of each country's/region's GDP without any emission restrictions and the estimates of γ_{jt}, Kverndokk estimates the b_{jt} values from the abatement cost function expressed as relative GDP loss as a function of emission reductions. He uses abatement cost figures at one specific reduction level from the Manne and Richel (1991) study to make the calculations. (Estimates of each country's/region's GDP without any emission restrictions can be found in Manne and Richels 1991.)

2.2. The CO_2 reduction agreement

The Framework Convention on Climate Change (FCCC) emphasizes the need for developed countries to demonstrate that they have a leading role in policies to control greenhouse gas emissions. In essence, the developed countries' signatories have agreed to that role. Developing countries' signatories are under no such obligation. Further, in the Kyoto Protocol it is only the developed country parties that have a commitment to reduce their

https://doi.org/10.1017/S1355770X00000140 Published online by Cambridge University Press

emissions of CO_2. In my study, this is initially reflected by assuming that the developing countries do not make any efforts to reduce their CO_2 emissions until year 2050. The agreement that incorporates this assumption is referred to as the initial agreement in my study. However, a special case is also analysed. The developed countries compensate the developing countries through quota allocation for reducing their CO_2 emissions in the period from year 2000 until year 2050. In this way the developed countries can reduce the abatement costs of reaching their emission goal. This special case is called the compensating agreement and is further described below.

The developed countries are assumed to reduce their CO_2 emissions to the 1990 level by year 2000. In year 2030, they should further have reduced their emissions by 20 per cent from the 1990 level of emissions. Their CO_2 emissions are then stabilized at that level until the end of the time horizon, year 2100. It is likely that when the developing countries reach a sufficient level of GDP per capita they will be prepared to make emissions reductions, which as stated above is assumed to happen in year 2050.[6] The developing countries should stabilize their emissions to the 2050 level of emissions from year 2050 and until the end of the time horizon. (The total global emissions that these emission goals result in by the end of each decade are given in the appendix.)

Quotas corresponding to these total global emission levels are allocated to the different parties that have committed themselves to reduce their emissions of CO_2 (i.e., in the initial agreement the developing country parties do not get any quotas until 2050, neither do they participate in trade of quotas until that date). The quota allocation is made at the beginning of each decade.

Quotas are initially allocated to the different parties proportional to their CO_2 emissions in 1990 for the developed countries and with the emission levels in 2050 for the developing countries. When conducting the sensitivity analyses, three other ways of initially allocating quotas between countries/regions are considered in the comparison of the two different CO_2 quota trading systems:[7]

1. Allocation of quotas proportional to the GDP level of 1990 for the developed countries during the period from 2000 to 2050. From 2050 to 2100 quotas are allocated proportional to the GDP levels of 2050 for all countries.
2. Quotas are allocated proportional to population levels in 1990 for all countries.

[6] It is however, assumed that the developing countries are signatories of an agreement to reduce CO_2 emissions, but without any commitments to reduce their CO_2 emissions until year 2050. This implies for instance that an agreement will state the baseline emission scenario which can be expected for these countries, such that strategic behaviour related to their baseline emissions is avoided later on.

[7] Observe that all allocation rules result in the same level of total global emissions. It is only the way which quotas are allocated *between* agents that differ across the different allocation rules. The exact proportions of total emissions for each region that result from the different allocation rules are given in the appendix.

3. Allocation of quotas according to a combination of allocation rules 1 and 2 with a 50 per cent weight on each of them.

In the agreement referred to as the compensating agreement, the initial assumption that the developing country parties do not make any efforts to reduce their CO_2 emissions until year 2050 is changed. Here it is assumed that the developed countries in order to reduce their costs of reaching the total global emission goal specified above during the period from year 2000 until year 2050, compensate the developing country parties in this period for participating in the CO_2 emission reductions. The compensation is given through quota allocation such that the developing countries' net costs of making emissions reductions after sale/purchase of quotas, from year 2000 and until year 2050, equal zero. Hence, the amount of quotas allocated to China and ROW during this period is given by the compensation required to make them as well off as without any emission reductions conducted. The remaining amount of quotas is allocated between USA, OOECD, and SU-EE proportional to their CO_2 emissions in 1990.[8] From year 2050 and until the end of the time horizon, the developing countries participate in the quota trade without any compensation paid from the developed nations. During this period quotas are allocated to the different parties proportional with their CO_2 emissions in 1990 for the developed countries and with the emission levels in 2050 for the developing countries such that the total global emission goals described in the appendix are reached.

Theoretically, the compensating agreement dominates the initial agreement since in the compensating agreement the developed countries reach their emission goal at a lower cost level, with no costs for the developing countries. However, in practice an agreement like the compensating agreement could be difficult to reach, because of the difficulties of calculating the compensations needed to leave the developing country parties as well off as without any commitments to reduce their emissions.[9] This makes it interesting to study both kinds of agreements when the abatement costs of the banking system are compared to the abatement costs of the banking and borrowing system.

In the calculations carried out below, abatement costs are discounted to year 2000 by 5 per cent per year. In the sensitivity analyses the discount factor is set to 3 per cent per year to study the effects of this factor on the abatement costs and the distribution of abatement costs among countries/regions with the two different CO_2 quota systems studied in this paper.

[8] The compensating agreement can be considered as a kind of all paid 'Joint Implementation Program' where the compensation to developing countries for reducing their emissions is not made through investments in emission reduction projects, but through quota allocation.

[9] The Kyoto Protocol permits developed nations to invest in projects that reduce emissions of climate gases in developing countries. However, the so-called 'Clean Development Mechanism' sets strong limitations to these activities. Only specific investment projects will be certified as projects that contribute to compliance with part of the developed nations' emission reduction commitments.

Table 1. *Percentage-reduced total cost (TC) with a banking and borrowing system (BB) compared to a banking system (BA) (5% discount rate. 1000 billion $)*

Agreement	*TC BA*	*TC BB*	*% red. TC*
Initial	0.856	0.243	71.61
Compensating	0.515	0.243	52.82

3. Cost differences between the banking and borrowing system and the banking system

Table 1 summarizes the results concerning the abatement costs of the banking and borrowing system and the banking system.[10] With the initial agreement, the total abatement costs are reduced by approximately 70 per cent with the banking and borrowing system compared to the banking system at a discount rate of 5 per cent. Introducing the banking and borrowing system to the compensating agreement reduces total abatement costs by approximately 55 per cent compared to the banking system. Hence, both with the initial and the compensating agreement, allowing postponement of emission reductions through borrowing of quotas will reduce total cost of a climate agreement significantly.[11]

Further, table 1 shows that there are practically no cost advantages of a compensating agreement in a banking and borrowing system of quotas. However, with a banking system, introducing a compensating agreement considerably reduces total abatement costs compared to the initial agreement. With a banking and borrowing system of quotas, it is possible to obtain nearly the same effects under the initial agreement as under the compensating agreement, since total abatement costs can be minimized under no restrictions on when emission reductions are done, as long as the target for emission reductions is reached. However, when such restrictions are present, there are considerable cost reductions (total abatement costs are reduced by approximately 40 per cent) with the compensating agreement compared to the initial agreement.

To analyse the distribution of abatement costs of reducing CO_2 emissions among different countries/regions[12] in the banking and borrowing

[10] The GAMS / MINOS system is used to carry out the numerical calculations in this paper. The simulation programs are available in Westskog (1997).

[11] Further calculations with the model used in this study show that abatement costs are not reduced in a banking system compared to a non-intertemporal trading system, where a target for CO_2 emissions has to be reached in each time period with a 5 per cent discount rate. It is the possibility of borrowing that gives the cost advantages.

[12] The division of the world countries into five regions is very broad. Meaningful information concerning burden-sharing issues is still possible to obtain. As Manne and Richels (1991) argue, the climate problem is likely to require differentiated responses by industrialized and developing countries. This distinction is covered by the disaggregation used here. The CO_2 problem is primarily a coal problem today, and, as Manne and Richels argue, 97 per cent of the world's coal resources are contained in OECD, Former Soviet Union, Eastern Europe, and China. Further, the category SU-EE covers the transition economies.

system and the banking system, revenue-adjusted costs are calculated. Revenue-adjusted costs are the total abatement costs of reducing emissions minus (plus) the income (costs) from sale (purchase) of quotas

$$RTC_j^K = \sum_{t=1}^{T} (\delta_t C_{jt}(a_{jt}^{K*}) - \delta_t p_t^{K*} q_{jt}^{K*}) \quad (3)$$

where $K = BA$ and BB. BA denotes the banking system and BB denotes the banking and borrowing system. RTC denotes revenue-adjusted costs

$$\delta_t = \left(\frac{1}{1+r}\right)^t$$

is the discount factor for period t, r is the discount rate and p_t is the price of a quota in period t. q_{jt} denotes the amount of quotas purchased by agent j in period t (if an agent sells quotas, q_{jt} is negative). * indicates optimal values.

As discussed above, the total abatement costs of the banking and borrowing system are much lower than the total abatement costs of the banking system under both types of agreements studied here. The estimates of revenue adjusted costs show that with the initial agreement all countries/regions will prefer the banking and borrowing system to the banking system when quotas are allocated according to emissions (table 2). They will all gain substantially by introducing a banking and borrowing system compared to a banking system. However, under the compensating agreement this picture changes. China and ROW will experience higher total abatement costs, while the total abatement costs for USA, OOECD, and SU-EE will be lower with the banking and borrowing system compared to the banking system of quotas. (Observe that the calculated total abatement costs are for the period from 2000 to 2100. The net costs of emission reductions for China and ROW during the period from

Table 2. *Percentage-reduced revenue adjusted costs (RTC) in different regions with a banking and borrowing system (BB) compared to a banking system (BA) (5% discount rate. 1000 billion $)*

Region	*RTC BA*	*RTC BB*	*% red. RTC*
Initial agreement			
USA	0.398	0.102	74.37
OOECD	0.201	0.080	60.20
SU-EE	0.204	0.036	82.35
CHINA	0.011	0.004	63.64
ROW	0.042	0.021	50.00
Total	0.856	0.243	71.61
Compensating agreement			
USA	0.263	0.070	73.38
OOECD	0.128	0.046	64.06
SU-EE	0.071	−0.001	101.41
CHINA	0.011	0.051	−363.64
ROW	0.042	0.077	−83.33
Total	0.515	0.243	52.82

Table 3. *Percentage-reduced revenue adjusted costs (RTC) in different regions with the compensating agreement (Comp) compared to the initial agreement (Init). banking system (BA) (5% discount rate. 1000 billion $)*

Region	*RTC BA init*	*RTC BA comp*	*% red. RTC*
USA	0.398	0.263	33.92
OOECD	0.201	0.128	36.32
SU-EE	0.204	0.071	65.20
CHINA	0.011	0.011	0.00
ROW	0.042	0.042	0.00
Total	0.856	0.515	39.84

2000 until year 2050 will however, as explained above, equal zero under the compensating agreement.) Hence, China and ROW will prefer a banking system to a banking and borrowing system of quotas with the compensating agreement, while OOECD, SU-EE, and USA will prefer the opposite.

As shown above, with a banking system, there are cost advantages from introducing the compensating agreement rather than the initial agreement, and, as can be seen from table 3, all countries/regions will prefer or be indifferent with the compensating agreement compared to the initial agreement. With the banking and borrowing system there are practically no total cost advantages with introducing the compensating agreement compared to the initial agreement (table 1). Some parties will gain and others lose with the introduction of this kind of agreement.

4. Sensitivity analysis

As pointed out above, technological progress in abatement, economic growth which increases the demand for fossil fuels, discounting, and the amount of quotas allocated to different agents influence the present value price of quotas, and hence the amount of quotas that are borrowed or banked by each agent. The results obtained above can then be modified if the values of these factors are changed in the model. Below it is considered how alterations in the discount factor and the way quotas are allocated between agents will change the results obtained above. How different assumptions of technological progress and economic growth will influence the results are also commented on briefly.

Above, a 5 per cent discounting per year is assumed. A lower discount factor would, *ceteris paribus*, lead to an increased present value price of quotas and hence make the borrowing option less attractive. Hence, with a lower discount factor, a lower difference in total costs between the banking and borrowing system and the banking system can be expected. Table 4 shows that the difference is now 45 per cent in favour of the banking and borrowing system with the initial agreement and 25 per cent with the compensating agreement with a 3 per cent discount rate, which is lower than with a 5 per cent discounting per year.

However, a discount factor of 3 per cent will not alter the other results obtained above significantly. As with a 5 per cent discount rate, table 4 shows that it is the banking system that provides cost advantages for the

Table 4. *Percentage-reduced total cost (TC) with a banking and borrowing system (BB) compared to a banking system (BA) (3% discount rate. 1000 billion $)*

Agreement	*TC BA*	*TC BB*	*% red. TC*
Initial	2.320	1.282	44.74
Compensating	1.702	1.278	24.91

Table 5. *Percentage-reduced revenue adjusted costs (RTC) in different regions with a banking and borrowing system (BB) compared to a banking system (BA) (3% discount rate. 1000 billion $)*

Region	*RTC BA*	*RTC BB*	*% red. RTC*
Initial agreement			
USA	0.911	0.453	50.27
OOECD	0.594	0.371	37.54
SU-EE	0.474	0.186	60.76
CHINA	0.096	0.079	17.71
ROW	0.245	0.193	21.22
Total	2.320	1.282	44.74
Compensating agreement			
USA	0.678	0.320	52.80
OOECD	0.448	0.232	48.21
SU-EE	0.235	0.032	86.38
CHINA	0.096	0.286	−197.92
ROW	0.245	0.408	−66.53
Total	1.702	1.278	24.91

Table 6. *Percentage-reduced revenue adjusted costs (RTC) in different regions with the compensating agreement (Comp) compared to the initial agreement (Init). Banking system (BA) (3% discount rate. 1000 billion $)*

Region	*RTC BA init*	*RTC BA comp*	*% red RTC*
USA	0.911	0.678	25.58
OOECD	0.594	0.448	24.58
SU-EE	0.474	0.235	50.42
CHINA	0.096	0.096	0.00
ROW	0.245	0.245	0.00
Total	2.320	1.702	26.64

compensating agreement compared to the initial agreement with a 3 per cent discount rate. There are practically no cost advantages to introducing a compensating agreement with the banking and borrowing system. Abatement costs will only be distributed differently among agents, some will gain and others lose (or stay at the same cost level as before) (table 4). Under the banking system all countries/regions will prefer (or be indifferent) a compensating agreement to an initial agreement (table 6). Further, all countries/regions will prefer a banking and borrowing system to a banking system with a 3 per cent discount factor under the initial agreement when quotas are allocated according to emissions (table 5). With the compensating agreement, the picture is also equivalent as with a

5 per cent discounting per year. China and ROW will prefer a banking system to a banking and borrowing system, and the other agents will prefer the opposite.

Changing the amount of quotas initially allocated to an agent in a period without reducing the amount allocated to other agents in that period (i.e., the total amount of quotas are changed) will, *ceteris paribus*, change the present value price of quotas. In this study it has only been analysed how a change in the way quotas are allocated between agents without increasing the total amount of quotas available, influence the results. This will not affect the total cost of reducing emissions in a competitive market (Montgomery, 1972). Hence, it is only the distribution of abatement costs among agents that is affected by choosing a different allocation of quotas among agents. Above it is assumed that quotas are allocated according to emissions. Below three other allocation rules are considered: quotas are allocated according to GDP, according to population, and a combination between these two allocation rules (see section 2.2 for a further explanation).

As discussed above, the total abatement costs of the banking and borrowing system are much lower than the total abatement costs of the banking system under both the initial agreement and the compensating agreement. Further, all countries/regions prefer the banking and borrowing system to the banking system under the initial agreement when quotas are allocated according to emissions. However, the estimates of revenue adjusted costs show that not all countries/regions prefer the banking and borrowing system to the banking system with the initial agreement under the other allocation rules considered here. OOECD will prefer a banking system where quotas are allocated proportional to GDP, population, or a combination of these two. ROW will prefer a banking system when quotas are allocated proportional to population. All the other countries/regions will however prefer a banking and borrowing system to a banking system with all allocation rules discussed under the initial agreement. Hence, allocating quotas proportional to emissions, is the only allocation rule where OOECD and ROW will not oppose a banking and borrowing system and prefer a banking system under the initial agreement (see table 7).

Countries/regions have different preferences when choosing between allocation rules under the initial agreement. Looking at revenue adjusted total costs in table 7 shows that USA will prefer that quotas are allocated proportional to GDP. OOECD will prefer the same as USA under a banking and borrowing system, but in a banking system, allocating quotas proportional to population will give the best outcome for them. Allocating quotas proportional to emissions is preferred by China and SU-EE under both systems, while ROW prefers that quotas are distributed proportional to population. Hence, there is no allocation rule that is preferred by all parties in the two systems that are studied here. However, allocating quotas proportional to emissions is the only allocation rule where all countries/regions will prefer a banking and borrowing system to a banking system, such that the substantial gain of introducing a banking and borrowing system can be secured. In addition, this is the best allocation rule

Table 7. *Percentage-reduced revenue adjusted costs (RTC) in different regions with a banking and borrowing system (BB) compared to a banking system (BA). Initial agreement (5% discount rate. 1000 billion $)*

	Allocation rule		
		Emission	
Region	*RTC BA*	*RTC BB*	*% red. RTC*
USA	0.398	0.102	74.37
OOECD	0.201	0.080	60.20
SU-EE	0.204	0.036	82.35
CHINA	0.011	0.004	63.64
ROW	0.042	0.021	50.00
Total	0.856	0.243	71.61
		GDP	
	RTC BA	*RTC BB*	*% red. RTC*
USA	0.339	0.056	83.48
OOECD	−0.332	−0.043	−87.05
SU-EE	0.534	0.042	92.13
CHINA	0.162	0.098	39.51
ROW	0.153	0.090	41.18
Total	0.856	0.243	71.61
		Population	
	RTC BA	*RTC BB*	*% red. RTC*
USA	0.779	0.148	81.00
OOECD	−0.441	0.029	−106.58
SU-EE	0.527	0.079	85.01
CHINA	0.045	0.025	44.44
ROW	−0.054	−0.038	−29.63
Total	0.856	0.243	71.61
		Combined	
	RTC BA	*RTC BB*	*% red. RTC*
USA	0.559	0.102	81.75
OOECD	−0.386	−0.006	−98.45
SU-EE	0.531	0.060	88.70
CHINA	0.103	0.061	40.78
ROW	0.049	0.026	46.94
Total	0.856	0.243	71.61

for China and SU-EE, the second-best alternative for the USA and ROW. It is only the OOECD countries that have this as the worst allocation alternative.

Technological progress in abatement will ceteris paribus lead to a decreasing present value price of quotas, and hence make the borrowing option more attractive. By assuming a higher/lower level of technological progress than in the Global 2100 model (for more details see section 2.1), a larger/lower difference in abatement costs between the banking and borrowing system and the banking system can be expected.

The so-called top–down and bottom–up analysts usually diverge considerably over the question of which values to use in a model when considering technological progress. Top–down models account for technological progress so valued by bottom–up analysis via two parameters: (1) the autonomous energy efficiency improvements (AEEI) and (2) the elasticity of price-induced substitution (ESUB). Of these two parameters, the values of AEEI are the most controversial. The values of AEEI assumed by Manne and Richels (1991) fall between these two modelling traditions for the first half of the twenty-first century. For the second half of the century they have assumed that the AEEI differentials between the regions are likely to decline, and is set to 0.5 per cent for all regions. (Further details on the values of AEEI can be found in section 2.1 above and in Manne and Richels, 1991.) A higher/lower value of AEEI (and ESUB) than assumed by Manne and Richels (1991) will ceteris paribus, as discussed above, lead to a larger/lower difference in total abatement costs between the banking and borrowing system and the banking system.

Economic growth which increases the demand for fossil fuels will ceteris paribus increase the present value price of quotas, and the banking option will be more attractive. The values assumed by Manne and Richels (1991) are as mentioned above (section 2.1) low by historical standards, and there will be a greater advantage from postponing abatement through borrowing of quotas than with a higher growth rate. Hence, a higher economic growth rate can, *ceteris paribus*, reduce the difference in abatement costs between the banking and borrowing system and the banking system.

5. Conclusions and discussion

Three main conclusions can be drawn from this study:

- The design of an intertemporal trading system is important. When both banking and borrowing of quotas are allowed the maximum gain from an intertemporal trading system is obtained, and total costs of abating CO_2 emissions are reduced considerably compared to a system where intertemporal trading is restricted by only allowing quotas to be banked. Lowering the discount factor from 5 to 3 per cent makes the difference in total abatement costs between the banking and borrowing system and the banking system smaller. However, the total abatement costs are still reduced considerably with a 3 per cent discount factor in the banking and borrowing system compared to the banking system.
- The total cost of implementing a climate treaty will also be affected by which countries/regions reduce their CO_2 emissions. In this study it is shown that the total cost of implementing a climate treaty can be reduced in a banking system by compensating developing country parties for participating in the CO_2 emission reductions. The compensation is given such that the developing country parties' net costs of making emissions reductions after sale/purchase of quotas, from year 2000 and until year 2050, equal zero. However, in a banking and borrowing system total abatement costs are practically not reduced by this compensation. In practice, it is only the distribution of total abatement costs between different parties that is changed. This is due to the post-

ponement of abatement by the developed countries through the borrowing of quotas. If the developed countries do most of the abatement after 2050 there are small or practically no cost advantages to compensating the developing countries to reduce emissions at an earlier date than assumed in the so-called initial agreement.
- The sensitivity analyses show that there is no allocation rule that is preferred by all parties in the two different systems that are discussed here. However, allocating quotas proportional to emissions is the only allocation rule where all countries/regions will prefer a banking and borrowing system to a banking system, such that the substantial gain of introducing a banking and borrowing system can be secured. In addition, this is the best allocation rule for China and SU-EE, the second-best alternative for the USA and ROW. It is only the OOECD countries that have this as the worst allocation alternative.

These results clearly show that issue of intertemporal cost effectiveness is important in the design of a climate treaty. The Kyoto Protocol does not permit borrowing of quotas. If it is difficult to reach an agreement where borrowing of quotas is permitted, how a banking system is designed is of importance. Incorporating developing countries in trading of quotas and paying them a compensation for this participation can considerably reduce abatement costs under a banking system. The Kyoto Protocol permits developing countries to participate in abating climate gases by what is referred to as the 'Clean Development Mechanism'. However, this participation is restricted to specific investment projects, and further development of this mechanism in lines with what is referred to as the compensating agreement in this paper, can lead to reductions in total abatement costs.

There are several other issues than those touched upon in this paper that need to be discussed concerning the design of a tradeable quota system. Among these is the chosen time horizon and the way the goal for a better climate is stated in an agreement to reduce greenhouse gas emissions.

In an article from 1996, Wigley, Richels, and Edmonds discuss the goal of the UN Framework Convention on Climate Change to stabilize greenhouse gas concentration at a level that will prevent dangerous anthropogenic interference with the climate system. If such a goal is to be achieved, it is the cumulative level of greenhouse gas emissions that is of importance. In an agreement to reduce greenhouse gas emissions, it is necessary to decide when this concentration level should be achieved. The economic question is to find the most cost-effective emission reduction path towards this point in time. However, different emission reduction paths over time that all lead to stabilization of the concentration at a certain date, can result in different concentration paths over the time horizon for the agreement, and hence different damage effects from climate change.

In such a way, the choice of time horizon for the agreement and the point in time when a specific concentration target is to be achieved will affect the damage costs from climate change. Stabilization at a later point in time can result in worse damage effects because of higher concentration levels of greenhouse gases in the atmosphere during the period towards stabilization, than a choice of stabilization at an earlier date. Hence, when a design of a tradeable quota system is to be discussed, it is important to have this issue in mind—the choice of time horizon will affect the damage from climate change.

The choice of a goal for a climate treaty is an issue closely connected to the choice of time horizon. In this study, the cost effectiveness of a specific emission reduction goal is analysed. This will not necessarily lead to a stabilization of greenhouse gases at a point in time, or neither to damage effects at a certain level. If a specific level of damage effects is chosen as the goal for a climate treaty, there will no longer be equivalence between the different quota systems discussed in this paper. Each quota system can lead to different concentration paths towards a specific point in time, even if the cumulative level of emissions are the same in all quota systems. The goal for a climate treaty in this paper is chosen because this has been the way different countries and regions until now have defined their climate policy. Changing this goal can change the cost estimates obtained in this study.

Acknowledgements

Comments from Michael Hoel, Desmond McNeill and three anonymous referees are highly appreciated.

References

Cronshaw, M. and J.B. Kruse (1996), 'Regulated firms in pollution permit markets with banking', *Journal of Regulatory Economics* **9**: 179–89.

Kosobud, R.F., T. Daly, D.W. South and K.G. Quinn (1994), 'Tradeable cumulative CO_2 permits and global warming control', *The Energy Journal*, **15**: 213–32.

Kverndokk, S. (1992), 'Global CO_2 agreements: a cost-effective approach', Memorandum from Dept of Economics, University of Oslo, No.4, January.

Kverndokk, S. (1993), 'Global CO_2 agreements: a cost-effective approach', *The Energy Journal* **14**: 91–112.

Manne, A.S. and R.G. Richels (1991), 'Global CO_2 emission reductions—the impacts of rising energy costs', *The Energy Journal* **12**: 87–107.

Mongomery, D.W. (1972), 'Markets in licenses and efficient pollution control programs', *Journal of Economic Theory* **5**: 395–418.

Richels, R. *et. al.* (1996), 'The Berlin Mandate: the design of cost-effective mitigation strategies', Energy Modeling Forum, Stanford University, Stanford California.

Rubin, J. (1996), 'A model of intertemporal emission trading, banking and borrowing', *Journal of Environmental Economics and Management* **31**: 269–86.

Westskog, H. (1997), 'Intertemporal flexibility versus non-intertemporal flexibility in a tradeable CO_2-quota system', SUM Working Paper 1997.9, Centre for Development and the Environment, University of Oslo.

Wigley, T.M.L., R. Richels and J.A. Edmonds (1996), 'Economic and environmental choices in the stabilisation of atmospheric CO_2 concentrations', *Nature* **379**: 240–3.

Appendix: Total global emissions and allocation rules

Table A1. *Total global emissions under the initial agreement and the compensating agreement (billion US tons of carbon)*

Year	*Emissions*
2000	6.079
2010	6.552
2020	7.266
2030	7.308
2040	8.013
2050	9.180
2060	9.180
2070	9.180
2080	9.180
2090	9.180
2100	9.180

Table A2. *Different allocation rules (proportions of total emissions)*

Allocation rule	*USA*	*OOECD*	*SU-EE*	*China*	*ROW*	*Total*
Decades: 2000–2040						
Emission	0.31057	0.326404	0.363029			1
GDP	0.30423	0.470763	0.225011			1
Population	0.17942	0.567026	0.253559			1
Combination	0.30423	0.470763	0.225011			1
Decades 2050–2090						
Emission	0.10937	0.114924	0.127778	0.266885	0.381045	1
GDP	0.21695	0.344776	0.161652	0.052752	0.223875	1
Population	0.04729	0.149459	0.066834	0.218608	0.517809	1
Combination	0.13212	0.247118	0.114242	0.13568	0.370842	1